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Evaluating the Carbon and Water Footprints of Livestock Transportation in Japan

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Abstract

This study investigates the environmental impact of rising meat consumption in Japan, focusing on water and carbon footprints associated with livestock production and transportation. We quantify the water footprint of beef cattle and swine, differentiating between direct water use (drinking and service water) and indirect water use (feed production). Our findings reveal a significant contribution of indirect water use to the overall water footprint, with 15,090.3 m^3/ton for beef and 4398.6 m^3/ton for swine, primarily attributed to feed crop production. These results are consistent with previous studies, with minor variations. Furthermore, we simulate transportation scenarios for beef and pork products, considering both road and rail transport. This analysis encompasses key parameters such as transportation volume, direct and indirect water use, CO_2 emissions, and fuel consumption. By evaluating the environmental implications of both livestock farming and product transportation, this study provides valuable insights for sustainable practices and informed policy development in Japan's specific context. Our research contributes to a nuanced understanding of water use patterns in livestock production by distinguishing between direct and indirect water footprints. The integration of transportation simulations further enhances the scope of the study, offering a holistic perspective on the interconnectedness of meat production and distribution. This comprehensive approach aims to support informed decision-making processes in sustainable agriculture, environmental conservation, and policy development within Japan's unique context.

Keywords: water footprint; livestock; virtual water trade; carbon emission

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1. Introduction

Japan has experienced significant shifts in food consumption patterns over recent decades. While annual per capita food consumption has remained relatively stable, a notable trend is the decline in grain consumption and a steady rise in meat consumption [1,2]. This transition towards meat-centric diets has implications for water resource management, particularly in the context of livestock production.

Globally, the increasing consumption of livestock products has led to a greater share of livestock water in total water resources [3–5]. This highlights the importance of understanding the water footprint of livestock production, which encompasses both direct water use (drinking and service water) and indirect water use (feed production). The concept of virtual water, defined as the total amount of water used to produce agricultural and

livestock products [6], provides a framework for assessing the water resource implications of food production and consumption.

The water footprint concept has been further refined to include the entire history of water use, from supply to consumption [7,8]. This includes the green water footprint (water from natural rainfall) and the blue water footprint (irrigation water from rivers or groundwater). Applying the water footprint concept to the agricultural and livestock sectors allows for the estimation of water use changes associated with shifts in production and consumption patterns. Furthermore, it enables the calculation of water resources required to achieve food self-sufficiency targets.

Previous studies have explored various aspects of water footprint calculation, including national water footprints [9,10], virtual water content of livestock products [11–14], and the impact of climate change on water resource availability [15]. However, there is a need for updated data and analysis specific to Japan's current meat consumption patterns and livestock production practices.

This study addresses this gap by calculating the water footprint of major Japanese livestock products, with a focus on distinguishing between direct and indirect water use.

Moreover, integrated meat-production systems have broader environmental externalities, including greenhouse-gas emissions from enteric fermentation and manure management, land and water use for feed production, nutrient runoff, and biodiversity loss [16–20]. Situating carbon and water footprints within a sustainability frame aligns this study with several UN Sustainable Development Goals (SDGs). By jointly quantifying water use (direct drinking/servicing and indirect feed-embedded water) and transport-related carbon emissions, we provide policy-relevant evidence for decarbonizing meat distribution and improving resource efficiency in Japan. This framing complements our country-specific analysis and connects it to global sustainability targets, offering insights for meat-consumption policy, food self-sufficiency, and livestock-water estimation in Japan, with potential applications to other countries with intensive livestock systems.

2. Materials and Methods

2.1. A Gravity Model Framework for Simulating Livestock Transportation

This study analyzes the food network to evaluate the impacts of local food policies on the food–water nexus. We employ a gravity model adapted for spatial interaction (SI) between food-producing and food-demanding areas. The gravity model conceptualizes SI as various movements, with the underlying assumption that flows are a function of the attributes of and the distance between origin and destination points [21,22].

To simulate SI within the food network, we use the balance of food supply and demand as the attraction factor and the distances between prefectures as the friction factor, as shown in Equation (1)

$$SI_{ij} = AE_i \times RI_j \times r_{ij}^{-\alpha} \quad (1)$$

where SI_{ij} represents the spatial interaction between prefectures i and j; AE is the amount of products available for exports; RI is the requirement of product import; r is the distance between prefectures, and α is the friction parameter. We have clarified that α is the friction (or distance-decay) parameter, representing the weighting of transportation distance relative to the production and consumption of livestock products. The assumption of $\alpha = 2$ is justified by referencing the conventional gravity model. This value, representing an inverse-square relationship, is a standard and widely accepted exponent in spatial interaction modeling.

Distance between prefectures acts as a friction factor in the food trade. Ideally, the friction parameter (α) should be estimated using observed data. However, due to the lack of inter-prefectural local trade data, we assume an α of 2 for the food network. For distance

calculation, we use the straight-line distance between prefectural center points calculated using ArcMap 10.1. This simplification acknowledges the complexity of real-world transportation systems, including variations in road types and infrastructure. Another limitation is the lack of data for validating the food network simulation. Given the availability of only local production and consumption data, we first simulate potential trade volumes and compare the simulated prefectural production and consumption with historical data. We then re-simulate the food network, adjusting for discrepancies between simulated and historical values (Equations (2)–(4)).

$$EX^1(i,j) = SI_{ij} \times \left(\sum_i SI_{ij}\right)^{-1} \times RI_j \quad (2)$$

$$EX^{2n}(i,j) = EX^{2n-1}(i,j) \times \left\{\sum_i EX^{2n-1}(i,j)\right\}^{-1} \times RI_j \quad (3)$$

$$EX^{2n+1}(i,j) = EX^{2n}(i,j) \times \left\{\sum_j EX^{2n}(i,j)\right\}^{-1} \times AE_i$$

$$D_i = \sum_j EX^{2n}(i,j) - AE_i \quad (4)$$

$$D_j = \sum_i EX^{2n+1}(i,j) - RI_j$$

where EX(i,j) is the export from prefecture i to prefecture j; RI_j is the import requirement in prefecture j; AE_i is the available export in prefecture i; $EX^n(i,j)$ is the iteration function of exports from prefecture i to prefecture j, and n represents the number of iterations. D_i represents the difference between the sum of simulated exports and AE in prefecture i, and D_j is the difference between the sum of simulated exports and RI in prefecture j. These processes were iterated until D_i and D_j reached less than 1% for both AE and RI in all prefectures.

2.2. Unveiling the Hidden Water Use in Livestock Products: Direct and Indirect Water Footprints

The water footprint of livestock products encompasses the total volume of water consumed throughout the production process [23]. It can be categorized into direct and indirect water use. Direct water use refers to the water consumed directly by livestock for drinking and cleaning purposes. Indirect water use accounts for the virtual water embedded in feed crops consumed by livestock [11]. This includes the water used for feed crop production and the virtual water associated with converting livestock into meat products. This study focuses on the water footprint of livestock production, providing valuable data for informing food policies.

$$WF = VWC_{feed} + VWC_{drink} + VWC_{serv} \quad (5)$$

In this formula, WF means the Water Footprint of livestock products, VWC_{feed} means the amount of water used for producing materials and virtual water as indirect water, and VWC_{drink} and VWC_{serv} mean the amount of virtual water used for drinking and servicing livestock as direct water.

2.2.1. Water Footprint from Drinking and Servicing Water (Direct Water)

The direct water footprint includes drinking and service water consumed by livestock during the breeding period. To calculate this, data on the total breeding period and daily water consumption per animal are required. This study utilizes research data from Japan and the United States to estimate the direct water footprint. The average breeding period for each livestock species in Japan was determined, and overseas research materials were used to estimate daily drinking and service water consumption per animal. The total drinking and service water consumption during the breeding period was then calculated.

To standardize the water footprint per unit of meat production, carcass weight was used as the denominator. The following formula was used to calculate the direct water footprint:

$$VWC_{drink}[a] = \frac{\int_{birth}^{slaughter} q_d[a]dt}{W_a[a]} \quad (6)$$

$$VWC_{serv}[a] = \frac{\int_{birth}^{slaughter} q_{serv}[a]dt}{W_a[a]} \quad (7)$$

In this formula, VWC_{drink} and VWC_{serv} mean virtual water quantities for drinking and servicing of livestock (a), which are calculated as the sum of daily drinking water (q_d) and daily servicing water (q_{serv}) used from the birth of the livestock (birth) to death of livestock (slaughter). The total amount of drinking and servicing water used per livestock was divided by the carcass weight at slaughter ($W[a]$).

2.2.2. Water Footprint by Feed Consumption (Indirect Water)

The indirect water footprint represents the virtual water consumption associated with the feed consumed by livestock during the breeding period. This was calculated by considering the consumption of concentrated feed and roughage during the breeding period and the water footprint of each feed crop. The indirect water footprint was then divided by carcass weight to determine the virtual water consumption per ton of meat produced for each livestock species. The following formula was used to calculate the indirect water footprint:

$$VWC_{feed}[a] = \frac{\int_{birth}^{slaughter} \{\sum_{c=1}^{n_c} WF[c] \times C[a,c]\}dt}{W_a[a]} \quad (8)$$

In this formula, VWC_{feed} and VWC_{serv} denotes virtual water quantities for producing feed crops as an indirect water quantity, which is calculated by utilizing the daily consumption of feed crop (c) per livestock (a) ($C[a,c]$) and the water footprint of feed crop ($WF[c]$) used from the birth of livestock (birth) to death of livestock (slaughter). This virtual quantity is used per head of livestock and is divided by the carcass weight at slaughter ($W[a]$).

2.3. Forecasting the Carbon Footprint of Livestock Transportation

To assess the energy consumption and carbon emissions associated with livestock transportation, a simulation of meat transportation was conducted. This simulation focused on the movement of livestock products within Japan, quantifying the transportation volume and energy consumed by producers. Domestic transportation distances were determined using Google Maps for road transport (distances between prefectural offices) and a station distance search tool (https://www.jorudan.co.jp/, accessed on 5 May 2025) for rail transport (distances between representative stations by prefecture). The simulation employed an optimization scenario based on a gravity model, considering distance, production, and consumption.

Transport CO_2 was computed using the fuel-based method (CO_2 = fuel energy × emission factor) [24].

2.4. Data Collection

Various data sources were used to calculate the water footprint of beef cattle and swine, the primary livestock species in Japan and Korea. Data on breeding periods and daily direct water consumption were collected to calculate the consumption of drinking and service water for each livestock species. Due to the limited availability of Korean and

Japanese studies, the results of [11] were utilized (Table 1). The livestock breeding method was assumed to be barn-type, the predominant method in Korea and Japan.

Table 1. Water from drinking and servicing.

Kind of Animal (Farming System: Industrial)	Water from Drinking		Water from Servicing	
Beef cattle	Clave	Adult	Clave	Adult
Age (month)	4	30	4	30
Daily consumption (L/day/animal)	5	38	2	11
Swine	Piglet	Adult	Piglet	Adult
Age (month)	0.4	6.19	0.4	6.19
Daily consumption (L/day/animal)	2	14	5	50

Note: Sources: [11].

For indirect water footprint calculations, data on breeding periods, daily feeding amounts, and water footprints of feed crops were collected. Japanese feeding standards were used for breeding periods and daily feeding amounts (Table 2). Water footprint data for major feed crops, such as corn and soybean meal, were obtained from [8], while data for other crops and roughage were sourced from [4,9] (Table 3). The formulation ratio of forage crops was determined using the feed usage status of beef cattle and swine from the Survey on [25] (Table 3).

Table 2. Breeding period and amount of feed.

Kind of Animal (Farming System: Industrial)	Breeding Period																								
	First						Second										Third							Fourth	
Beef cattle [1]																									
Age (month)	3	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Supply of formula feed (kg/day)	1.5	3.5	4	4	4.5	4.5	5	6	7	8	9	10	11	11	11	11	11	11	11	10	9.5	9.5	9.5	9.5	9.5
Supply of forage (Dry hay) (kg/day)	1.5	2.5	2.5	3	3	3	4.5	4.5	4.5	4.5	4	3.5	3.5	2.5	2.5	2	2	2	2	1.5	1.5	1.5	1.5	1.5	1.5
Swine [2]																									
Age (month)	2	4	6	7	9		10	11	12	13	15		16	18	20	25									
Supply of formula feed (kg/day)	5	10	15	20	25		1.5	1.7	1.8	2.2	2.6		2.8	3	3.2	3.4									

Notes: [1] Sources: Japanese Feeding standard for Beef cattle, Japan Livestock Technology association. [2] Sources: Japanese Feeding standard for Swine, Japan Livestock Industry Association.

Table 3. Water footprint of feed crops.

Feed Crops		Mixing Ratio (%)	Water Footprint of Crop (m^3/Ton)
Formula feed	Maize	40.00%	674.3
	Naked Barley	15.60%	1278.6
	Wheat Bran	15.50%	1805
	Soybean Meal	5.90%	1749.7
	Others	22.90%	1113.3
Forage (Dry hay)		-	494

Note: Sources: Results of the survey of the assorted feed industry by the Ministry of Agriculture, Forestry and Fisheries.

To calculate the water footprint per unit of meat production, data on meat yield from the Japanese Ministry of Agriculture, Forestry, and Fisheries were used to convert livestock numbers to production units (Table 4).

Table 4. Live weight of animal at slaughter and carcass.

Beef Cattle [1]		Swine [2]	
Live Weight (kg)	**Dressed Carcass (kg)**	**Live Weight (kg)**	**Dressed Carcass (kg)**
710	450	110	80

Notes: [1] Ministry of Agriculture, Forestry and Fisheries (https://www.maff.go.jp, accessed on 20 May 2025). [2] Hyogo Prefecture (https://web.pref.hyogo.lg.jp, accessed on 20 May 2025).

3. Results and Discussion

3.1. Livestock Water Footprint Calculation

Water footprint of beef cattle, the daily consumption of drinking water and servicing water corresponding to direct water is up to 38 and 11 L/day/animal, respectively, and the calculation of drinking and servicing water used per ton of beef by applying daily consumption, total breeding period, and 450 kg of carcass weight at slaughter was 77.3 m^3/ton and 22.4 m^3/ton, respectively (Table 5).

Table 5. Total water from drinking and servicing of beef cattle.

Kind of Animal: Beef Cattle (Farming System: Industrial)	**Water from Drinking**		**Water from Servicing**	
	Clave	**Adult Cow**	**Clave**	**Adult Cow**
Age (month)	4	30	4	30
Daily consumption (L/day/animal) [1]	5	38	2	11
Live weight of animal at slaughter (ton) [2]	0.45			
Total water required (m^3/ton)	1.4	77.3	0.5	22.4
	78.6		22.9	

Notes: [1] [11]. [2] Ministry of Agriculture, Forestry and Fisheries (https://www.maff.go.jp).

The total consumption of indirect water per beef cattle, including feed consumption, was calculated at 1629.9 m^3/animal for maize, 1207.5 m^3/animal for naked barley, 1805 m^3/animal for wheat bran, 1749.7 m^3/animal for soybean meal and 1113.3 m^3/animal for others. Therefore, the water footprint of feed consumption for each ton of beef with a carcass weight of 450 kg was calculated at approximately 15,090.3 m^3/ton, as shown in Table 6.

Table 6. Total water from feeding of beef cattle.

Component of Feed	**Mixing Ratio (%)** [1]	**Amount of Feed (Ton/Animal)**	**WF of Crop (m^3/Ton)**	**Water from Feeding**	
				(m^3/Animal)	**(m^3/Ton)**
Maize	40.00%	2.4	674.3	1629.9	3622
Naked Barley	15.60%	0.9	1278.6	1207.5	2683.3
Wheat Bran	15.50%	0.9	1805	1692.6	3761.3
Soybean Meal	5.90%	0.4	1749.7	621.3	1380.7
Others	22.90%	1.4	1113.3	1639.3	3643
Total indirect water footprint (m^3/ton)					15,090.3

Note: [1] Sources: Survey on [25].

The daily drinking and servicing water consumed for direct water in the water footprint of swine is up to 14 and 50 L/day/animal, respectively, and the drinking and servicing water used per ton of pork by applying the daily consumption, total breeding period, and carcass weight of 80 kg were 33.1 m^3/ton and 118.1 m^3/ton, respectively (Table 7).

Table 7. Total water from drinking and servicing of Swine.

Kind of Animal: Swine (Farming System: Industrial)	Water from Drinking		Water from Servicing	
	Piglet	Adult	Piglet	Adult
Age (month)	0	6.2	0.4	6.2
Daily consumption (L/day/animal) [1]	1.8	14	5	50
Live weight of animal at slaughter (ton) [2]	0.08			
Total water required (m^3/ton)	0.3	33.1	0.8	118.1
	33.4		118.9	

Notes: [1] [11]. [2] Hyogo Prefecture (https://web.pref.hyogo.lg.jp).

The total indirect water use per swine for feed consumption was calculated as 132.4 m^3/animal for maize, 64.6 m^3/animal for soybean meal, 10 m^3/animal for wheat bran, 4.7 m^3/animal for naked barley, and 140.2 m^3/animal for other crops. By applying the carcass weight to indirect water use the water footprint of feed consumption was calculated to be approximately 4398.6 m^3/ton, as shown in Table 8.

Table 8. Total water from feeding of swine.

Component of Feed	Mixing Ratio (%) [1]	Amount of Feed (Ton/Animal)	WF of Crop (m^3/Ton)	Water from Feeding	
				(m^3/Animal)	(m^3/Ton)
Maize	53.90%	0.2	674.3	132.4	1655
Naked Barley	1.00%	0	1278.6	4.7	58.9
Wheat Bran	1.50%	0	1805	10	125
Soybean Meal	10.10%	0	1749.7	64.6	807.8
Others	31.20%	0.1	1113.3	140.2	1751.9
Total indirect water footprint					4398.6

Note: [1] Sources: Survey on [25].

The water footprint calculation results for beef cattle and swine, implying the total sum of direct drinking and servicing water and indirect water by feed consumption, are shown in Table 9. First, the water footprint of beef cattle was 15,191.8 m^3/ton, and the ratios of direct to indirect water in the total water footprint were approximately 0.01% and 99.9%, respectively, indicating that most of the water footprint was dependent on indirect water. A difference of approximately 1831.3 m^3/ton was observed in the water footprint of beef cattle compared to the previous study in Korea [15], which was 17,023.1 m^3/ton, and a difference of about 4605.8 m^3/ton was noted compared to the United States study [9], which was 10,586.0 m^3/ton. The water footprint of swine was 4550.9 m^3/ton, that is, differing by approximately 315.1 m^3/ton compared to the previous study on the water footprint of swine in Korea [15] results in 4235.8 m^3/ton and by about 1748.9 m^3/ton compared to the United States study [9], which was 2802.0 m^3/ton.

Table 9. Comparison of water footprint between Korea and Japan.

Water Demand		Beef Cattle (m^3/Ton)	Swine (m^3/Ton)
Water footprint in Korea (m^3/ton) [1]	Direct water	91.2	129.7
	Indirect water	16,931.9	4106
Water footprint in Japan (m^3/ton)	Direct water	101.5	152.3
	Indirect water	15,191.8	4550.9

Note: [1] [15].

The results of this study and previous studies in Korea are similar because differences in the ratio of concentrated feeds and feed consumption are not very different owing to similarities in the livestock production environment and breeding management in Japan and Korea. However, the difference between the results of this study and those of the United States studies arises from variations in the ratio of feed concentration to feed consumption and the differences in the water footprint of the feed crops. Nonetheless, the results of this study are useful for estimating changes in water use due to changes in agricultural production and consumption in environments with intensive livestock production, such as Japan and Korea, and for estimating the amount of water resources needed to achieve the target of food self-sufficiency, and, significantly, the results for both countries are similar.

Compared with published estimates, Japan's beef water footprint (15,293.3 m^3/ton) is close to the Korean estimate (17,023.1 m^3/ton) and higher than the U.S. value (10,586.0 m^3 ton^{-1}); for swine, Japan (4550.9 m^3 ton^{-1}) is similar to Korea (4235.8 m^3 ton^{-1}) and exceeds the U.S. (2802.0 m^3 ton^{-1}). These differences are consistent with variation in feed composition, feed intake, and crop-specific water footprints reported in prior studies. The dominance of indirect (feed-embedded) water in our decomposition (>99% for beef) aligns with global assessments of livestock water use.

3.2. Simulation of Transportation Volume of Livestock Products

Simulation of Transportation Volume of Livestock Products is shown in Table 10. In road, rail and non-weight scenarios, based on a gravity-model spatial-interaction framework consistent with transport-geography practice and recent water–food network applications [21,22].

Table 10. Simulation of transportation volume of livestock products.

Region	Transportation Volume of Beef (1 Thousand Tons)				Transportation Volume of Pork (1 Thousand Tons)			
	Export (All)	Import (Road)	Import (Rail)	Import (Non-Weight)	Export (All)	Import (Road)	Import (Rail)	Import (Non-Weight)
Chubu region	34,213.3	77,196.7	77,222.5	77,141.3	104,848.7	200,843.1	201,044.7	200,710.2
Chugoku region	18,199.4	28,554.4	28,604.5	28,473.0	22,219.4	74,300.2	74,557.9	74,030.6
Hokkaido region	90,055.5	20,599.6	20,602.5	20,591.6	88,192.1	53,698.0	53,709.6	53,719.3
Kansai region	56,854.2	79,660.5	79,840.0	79,396.6	14,081.7	207,023.3	207,577.8	206,498.8
Kanto region	102,140.1	167,727.1	167,410.2	168,258.4	364,975.3	436,431.5	434,878.2	437,874.5
Kyushu region	123,951.3	50,042.9	50,124.0	49,879.1	376,055.1	130,361.1	130,830.1	129,812.0
Shikoku region	14,465.0	14,763.1	14,783.1	14,721.3	49,211.9	38,417.3	38,531.6	38,278.5
Tohoku region	41,780.6	43,115.3	43,072.7	43,198.1	233,710.1	112,220.0	112,164.7	112,370.4

Note: Simulated annual inter-regional imports/exports under Road, Rail, and Non-weight scenarios.

The main beef exporting regions were major beef-producing areas such as Kyushu, Kanto, and Hokkaido, with transportation volumes of 123,951.3, 102,140.1, and 90,055.5 thousand tons, respectively. The primary importing regions were Kanto, Kansai,

and Chubu, with corresponding volumes of 167,727.1, 79,660.5, and 77,196.7 thousand tons for road transport, 167,410.2, 79,839.9, and 77,222.5 thousand tons for rail transport and 168,258.4, 79,396.6, and 77,141.3 thousand tons for non-weight scenarios. This pattern highlights the movement of beef from production areas to major metropolitan regions. Figure 1 visualizes the simulation of road, rail and non-weight transport volumes.

The leading beef exporting prefectures were Hokkaido, Tokyo, Hyogo, Kagoshima, Saitama, Osaka, Miyazaki, Kumamoto, Ibaraki, and Fukuoka. The main importing prefectures were Tokyo, Osaka, Kanagawa, Saitama, Chiba, Hyogo, Fukuoka, Aichi, Shizuoka, and Hokkaido.

For pork, the dominant exporting regions were Kyushu, Kanto, and Tohoku, with transport volumes of 376,055.1, 364,975.3, and 233,710.1 thousand tons, respectively, in road, rail and non-weight scenarios. Similarly to beef, the main importing regions were Kanto, Kansai, and Chubu, with volumes of 436,431.5, 207,023.3 and 200,843.1 thousand tons for road transport, 434,878.2, 207,577.8, and 201,044.7 thousand tons for rail transport, and 437,874.5, 206,498.8 and 200,710.2 thousand tons for non-weight scenarios. Figure 2 visualizes the simulation of road, rail and non-weight transport volumes.

The leading pork exporting prefectures were Kagoshima, Ibaraki, Chiba, Aomori, Kanagawa, Saitama, Hokkaido, Gumma, Miyazaki, and Nagasaki. The primary importing prefectures were Tokyo, Kanagawa, Saitama, Chiba, Osaka, Hokkaido, Fukuoka, Aichi, Hyogo, and Shizuoka.

The simulation results reflect the population distribution in Japan. Kanto and Kansai, the two most populous regions, have populations of 42,486,114 and 19,661,745, respectively, as of 2020. This roughly twofold population difference is mirrored in the volume of meat transported to these regions. In the road transport scenario, beef imports to Kanto and Kansai were 167,727.1 and 79,660.5 thousand tons, respectively, and pork imports were 435,101.2 and 208,499.3 thousand tons, respectively. Similar proportions were observed in the whole scenario.

3.3. Analysis of VWT Embedded in Livestock Products Through Water-Footprint Assessment

3.3.1. Estimation of Water Footprint of Livestock

Table 11 presents the results of the Direct Virtual Water Trade (Direct VWT) analysis. In the result of Direct VWT analysis, Kyushu region exhibited the highest virtual water runoff attributable to beef food products, with an average annual runoff of approximately 12,581 million m^3 inherent in the movement of livestock products. The subsequent most substantial virtual water outflow was from the Kanto region, at 10,367 million m^3. However, a marked discrepancy in the movement of virtual water was observed between the Kyushu and Kanto regions. In the case of the Kanto region, 93% of the virtual water outflow was transferred to prefectures within the Kanto region, while in the case of the Kyushu region, only 38% of the virtual water outflow was transferred within the Kyushu region. This finding suggests that consumption in other regions is responsible for over 60% of the virtual water outflow. Figure 3 visualizes the results of the Direct Virtual Water Trade analysis of road, rail and non-weight scenarios.

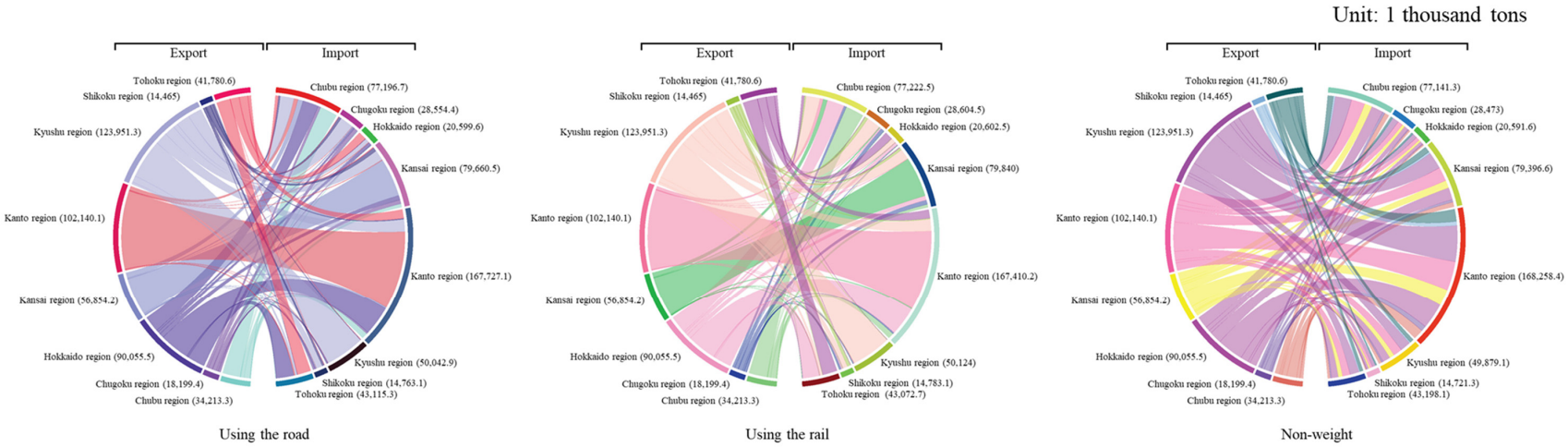


Figure 1. Simulating low-carbon transportation of livestock products (Beef). Simulated inter-prefectural transport volumes of beef under three scenarios—Road, Rail, and Non-weight—using a gravity model calibrated to prefectural production and demand. Flows are shown in 1 thousand tons. Road distances: prefectural offices via Google Maps; rail distances: representative stations via Jorudan.

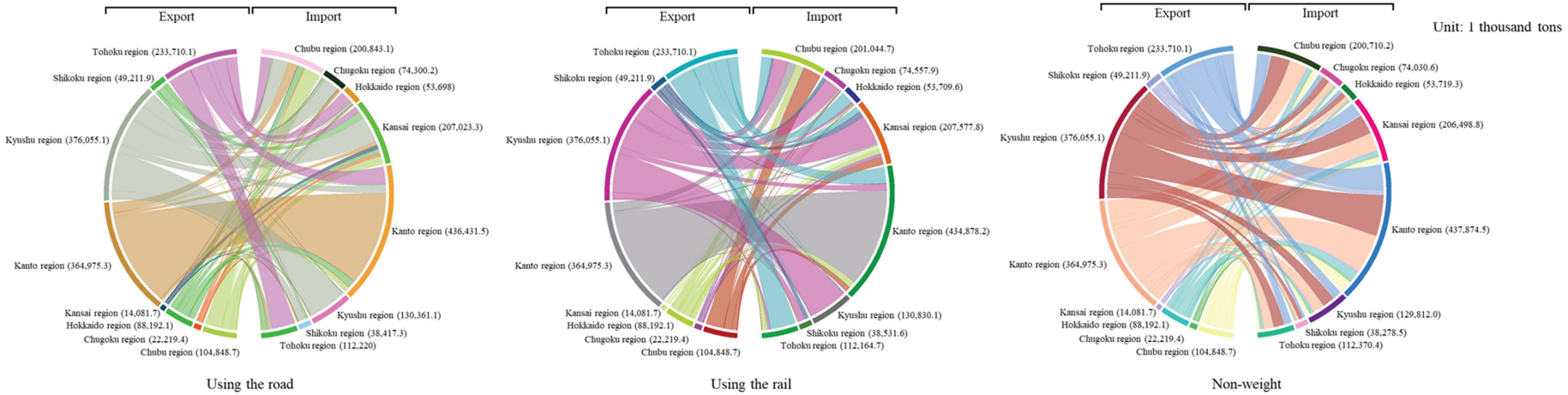


Figure 2. Simulating low-carbon transportation of livestock products (Pork). Simulated inter-prefectural transport volumes of pork under three scenarios—Road, Rail, and Non-weight—using a gravity model calibrated to prefectural production and demand. Flows are shown in 1 thousand tons. Road distances: prefectural offices via Google Maps; rail distances: representative stations via Jorudan.

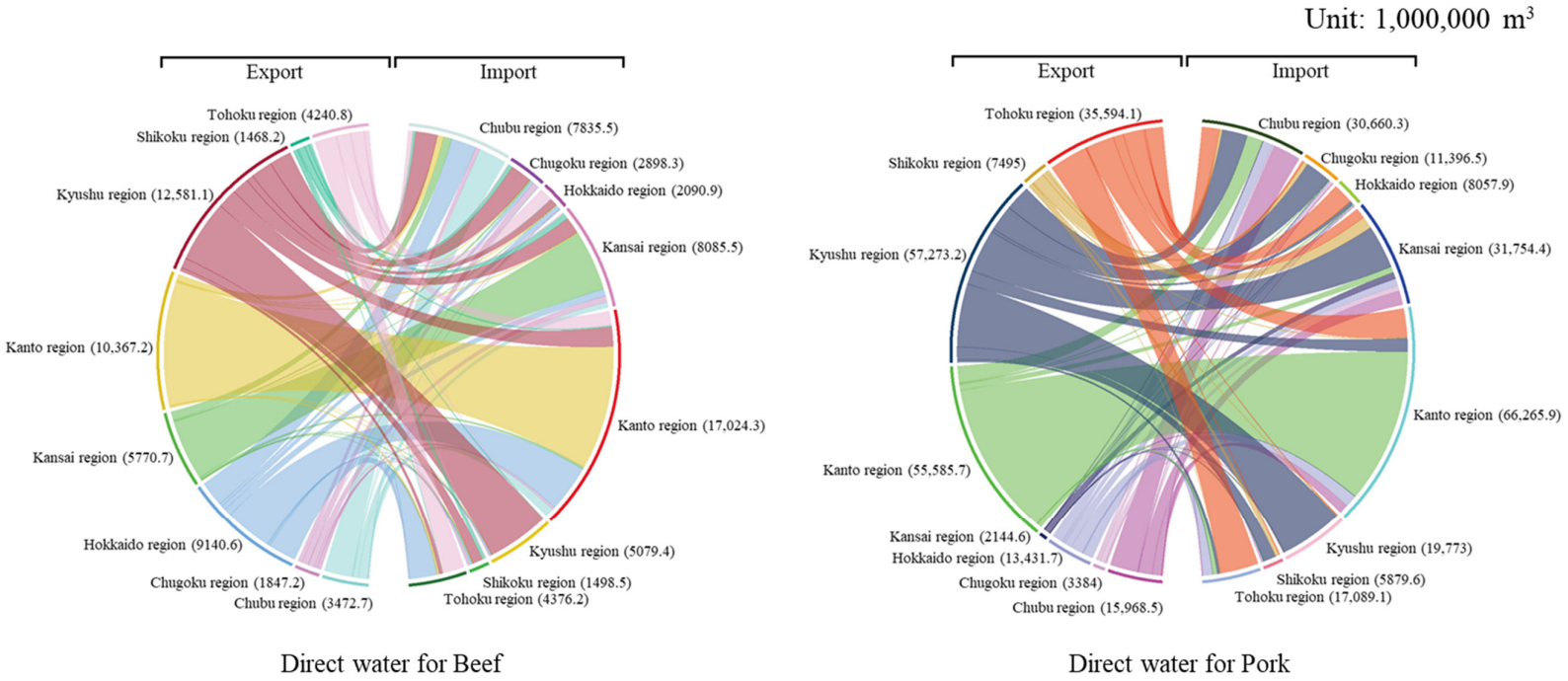


Figure 3. Results of the Direct Virtual Water Trade analysis. Regional Direct Virtual Water Trade for beef and pork. Results are identical across the three transport scenarios (Road, Rail, Non-weight). Flows are shown in 1,000,000 m^3. Road distances: prefectural offices via Google Maps; rail distances: representative stations via Jorudan.

Table 11. Direct and indirect virtual water trade.

Region	Direct VWT from Beef (1,000,000 m^3)		Direct VWT from Pork (1,000,000 m^3)	
	Direct VWT from Beef (1,000,000 m^3)	Indirect VWT from Beef (1,000,000 m^3)	Direct VWT from Pork (1,000,000 m^3)	Indirect VWT from Pork (1,000,000 m^3)
Chubu region	3473	519,762	15,968	477,156
Chugoku region	1847	276,482	3384	101,118
Hokkaido region	9141	1,368,105	13,432	401,354
Kansai region	5771	863,718	2145	64,085
Kanto region	10,367	1,551,691	55,586	1,660,966
Kyushu region	12,581	1,883,044	57,273	1,711,389
Shikoku region	1468	219,749	7495	223,959
Tohoku region	4241	634,723	35,594	1,063,591

Note: Direct and Indirect VWT calculated by combining transport flows with water-footprint intensities.

At the regional level, the Direct VWT of beef followed the order: Kyushu, Kanto, Hokkaido, Kansai, Tohoku, Chubu, Chugoku, and Shikoku. At the prefectural level, Hokkaido had the highest Direct VWT for beef production, while Wakayama had the lowest. For pork, the Direct VWT at the regional level followed the order: Kyushu, Kanto, Tohoku, Chubu, Hokkaido, Shikoku, Chugoku, and Kansai. Kagoshima had the highest Direct VWT for pork production, while Yamaguchi had the lowest.

3.3.2. Indirect VWT Embedded in Livestock Products

Table 11 shows the results of the Indirect Virtual Water Trade (Indirect VWT) analysis. Similarly to Direct VWT, the values were consistent across non-weight and weight transportation scenarios for both beef and pork. In the result of Indirect VWT analysis, Kyushu region exhibited the highest virtual water runoff attributable to beef food products, with an average annual runoff of approximately 57,273 million m^3 inherent in the movement of livestock products. The subsequent most substantial virtual water outflow was from the Kanto region, at 55,586 million m^3. Figure 4 visualizes the results of the Indirect Virtual Water Trade analysis of road, rail and non-weight scenarios.

At the regional level, the Indirect VWT of beef followed the order: Kyushu, Kanto, Hokkaido, Kansai, Tohoku, Chubu, Chugoku, and Shikoku. Hokkaido had the highest Indirect VWT for beef production, while Wakayama had the lowest. For pork, the Indirect VWT at the regional level followed the order: Kyushu, Kanto, Tohoku, Chubu, Hokkaido, Shikoku, Chugoku, and Kansai. Kagoshima had the highest Indirect VWT for pork production, while Yamaguchi had the lowest.

The regional ordering observed for Direct and Indirect VWT (e.g., Kyushu and Kanto leading for beef; Kyushu and Tohoku for pork) is consistent with our simulated transport volumes and with the virtual-water trade framework linking commodity flows to embedded water in agricultural products.

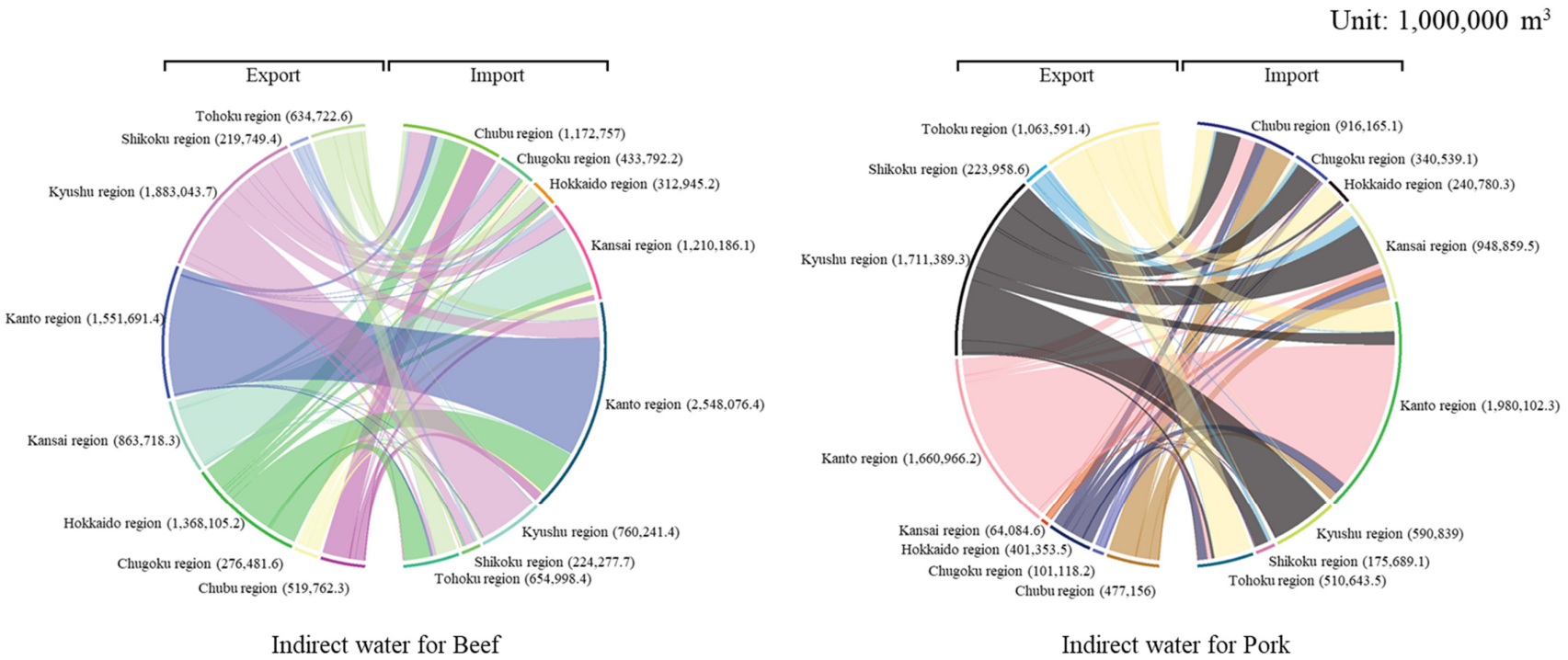


Figure 4. Results of the Indirect Virtual Water Trade analysis. Regional Indirect Virtual Water Trade for beef and pork. Results are identical across the three transport scenarios (Road, Rail, Non-weight). Flows are shown in 1,000,000 m^3. Road distances: prefectural offices via Google Maps; rail distances: representative stations via Jorudan. Regionally, Kyushu had the highest fuel consumption for road, rail and non-weight scenarios, while Kansai had the lowest.

3.4. Analysis of Low-Carbon Transportation of Livestock Products

3.4.1. Energy Consumption for Transporting Livestock Products

Table 12 presents the estimated fuel consumption for transporting livestock products in the road, rail and non-weight scenario. For beef, road transport consumed 3,485,652 billion tons of fuel GJ/year, while rail transport consumed 78,645 billion tons of fuel GJ/year and non-weight consumed 7563 billion tons of fuel GJ/year.

Table 12. Fuel consumption for transporting livestock products.

Region	Fuel Consumption for Beef (1 Billion Tons of Fuel GJ/yr)			Fuel Consumption for Pork (1 Billion Tons of Fuel GJ/yr)		
	Road	Rail	Non-Weight	Road	Rail	Non-Weight
Chubu region	88,276	1694	537	286,684	5813	1646
Chugoku region	106,203	2392	286	99,755	2184	349
Hokkaido region	1,530,826	33,826	1414	1,568,383	35,223	1385
Kansai region	74,847	1445	893	12,148	234	221
Kanto region	129,881	2177	1604	766,769	12,669	5731
Kyushu region	1,256,226	30,168	1946	3,787,837	89,319	5905
Shikoku region	63,736	1637	227	194,213	5404	773
Tohoku region	235,656	5306	656	1,566,520	36,220	3670

Note: Estimated fuel use for transport scenarios by region and commodity.

Regionally, Hokkaido had the highest fuel consumption for road and rail transportation. In the non-weight scenario, Kyushu was the highest fuel consumption region.

For pork, road transport consumed 8,282,310 billion tons of fuel GJ/year, rail transport consumed 187,066 billion tons of fuel GJ/year, and non-weight scenario consumed 19,679 billion tons of fuel GJ/year (Table 12).

3.4.2. CO_2 Emissions Embedded in the Transportation of Livestock Products

Table 13 presents the estimated CO_2 emissions associated with livestock transportation. Road-transport CO_2 exceeded rail for both commodities (beef: 266,606 vs. 6015 thousand tons/year; pork: 633,486 vs. 14,308 thousand tons/year), a 44 times difference in each case (Table 13). Pork produced higher national transport emissions than beef across all modes (2.4 times for road and rail; 2.6 times in the non-weight case), consistent with the larger transport volumes (Tables 10 and 13). Regionally, beef emissions were highest in Hokkaido for road and rail, whereas pork emissions were highest in Kyushu across all scenarios; in the non-weight scenario, beef also peaked in Kyushu (Tables 12 and 13). These ordering patterns are consistent with the spatial distribution of production and demand described in Section 3.2.

Table 13. CO_2 Emission by fuel consumption for transporting livestock products.

Region	Fuel Consumption for Beef (1 Billion Tons of Fuel GJ/yr)			Fuel Consumption for Pork (1 Billion Tons of Fuel GJ/yr)		
	Road	Rail	Non-Weight	Road	Rail	Non-Weight
Chubu region	6752	130	41	21,928	445	126
Chugoku region	8123	183	22	7630	167	27
Hokkaido region	117,088	2587	108	119,960	2694	106
Kansai region	5725	111	68	929	18	17

Table 13. *Cont.*

Region	Fuel Consumption for Beef (1 Billion Tons of Fuel GJ/yr)			Fuel Consumption for Pork (1 Billion Tons of Fuel GJ/yr)		
	Road	**Rail**	**Non-Weight**	**Road**	**Rail**	**Non-Weight**
Kanto region	9934	166	123	58,648	969	438
Kyushu region	96,085	2307	149	289,719	6832	452
Shikoku region	4875	125	17	14,855	413	59
Tohoku region	18,025	406	50	119,818	2770	281

Notes: Estimated CO_2 Emission for transport scenarios by region and commodity. CO_2 from transport = fuel use × emission factor.

4. Conclusions

This study addressed the need for an updated assessment of water use in livestock production in Japan, considering the significant increase in meat consumption and the limitations of historical data. By calculating the water footprints of beef cattle and swine, the primary meat sources in Japan, this research provides valuable insights into water resource requirements per unit of meat production.

The study differentiated between direct water use (drinking and service water) and indirect water use (water embedded in feed production). This distinction allows for a more comprehensive understanding of water use patterns in livestock production and enables the estimation of water requirements for feed crop production in response to changes in meat consumption and national policies.

The results revealed that indirect water use accounts for more than 99% of the total water footprint of beef cattle, highlighting the substantial water resource requirements associated with feed production. The estimated water footprints for both beef cattle and swine were similar to those reported in previous studies conducted in Korea, likely due to similarities in livestock production systems and management practices. However, differences were observed compared to studies conducted in the United States, possibly attributed to variations in feed composition, feed consumption rates, and water footprints of feed crops.

This study provides a valuable tool for estimating water resource requirements in countries with intensive livestock production systems, such as Japan and Korea. The findings can inform various aspects of water resource management, including assessing the impact of changing meat consumption patterns, developing food policies to promote self-sufficiency, and optimizing transportation systems to minimize carbon emissions and fuel consumption.

Furthermore, the transportation simulations conducted in this study offer insights into the carbon footprint of livestock product transportation. The results can guide the adoption of efficient transportation routes and inform the development of food policies aimed at decarbonizing domestic transportation in Japan.

Overall, this research contributes to a more comprehensive understanding of the water and carbon footprints associated with livestock production and transportation in Japan. The findings have implications for sustainable water resource management, food security, and environmental conservation in the context of increasing meat consumption.

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