ORIGINAL ARTICLE

Nitrogen footprint of Korean beef cattle farms: Scenarios toward more sustainable production

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Abstract Nitrogen (N) lost during beef cattle production accompanies various environmental risks and has become a rising concern among agricultural stakeholders. The objective of this study was to quantify the N footprint of producing Hanwoo beef cattle, which is a Korean indigenous breed of cattle, in Korea at the farm gate through a life cycle assessment approach. Field surveys were conducted on 106

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farms across 9 provinces to identify regional distinctions in farming systems and evaluate total N losses from beef production. N losses were calculated using emission factors from the refined IPCC guidelines, which were then expressed as N footprint (g N/kg of live body weight (LBW)). Uncertainty and sensitivity analyses were deployed to evaluate the precision of the results and identify factors that contributed to the output. The N footprint averaged 132.7($\pm$61.8) g N/kg LBW and varied between provinces according to animal categories, manure management systems, land use and fertilizer application rates. Volatilization was the highest contributing factor, followed by leaching and denitrification, each representing 68.5, 21.4, and 10.1 percent of the N footprint, respectively. The uncertainty of the result was found to be 46.6 percent and was highly associated with emission factor uncertainties. We devised five mitigation scenarios that are cost effective and do not penalize productivity and evaluated their capacity for reducing N footprint: (i) dietary modifications to decrease animal N excretion rate; (ii) microorganism additives to reduce volatilization from housing; (iii) manure storages recycling manure within the farm to replace synthetic fertilizers; (iv) distributing biochar to the field after fertilizer application to curtail losses from crop production; (v) combination of i, ii, iii, and iv. Combining these scenarios demonstrated the potential to reduce 12.1 percent of the total N footprint. The extents of mitigation scenarios varied across provinces (ranging from 5.2 to 21.7 percent) and were shown to be contingent on

feeding practices and type of crop cultivated. Overall, our study provides a national metric that can be utilized to communicate the environmental impacts of Korean beef production. The analyses indicate that more precise results could be achieved with future endeavors towards developing country-specific emission factors. The mitigation potentials of the presented scenarios propose possibilities for feasible and sustainable beef production in Korea.

Introduction

Nitrogen (N) is a key component in agriculture which is essential for sustaining the global nutritional demands. During agricultural production, N is lost in the form of reactive N (Nr), entailing various environmental risks to the surrounding environment (Galloway et al. 2003). In the context of Nr lost through the atmosphere, nitrous oxide (N_2O) is a greenhouse gas having a global warming potential of 265, far surpassing that of methane (CH_4) (IPCC 2019a). Ammonia (NH_3) and nitrogen oxide (NO_x) are precursors of inorganic aerosols and pose threats to air quality and human health (Fuzzi et al. 2015). NH_3 is also known to have adverse effects on the capacity of the soil to act as CH_4 sinks (Steudler et al. 1989). Nr is lost through water as leached nitrate (NO_3^-) which gives rise to eutrophication in water bodies, consequently declining biodiversity (Smolders et al. 2010). While advances in agricultural technology have enabled lower Nr emissions per unit of production, overall emissions have increased due to a rise in global population (Malik et al. 2022). As an effort to mitigate the effects of agricultural activities on the environment, a wide array of research has been carried out to assess the N losses from livestock production (Du et al. 2018; Mori et al. 2020; Uwizeye et al. 2016; Velthof et al. 2009).

The agricultural sector in the Republic of Korea (ROK) was responsible for 62.7% of the annual N_2O emissions in 2019, with livestock production and agronomic activities each contributing 24.4% and 38.3%, respectively (GIR 2021). Despite the high share of agriculture in N_2O emissions and N input to the land, studies on identifying the N losses from the agricultural sector are scarce. The Hanwoo beef cattle industry is a strategic activity in Korean agriculture and comprises a complex system integrating both livestock production and rice cultivation. Thus, it is crucial that a comprehensive assessment of N losses at farm scale be conducted to reflect the impacts of this farming activity and practices in ROK. Evaluating N emissions to the environment on an N footprint basis is considered to be an efficient form of assessment, where an N footprint is defined as the net amount of N emissions generated from producing a kg of product (Leach et al. 2012). The Livestock Environmental Assessment and Performance Partnership (LEAP) identified the N footprint as an indicator of N losses from livestock systems and developed guidelines using a life cycle assessment (LCA) approach to quantify N flows and determine the impacts of livestock production (FAO 2018).

N lost during cattle production and crop cultivation for feed far surpassed that of the consumption chain (Chatzimpiros and Barles 2013; Joensuu et al. 2019). Therefore, the aims of this study were first, to screen the N footprint of Hanwoo beef farms at farm gate in ROK across nine provinces through an LCA approach; second, to analyze the uncertainties of the input and output data, and finally to simulate mitigation scenarios to reduce the N footprint.

Method and materials

Study area and data collection process

This study was carried out in 9 governorates (provinces) of the Republic of Korea (ROK). Activity data of the year 2020 were collected between July 2021 and July 2022 using field surveys from a random sample of Hanwoo beef farms (n = 106). The survey was conducted in the most relevant provinces of ROK in terms of Hanwoo beef cattle breeding. Within each province, data collection was standardized by using the same questionnaire. Farms were selected using a random sampling algorithm with the statistical software R (R Core Team 2021) on a list of beef cattle farms affiliated with the Hanwoo Beef Cattle Association. The number of farms surveyed for provinces with a larger Hanwoo population was higher than the provinces with
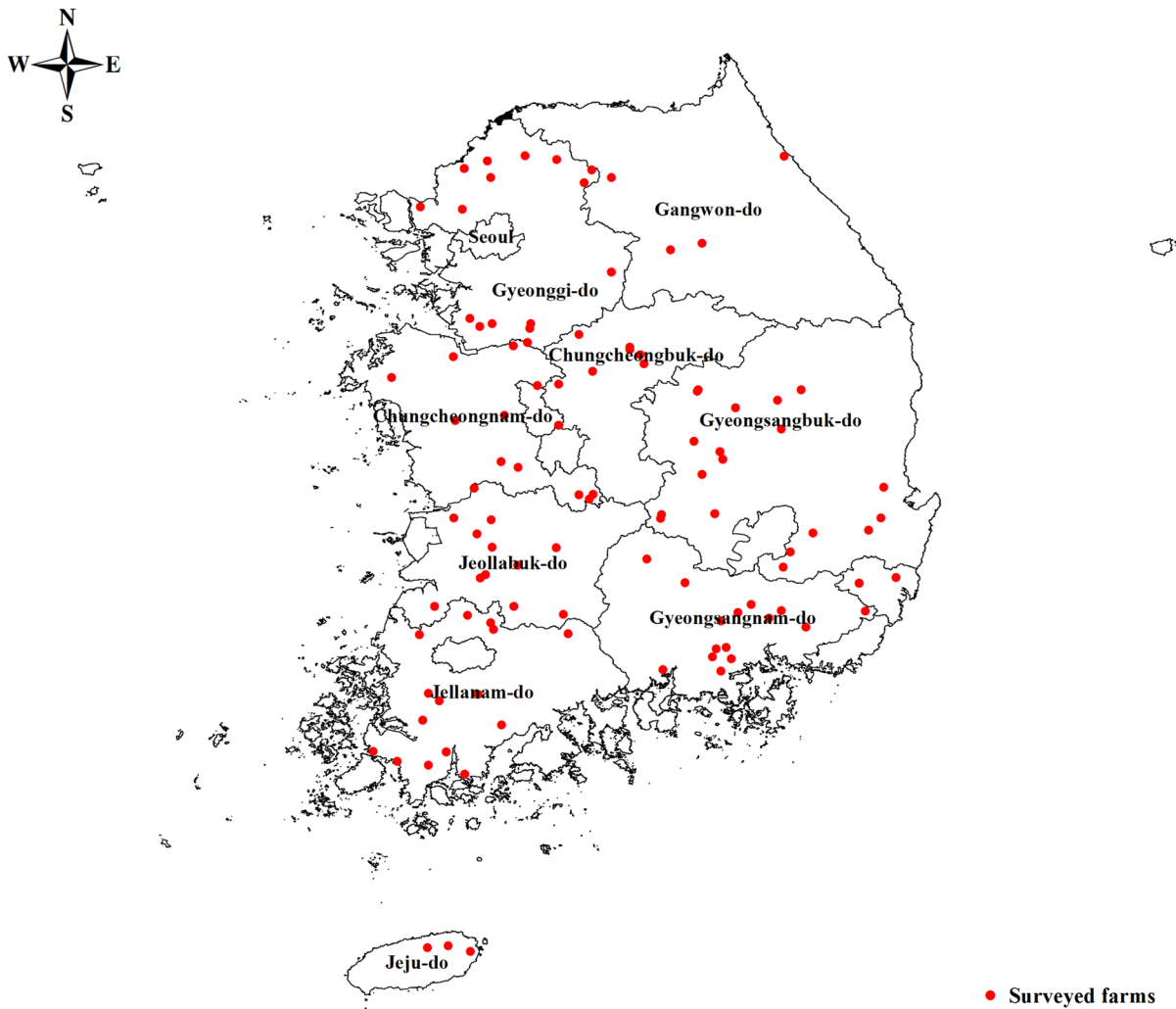
Fig. 1 Spatial distribution of the 106 surveyed Hanwoo beef farms in the Republic of Korea

a smaller population (Fig. 1). The survey included information on the production purpose, farms size, cropping practices, fertilizer application rate, animal number categories, productivity, feeding practices, and manure management systems. Farms were categorized according to the production purpose into three categories: fattening, breeding, and mixed. Fattening farms raised only steers and fattening cows with the aim of producing only meat, while breeding farms raised only breeding cows for producing calves. Mixed farms raised both steers and breeding cows with a primary purpose for producing meat. The cattle were divided into eight categories according to growth stage and production

purpose following the Korean feeding standard (NIAS 2017). To acquire information for the field survey, farmers were requested to access private information available on government databases. Unavailable data were procured from individual farm records and assumptions based on existing data; LBW of cattle exported out of the farm for meat was estimated by dividing their carcass weight by 0.6 (NIAS 2017) and LBW of calves sold were taken from the average LBW of calves traded provided by the Livestock and Agricultural Cooperative Association (NH 2020). All data were incorporated into the initial database and arranged to identify the N footprint of each farm.

Life cycle assessment approach

A cradle-to-farm gate LCA was deployed to determine the annual N losses in accordance with guidelines provided by LEAP (FAO 2016). The system boundary includes all losses from animal housing, manure storage, and on-farm organic and synthetic fertilizer application to the field for feed production. Annual N losses were estimated as the sum of emissions from denitrification, volatilization, and leaching. Upstream emissions occurring from producing, transporting, and distributing N inputs such as feed and fertilizer used in the farm were excluded. All N losses from rice production were included, since no allocations were made between rice used for human consumption and animal feed. The functional unit was 1 kg LBW at the farm gate. Manure exported out of the farm was considered a residual, and concomitant off-farm emissions occurring from application to crop fields outside of beef cattle farms or composting in manure treatment facilities were not considered (Fig. 2).

Nitrogen losses

Activity data for N loss were classified as animal housing and manure storage, N field application, and agricultural machinery. N losses from each source were estimated following the Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC 2019a, 2019b) and aggregated to determine the annual N loss (Table 1).

Nitrogen excretion from animals

Annual amount of N excretion (N_{ex}) from the animals were determined using an IPCC tier 2 approach by subtracting daily N retention rates ($N_{retention}$) from daily N intake rates (N_{intake}). To calculate the N_{intake}, the crude protein contents (CP%) of feed fed to each animal category for every farm were identified from field surveys. The gross energy (GE) was estimated for steers and growing animals as the amount of net energy (NE) required for growth and maintenance. For breeding Hanwoo cows, the GE was calculated based on the NE required for maintenance, growth, lactation, and pregnancy. NE for activity was disregarded due to confined feeding practices. Since the digestible energy (DE) of the feed was required to estimate the NE for growth and maintenance, we converted the total digestible nutrient (TDN) and dry matter intake (DMI) acquired from field surveys to DE as proposed by Ibidhi et al. (2021). This was because the commercial feed in ROK does not provide energy content in DE units. LBW of animals raised for meat production were assumed from carcass weights (CW) and default weights from the (NIAS 2017) were applied to those raised for breeding. In the estimation of $N_{retention}$ the amount of milk production was ignored as this only applies to dairy cattle. The CW of slaughtered cattle obtained from the survey and default weights of calves and breeding cows from (NIAS 2017) were used to assume the daily weight gain (WG). N_{ex} was calculated for each animal category for every farm accordingly.

Fig. 2 N loss sources for life cycle assessment of the nitrogen footprint of Hanwoo beef cattle farm systems. The red dotted line represents the system boundary, input in the black dotted line are the off-farm N inputs, and N losses in the blue dotted line are the outputs of the system boundary. and manure exported from the farm is considered a residual
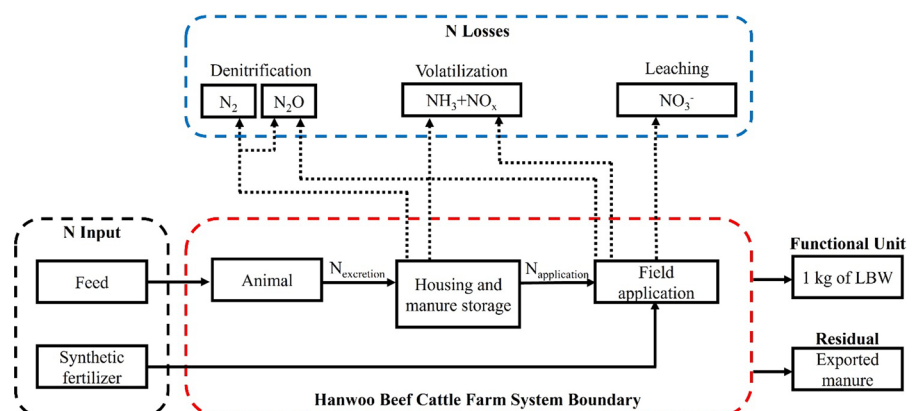
Table 1 Equations used to estimate N losses from the system boundary

Activity sources	Unit	Equation	Reference
N excretion[a]			
Daily N intake rates	kg N/animal/day	$N_{intke} = GE/18.45 \times CP\%/100/6.25$	IPCC (2019a)
Daily N retention rates	kg N/animal/day	$N_{retention(T)} = [Milk \times Milk\ PR\%/100]/6.38 \times [WG(268 - (7.03 \times NE_G))/WG]/1000/6.25$	IPCC (2019a)
Annual N excretion rates	kg N/animal/yr	$NEX_{(T)} = (N_{intake(T)} - N_{retention(T)}) \times 365$	IPCC (2019a)
Losses from housing and manure storage[b]			
Annual N_2O emissions from denitrification	kg N_2O/yr	$N_2O_{D(mm)} = [\sum_S (N \times Nex \times AWMS_S)] \times EF_{3(S)} \times 44/28$	IPCC (2019a)
Annual amount of N lost from volatilization of NH_3+NO_x	kg N/yr	$N_{volatilization-MMS} = [\sum_S (N \times NEX \times AWMS_S) \times Frac_{GasMS(S)}]$	IPCC (2019a)
Fraction of N lost as N_2	fraction of N_{ex}	$FracN2(N2O) = R_{N2(N2O)} \times EF_{3(S)}$	IPCC (2019a)
Losses from N field application[b]			
Annual N_2O emissions from denitrification	kg N_2O/yr	$N_2O - N_{N\ inputs} = [(F_{SN} + F_{ON} + F_{CR} + F_{SOM}) \times EF_1] + [[F_{SN} + F_{ON} + F_{CR} + F_{SOM}) \times EF_{1FR}]$	IPCC (2019b)
Annual amount of N lost from volatilization of NH_3+NO_x	kg N/yr	$(F_{SN} \times Frac_{GASF}) + (F_{ON} \times Frac_{GASM})$	IPCC (2019b)
Annual amount of N lost from leached NO_3^-	kg N/yr	$(F_{SN} + F_{ON} + F_{CR} + F_{SOM}) \times Frac_{LEACH-(H)}$	IPCC (2019b)

[a] N excretion was calculated using the tier 2 approach

[b] All subsequent N emissions and losses were calculated using default emission factors

N losses from housing and manure storage

All surveyed farms housed cattle in confinement and stacked manure in adjacent storages with metal ceilings and concrete floors. The manure management system was identified as 'solid storage—covered/compacted' and default emission factors were deployed to calculate N losses. N from rice straw used for bedding was excluded from the calculation. Emission sources were N_2O and N_2 from denitrification, and NH_3 and NO_x from volatilization. N lost from leaching as NO_3^- was not considered to occur due to the concrete floors. The amount of N_2O produced was estimated using the number of cattle, N_{ex}, and the emission factor of 0.01 for direct N_2O-N emissions from manure management (EF_3). The resulting value was multiplied by the molar mass ratio between N_2 and N_2O of 28/44 to quantify the amount of N lost as N_2O. The fraction of N lost as N_2 ($Frac_{N2MS(S)}$) was calculated to be three times larger than EF_3, following the default ratio of N_2 to N_2O ($R_{N2(N2O)}$). N losses as NH_3 and NO_x were estimated using the number of cattle, N_{ex}, and the default value of 0.22 for the fraction lost from volatilization in manure management ($Frac_{GasMS(S)}$). Identical manure management systems (AWMS) were applied to all farms.

N losses from field application

N losses from the field application of N for feed production were determined using N inputs of organic and synthetic fertilizers and default emission factors. The amount of N applied as organic fertilizers (F_{ON}) were estimated from the remainder of N_{ex} after denitrification and volatilization during manure management, and the fraction of that remainder applied to the field. The amount of N input from synthetic fertilizers (F_{SN}) were estimated using application rates obtained from field surveys and the N content of commercial fertilizers. The amount of N in crop residues (F_{CR}) and mineralized in mineral soils (F_{SOM}) were not considered due to the lack of available data. Emission sources were N_2O from denitrification, NH_3 and NO_x from volatilization, and NO_3^- from leaching. To identify the amount of N_2O produced, default emission factors of 0.01 and 0.004 for N_2O emissions from the application of organic and synthetic fertilizers to the field (EF_1) and flooded rice (EF_{1FR}) were deployed.

The resulting value was multiplied by 28/44 to quantify the amount of N lost as N_2O. The default values of 0.21 and 0.11 were applied for the fraction of N volatilized from organic fertilizers ($Frac_{GASM}$) and from synthetic fertilizers ($Frac_{GASF}$). To estimate the amount lost as NO_3^-, a default value of 0.24 was used for the fraction of N lost from leaching ($Frac_{LEACH-(H)}$). All emission factors used to estimate N losses from field application were derived from (IPCC 2019b).

Impact assessment

The N footprint was determined from the total amount of N lost inside the system boundaries on a gram (g) N basis by functional unit. Physical allocations were used to calculate the N losses by LBW and were set differently for each production purpose; losses from fattening and mixed farms were divided by the total LBW of steers and fattening cows slaughtered for meat, while losses from breeding farms were divided by the total LBW of fattening cows slaughtered for meat and calves sold to other farms. Calculations were made for individual farms and an average value for each production purpose was computed.

Statistical analyses

An uncertainty analysis was deployed to quantify the confidence interval in the predicted N footprint of Hanwoo farming systems. Uncertainty is an error between the true and estimated value, and in the context of LCA it stems from flaws in the model, inaccurate or insufficient data, and spatial or temporal variability in the system (Huijbregts 1998; Walker et al. 2003). In this study, the uncertainty analysis followed a twofold procedure: 1) identifying the uncertainty of the surveyed parameters and referenced emissions factors; 2) performing stochastic simulation by propagating the uncertainties through the Monte Carlo (MC) simulation method. The uncertainties of the input parameters were determined by computing the standard error of each parameter. Default values from the IPCC guidelines (IPCC 2019a, 2019b) were deployed for the uncertainties of emission factors (Table 2). The MC approach is generally used to transform a deterministic model to a stochastic one and elucidate the range of its outcomes and likelihoods (Griffin et al. 1999). To execute the MC

Table 2 Average and referenced values and uncertainties of input parameters and emission factors

Classification	Input parameters	Average value	Unit	Uncertainty (% or range)	PDF	Reference
N excretion per animal category	Steers (> 22 months)	74.69	kg N/head/year	± 0.42%	Normal	Calculation
	Steers (14 ~ 21months)	71.80	kg N/head/year	± 0.61%	Normal	Calculation
	Growing males (6 ~ 13months)	60.29	kg N/head/year	± 0.73%	Normal	Calculation
	Fattening cows	70.68	kg N/head/year	± 0.65%	Normal	Calculation
	Breeding cows	48.05	kg N/head/year	± 0.37%	Normal	Calculation
	Heifers	44.30	kg N/head/year	± 0.65%	Normal	Calculation
	Growing females (6 ~ 13months)	55.76	kg N/head/year	± 0.66%	Normal	Calculation
	Calves (< 6months)	29.53	kg N/head/year	± 1.05%	Normal	Calculation
Activity sources	Emission factors	Reference value	Unit	Uncertainty (% or range)	PDF	Reference
Losses from housing and manure storage	EF_3	0.01	kg N_2O–N / kg N excreted	± 100%	Log-normal	IPCC (2019a)
	$Frac_{GasMS(S)}$	0.22	kg N volatilized / kg N excreted	0.03–0.26	Log-normal	IPCC (2019a)
	$R_{N2(N2O)}$	3	kg N_2-N / kg N_2O-N	1–10	Log-normal	IPCC (2019a)
Losses from N field application	EF_1	0.01	kg N_2O-N / kg N applied	0.001–0.018	Log-normal	IPCC (2019b)
	EF_{1FR}	0.004	kg N_2O-N / kg N applied	0.000–0.029	Log-normal	IPCC (2019b)
	$Frac_{GASF}$	0.11	kg N volatilized / kg N applied	0.02–0.33	Log-normal	IPCC (2019b)
	$Frac_{GASM}$	0.21	kg N volatilized / kg N applied	0.00–0.31	Log-normal	IPCC (2019b)
	$Frac_{LEACH-(H)}$	0.24	kg N from leaching and run off / kg N applied	0.01–0.73	Log-normal	IPCC (2019b)

simulation, the probability distribution functions (PDF) of all input variables were estimated using the Anderson–Darling goodness-of-fit method (Anderson & Darling 1952). The variables were placed under the null hypothesis that they either followed normal or log-normal distributions, and if the p-value for the test statistic was above 0.05, the null hypothesis was not rejected, and their distributions were identified accordingly (Table 2). Subsequently, 50,000 iterations were run simultaneously to obtain the PDF of the predicted N footprint.

To analyze how the output of the model can be attributed to the uncertainties of individual input variables, a sensitivity analysis using the Sobol method was performed (Groen et al. 2017). The contribution of each variable and major source of emission was evaluated through a sensitivity index. Indices close to 0 indicated low sensitivity and thus little contribution while the contrary was true for indices close to 1.

The number of farms by province showed huge variation, so both the uncertainty and sensitivity analysis were conducted on all farms for more robust predictions. Both analyses were conducted using the NumPy package in python (Harris et al. 2020).

Table 3 Mitigation scenarios and expected effects on N losses by activity source

Scenario	Characteristic	Expected effect	Reference
Feed			
Feed less CP but higher RUP to steers and fattening cows (Applied to 62 farms)	Steers (> 22 months) and fattening cows—13% CP, 51.5% RUP. Steers (14~21 months)—14% CP, 44.6% RUP. Growing males (6~13 months)—15% CP, 45.8% RUP	Decrease in N_{ex} in proportion to decrease in CP intake	Lee et al. (2020)
Housing and manure storage			
Application of microorganism additives to manure (Applied to 106 farms)	Spraying CC-E and EM in housing and manure storage	Decrease in volatilization by 9.15% ($NH_3 + NO_x$)	Ba et al. (2020)
N Field application			
Replacing synthetic fertilizers with organic fertilizers (Applied to 29 farms)	Replacement of synthetic fertilizers with organic fertilizers for farms exporting manure (amount of exported manure > amount of synthetic fertilizer applied)	Decrease in denitrification by 12.3% for rice cultivation (N_2O). Decrease in volatilization by 26.8% for all fields ($NH_3 + NO_X$). Decrease in leaching by 28.9% for all fields (NO_3^-)	Xia et al. (2017)
Biochar (Applied to 72 farms)	One-time addition of straw biochar after N application (10~20 t/ha)	Decrease in volatilization by 19.5% for rice cultivation ($NH_3 + NO_x$)	Dong et al. (2019)
		Decrease in leaching by 23.1% for rice cultivation (NO_3^-)	Sun et al. (2018)
		Decrease in denitrification by 19% for field crops (N_2O)	Liu et al. (2019)
		Increase in volatilization by 14% for field crops ($NH_3 + NO_x$)	
		Decrease in leaching by 20.8% for field crops (NO_3^-)	

Mitigation scenarios

Four potential individual mitigation scenarios to reduce N losses and a single combined scenario were simulated for all farms. All scenarios were confirmed feasible by farmers, in that they would not induce any changes in farm structure nor revenue, to ensure that they did not affect productivity nor require initial expenses for equipment installment. The individual scenarios were farm-specific and targeted three farm levels: animal feed, housing and manure storage, and N field application (Table 3).

The dietary mitigation scenario focused on modifying the CP and rumen undegradable protein (RUP) contents to reduce N_{ex}. RUP is a type of protein that is not consumed by rumen microbes but passed into the intestines to be directly assimilated by the cow. For 62 farms, the CP contents for farms feeding steers (> 22 months), steers (14~21 months), and growing males (6~13 months) over 13, 14, and 15 percent were adjusted to 13, 14, and 15 percent, respectively. The RUP contents were also adjusted to 51.5, 44.6, and 45.8 percent, respectively, as suggested by Lee et al. (2020). Feed adjustment for fattening cows followed the same CP and RUP content applied to steers (> 22 months).

To curtail N losses from housing and manure storages, microorganism additives such as EM (Effective Microorganisms) were applied to all farms (Fig. 2). The applied EM consisted of a *Bacillus subtilis, Rhodopseudomonas palustris, Lactobacillus, Saccharomyces cerevisiae,* and *Nitrosomas,* all of which were sourced from regional agriculture technology centers.. These microorganisms were expected to reduce volatilization by 9.15 percent by mineralizing organic N to ammonium N (NH_4^+) to be used for microbial protein (Ba et al. 2020).

Table 4 Characteristics and resource use of Hanwoo farm systems for the 9 provinces and the total surveyed farms

Region (Surveyed farms)	Chungcheongbuk (n=7)	Chungcheongnam (n=12)	Gangwon (n=4)	Gyeonggi (n=16)	Gyeongsangbuk (n=19)	Gyeongsangnam (n=18)	Jeju (n=2)	Jeollabuk (n=12)	Jeollanam (n=16)	Total (n=106)
Total surveyed animals (head)	1323	1464	1232	4528	4712	4140	404	2280	4320	24,372
Proportion of each animal category (%)										
Steers (>22 months)	6.9	10.7	19.8	17.7	16.5	8.3	16.8	9.5	5.9	12.2
Steers (14~21 months)	7.9	7.4	8.1	10.2	13.3	10.0	6.7	6.3	8.1	9.6
Growing males (6–13 months)	6.3	9.0	13.3	8.8	11.7	8.7	18.1	5.8	9.6	9.2
Fattening cows	4.8	5.7	3.2	4.2	1.2	11.3	0	7.4	6.7	5.7
Breeding cows	34.9	27.9	30.2	28.6	27.4	30.0	26.5	34.7	40.7	31.9
Heifers	11.6	10.7	11.0	10.2	12.1	11.3	6.2	12.6	8.1	10.9
Growing females (6–13 months)	11.1	12.3	12.7	9.2	9.3	8.3	9.9	9.5	11.1	9.6
Calves (<6 months)	16.4	16.3	1.6	11.0	8.5	12.2	15.8	14.2	9.6	10.9
Exported LBW (ton)										
Meat	23.0	14.5	58.3	49.0	54.3	42.8	42.7	30.5	31.9	38.9
Calves	3.5	1.0	0	0.4	1.8	0.5	0	0.5	5.8	1.7
Supplied amount (% of feeding system)										
TMR	23	18	45	56	30	35	35	26	39	36
Separate feeding	77	82	55	44	70	65	65	74	61	64
Concentrate (%SF)	61	49	65	57	56	52	16	47	48	51
Forage (%SF)	39	51	35	43	44	48	84	53	52	49
CP (%DM)	13	11	11	14	13	13	13	13	14	13
Field area (ha)										
Feed production	6.2	2.1	3.3	4.0	4.3	10.4	61.2	13.5	16.9	9.2
Rice cultivation	0	1.0	0	1.4	2.1	5.1	0	13.0	11.4	4.7
Exported to facility	0	17	0	28	38	47	34	16	38	29
Internal use	100	83	100	72	62	53	66	84	62	71
Field application	96	54	70	81	55	57	33	70	71	68
Shared with other farms	4	46	30	19	45	43	33	30	29	32
N field input (kg N/ha)										
Organic fertilizer	1178	1118	2424	1205	741	267	23	292	361	434
Synthetic fertilizer	192	107	44	32	74	116	55	79	139	96

Two mitigation scenarios were considered for N field application: replacing synthetic fertilizers with organic fertilizers and deploying biochar. For 29 farms that exported manure while utilizing synthetic fertilizers, the fertilizers were replaced with exported manure containing equal amounts of N. From the amount of N replaced, losses from denitrification in rice cultivation were expected to decrease by 12.3 percent, and losses occurring from volatilization and leaching for all fields were expected to decrease by 26.8 and 28.9 percent (Xia et al. 2017). This was attributed to a more gradual release of N and enhanced ammonium immobilization (Zhou et al. 2016). Straw derived biochar was added after manure and fertilizer application to 73 farms that practiced crop cultivation (Fig. 2). This was assumed to reduce losses from volatilization and leaching for rice cultivation by 19.5 and 23.1 percent (Dong et al. 2019; Sun et al. 2018). For field crops, biochar application was expected to reduce losses from denitrification and leaching by 19 and 20.8 percent while increasing losses from volatilization by 14 percent (Liu et al. 2019).

Results

Farm presentation

A wide range of activities data (farm characteristics, animal category, feeding and cropping practices, manure management system, and energy use) from Hanwoo beef farms across nine provinces were collected and reported in Table 4. The visited farms practiced breeding and fattening production in all provinces. The proportion of cattle raised for fattening was prominent in Gangwon, Gyeonggi, and Gyeongsangbuk, while the proportion of cattle raised for breeding was higher in Chungcheongbuk, Jeollabuk and Jeollanam. LBW exported from farms was higher in provinces with higher number of cattle raised for fattening. All cattle were fed in feedlots. Feed ingredients composition in each province showed similar ratios of total mixed ration (TMR), concentrate and forage. Concentrates were supplied from commercial providers and TMR were formulated by farm owners mixing either a combination of by-products, or commercial concentrates and forages cultivated in farms. The CP content of the feed is a determinant factor in predicting N excretion. The southern regions of Korea such as Gyeongsangnam, Jeju, Jeollabuk and Jeollanam have large land use for cropping, so farms in these areas had the largest fields for feed production. Farms in Jeollabuk and Jeollanam had the largest fields for rice cultivation as these two provinces are

Table 5 Nitrogen footprints by activity source for the 9 provinces and the total Republic of Korea

Activity sources[a] (g N/ kg LBW)	Housing and manure storage			N field application			Total N footprint
	Denitrification		Volatilization	Denitrification	Volatilization	Leaching	
	N_2O	N_2	$NH_3 + NO_x$	N_2O	$NH_3 + NO_x$	NO_3^-	
Region							
Chungcheongbuk	3.8	11.5	84.4	3.2	63.1	77.3	243.3
Chungcheongnam	3.6	10.7	78.6	1.2	29.3	34.5	157.9
Gangwon	2.4	7.2	53.2	1.5	30.4	35.0	129.7
Gyeonggi	3.1	9.5	69.4	0.9	20.7	23.8	127.4
Gyeongsangbuk	2.3	7.2	52.7	0.5	11.9	14.0	88.6
Gyeongsangnam	2.9	8.6	63.4	0.8	16.1	21.0	112.8
Jeju	3.6	10.9	79.9	1.1	15.5	26.7	137.7
Jeollabuk	3.1	9.3	68.1	1.1	28.4	34.2	144.2
Jeollanam	4.2	12.6	92.2	1.8	37.8	47.3	195.9
National	3.1	9.2	67.6	1.1	23.3	28.4	132.7

[a]N_2O, N_2, NH_3, NO_x, and NO_3^- represents nitrous oxide, dinitrogen, ammonia, nitrogen oxides, and nitrate, respectively

known for intensive rice production in Korea. Farms cultivating both rice and other crops practiced double cropping by harvesting rice in autumn and the latter in spring. All farms adopted conventional tillage and turned the soil during crop cultivation. Manure was managed in solid storages with a concrete floor and metal ceiling. After leaving the storage, manure was applied to fields reserved for feed production or sent out to be either shared with other farms or processed in manure composting facilities to produce fertilizers. Chungcheongbuk recorded the highest percentage of manure field application out of all provinces, while Gyeongsangnam sent most of its manure to other farms or facilities. While the average N input from organic and synthetic fertilizers of all surveyed farms recorded 434 and 96 kg N/ha, respectively, there was a disparity in the intensity of N field input to the field across regions. Gangwon showed the highest intensity as mountains constitute most of its land, requiring a high input to make up for N lost during runoff due to the steep slope. Jeju had the least input per unit of land because of its stringent environmental regulations to protect contiguous reservoirs.

Nitrogen footprint composition and regional variances

The total N footprint of beef production was 132.7 g N/kg LBW. Volatilization was the dominant source of N losses and was responsible for 68.5 percent of the total footprint. The second main contributor was leaching at 21.4 percent, followed by denitrification as N_2 and N_2O, each representing 6.9 and 3.2 percent. The N footprints were presented by activity source for all regions in Table 5. The N footprints by activity source for all farms were provided in supplementary material (Table S1) to show the variations between farms within the same region.

Between the 9 provinces, the total N footprint of beef cattle production ranged from 88.6 to 243.3 g N/kg LBW. Regional variances were found to be associated with differences in farm characteristics and resource use parameters between the 9 provinces. The magnitude of N footprints in housing and manure storage was mainly driven by LBW at farm gate and animal category composition. N footprints were higher in regions that recorded lower LBW at farm gate per animal, such as Chungcheongbuk and Chungcheongnam provinces. This was explained by the
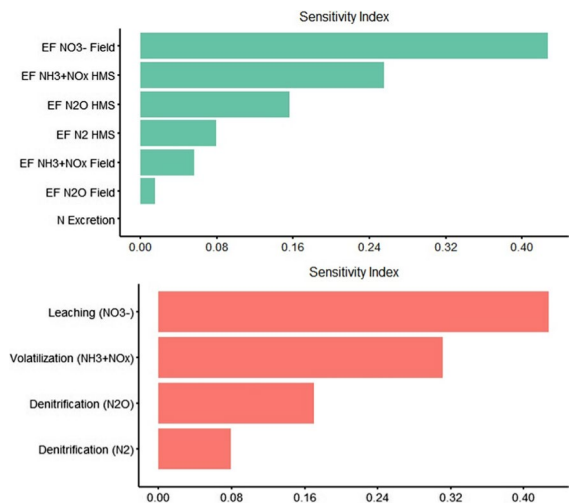

Fig. 3 Sensitivity indices by input parameters and N loss sources. EF for HMS and Field indicates emission factors used in calculating losses from housing and manure storage and N field application, respectively

fact that N losses from housing and manure storage in these regions were divided by a relatively lower denominator to be expressed as N footprint. Likewise, Gangwon and Gyeongsangbuk provinces recorded lower N footprints due to Hanwoo higher LBW. The ratio of steers (> 22 months) and fattening cows to breeding cows was another contributing factor. Although Chungcheongnam province showed lower LBW at farm gate compared to Chungcheongbuk, it had a higher steers and fattening cows to breeding cow's ratio which generated a lower N footprint. Gangwon province showed a lower ratio compared to Gyeongsangbuk, which resulted in a slight difference of 0.6 g N/kg LBW despite its lower LBW at farm-gate per animal. Jeollanam showed the lowest ratio and thus recorded the highest footprint in housing and manure storage. The variability in animal category was assumed to be related to differences in farming practices. According to (MAFRA 2020), 51 percent of the breeding cows were slaughtered for meat after second parity while 99 percent of the steers were slaughtered before 37 months of age. Since cows generally reach second parity by 36 months of age (NIAS 2017), it can be inferred that farms that recorded a low steer (> 22 months) and fattening cow to breeding cow ratio practiced breeding with relatively high parity. Thus, our results indicate that regions with

Table 6 Effects of mitigation scenarios on N footprints by loss source for the total Republic of Korea

Activity sources (g N/kg LBW)	Housing and manure storage			N field application			Total N footprint
	Denitrification		Volatilization	Denitrification	Volatilization	Leaching	
	N_2O	N_2	$NH_3 + NO_x$	N_2O	$NH_3 + NO_x$	NO_3^-	
Mitigation scenarios							
Baseline	3.0	9.1	66.5	1.1	23.4	28.7	131.7
Scenario 1[a]	2.9	8.6	63.1	1.0	22.4	27.6	125.5
PC	− 5.0	− 5.2	− 9.2	− 4.0	− 4.1	− 3.9	− 4.7
Scenario 2[b]	3.0	9.1	60.4	1.1	24.0	29.3	126.9
PC[f]	0.0	0.0	− 9.2	+ 1.8	+ 2.4	+ 2.3	− 3.6
Scenario 3[c]	3.0	9.1	66.5	1.1	23.1	28.1	130.9
PC[f]	0.0	0.0	0.0	0.0	− 1.1	− 2.1	− 0.6
Scenario 4[d]	3.0	9.1	66.5	0.9	24.8	22.6	126.9
PC[f]	0.0	0.0	0.0	− 16.7	+ 6.2	− 21.3	− 3.7
Combined[e]	2.9	8.6	57.3	0.9	24.2	21.9	115.7
PC[f]	− 5.0	− 5.2	− 13.9	− 18.5	+ 3.7	− 23.8	− 12.1

[a]Feed modification using RUP

[b]Deploying microorganism additives to manure in storage

[c]Replacing synthetic fertilizers with organic fertilizers

[d]Distributing biochar to field after N application

[e]Combined effects of all scenarios

[f]Percentage of change to N footprint compared to baseline

farms producing calves with lower-parity breeding cows were more likely to record lower N footprints.

The regional variability of N footprints in N field application was influenced by LBW at farm gate and animal category, as well as manure management and cropping practices. Chungcheongbuk recorded the highest numbers as 96 percent of its manure was directed to the field for crop production. Jeollanam and Gangwon followed with 71 and 70 percent. Gyeongsangbuk and Gyeongsangnam recorded the lowest footprints, which was related to these regions applying the lowest proportion of their manure to the field (34 and 30 percent). The high footprints in N field application in Chungcheongbuk and Gangwon were presumed to be associated with the low availability of manure composting facilities in the vicinity. Surveyed farms in these regions reported difficulties in locating nearby facilities to export their manure, leading to excessive N field inputs from organic fertilizers which contributed to increases in footprints.

Uncertainty and sensitivity analyses

The uncertainty analysis generated represents 46.6 percent of the total N footprint of Hanwoo beef production putting the uncertainty of the total N footprint in the range between 70.9 and 194.5 g N/kg LBW. Emission factors uncertainties were shown to be related to the uncertainty range of the N footprint; the sensitivity analysis indicated that the emission factors were the key drivers of high uncertainty, while the contribution of N excretion was marginal. In terms of activity sources, leaching was the primary contributor, followed by volatilization, and denitrification. (Fig. 3).

Effects of mitigation scenarios to reduce the nitrogen footprints of Hanwoo production

The effects of the five mitigation scenarios were simulated to evaluate their potentials for reducing N footprints of Hanwoo beef production (Table 6). Modifying the content of CP fed to steers and fattening cows using RUP was the most efficient

Table 7 Effects of combined scenarios on N footprints by source losses for the 9 provinces

Activity sources (g N/kg LBW)	Housing and manure storage			N field application			Total N footprint
	Denitrification		Volatilization	Denitrification	Volatilization	Leaching	
	N_2O	N_2	$NH_3 + NO_x$	N_2O	$NH_3 + NO_x$	NO_3^-	
Province							
Chungcheongbuk							
B[a]	3.8	11.5	84.4	3.2	63.1	77.3	243.3
M[b]	3.8	11.4	75.8	2.6	73.0	62.0	228.6
PC[c]	0.0	− 0.9	− 10.2	− 18.8	+ 15.7	− 19.8	− 6.0
Chungcheongnam							
B	3.6	10.7	78.6	1.2	29.3	34.5	157.9
M	3.5	10.6	71.0	1.0	30.9	27.5	144.6
PC	− 2.8	− 0.9	− 9.7	− 16.7	+ 5.5	− 20.3	− 8.4
Gangwon							
B	2.4	7.2	53.2	1.5	30.4	35.0	129.7
M	2.4	7.2	48.3	1.2	35.5	28.4	123.0
PC	0.0	0.0	− 9.2	− 20.0	+ 16.8	− 18.9	− 5.2
Gyeonggi							
B	3.1	9.5	69.4	0.9	20.7	23.8	127.4
M	2.9	8.7	57.8	0.7	22.3	18.5	110.9
PC	− 6.5	− 8.4	− 16.7	− 22.2	+ 7.7	− 22.3	− 12.9
Gyeongsangbuk							
B	2.3	7.2	52.7	0.5	11.9	14.0	88.6
M	2.3	6.8	45.2	0.4	12.3	10.8	77.8
PC	0.0	− 5.6	− 14.2	− 20.0	+ 3.4	− 22.9	− 12.2
Gyeongsangnam							
B	2.9	8.6	63.4	0.8	16.1	21.0	112.8
M	2.8	8.3	55.3	0.7	17.0	16.3	100.4
PC	− 3.4	− 3.5	− 12.8	− 12.5	+ 5.6	− 22.4	− 11.0
Jeju							
B	3.6	10.9	79.9	1.1	15.5	26.7	137.7
M	3.2	9.6	63.7	0.8	14.1	16.4	107.8
PC	− 11.1	− 11.9	− 20.3	− 27.3	− 9.0	− 38.6	− 21.7
Jeollabuk							
B	3.1	9.3	68.1	1.1	28.4	34.2	144.2
M	3.0	8.9	59.0	0.9	26.2	25.8	123.7
PC	− 3.2	− 4.3	− 13.4	− 18.2	− 7.7	− 24.6	− 14.2
Jeollanam							
B	4.2	12.6	92.2	1.8	37.8	47.3	195.9
M	3.9	11.8	78.7	1.4	35.7	33.6	165.1
PC	− 7.1	− 6.3	− 14.6	− 22.2	− 5.6	− 29.0	− 15.7

[a]Baseline N footprint

[b]N footprint after application of combined mitigation scenarios

[c]Percentage of change to N footprint compared to baseline

scenario that decreased the total N footprint by 4.7 percent. The application of microorganism additives to housing and manure storages showed an overall reduction of 3.7 percent. Replacing synthetic fertilizers with organic fertilizers in farms that exported manure was the least effective and reduced the total N footprint by 0.6 percent. The relatively low efficacy is assumed to be associated with the fact that most farms directed all their manure to the field as organic fertilizers. Distributing biochar after fertilizer application curtailed the total N footprint by 3.6 percent. Losses from denitrification and leaching decreased, but an increase in losses from volatilization was observed. This was explained by the increase in volatilization from crop fields being higher in intensity than the mitigation effects of biochar on rice cultivation. These four scenarios were combined which led to an overall N footprint reduction of 12.1 percent. The effect of this combination is not additive of all four single scenarios because the application of EM increased the amount of N in manure sent for field application in exchange for reducing volatilization, but was shown to reduce N loss from all sources, excluding volatilization from N field application.

The mitigation effects of the combined scenarios were simulated for each of the provinces (Table 7). The highest N footprint reduction was seen in Jeollanam (21.7 percent) and the lowest in Gangwon (5.2 percent), but the variation of reductions between N loss sources reflected the regional differences in farm management characteristics. Decreases in N losses as denitrification from housing and manure storage in Chungcheongbuk, Chungcheongnam, and Gangwon were relatively low, signifying that these provinces fed steers and fattening cows with low CP feed. The contrary was implied in Gyeonggi, Jeju, and Jeollanam, where reductions in denitrification were high. N lost through denitrification and leaching from the field decreased in all provinces but changes to volatilization were shown to be related to the type of crop produced. Jeollabuk and Jeollanam were the major beneficiaries of biochar application, as volatilization rates decreased due to the high portion of their field area being dedicated to rice cultivation. Conversely, farms in Chungcheongbuk, Gangwon, and Jeju did not cultivate rice and thus recorded higher losses. However, in Jeju, the effects of feeding RUP

partially negated the rise in volatilization from N field application.

Discussion

The nitrogen footprint of Korean beef cattle is lower than global findings

The N footprint found in this study averaged 132.7 (± 61.8) g N/kg LBW, exhibiting a broad regional range varying from 88.6 to 243.4 g N/kg LBW. This variability is explained by several factors, such as herd composition, manure management systems, land use, and fertilizer application rates. The N footprint of beef cattle meat varies among farming systems, assessment methods, system boundaries, and functional units. As a generalization, the average N footprint of the current study is lower than N footprint in others international studies (Angelidis et al. 2022; Joensuu et al. 2019; Leip et al. 2014; Mori et al. 2020; Rotz et al. 2015, 2019). Rotz et al. (2015) estimated the N footprint of beef cattle production in the midsouth United States using a partial LCA method integrated into the Integrated Farm System Model (IFSM) averaging 138 g N/kg carcass weight. Subsequently, Rotz et al. (2019) extended this to the entire United States using the IFSM model and estimated the N footprint to be 160 g N/kg carcass weight. Angelidis et al. (2022) calculated the N losses from grazing farms in England using IPCC emission factors and yielded a N footprint of 210 g N/kg live weight gain. Studies in the United States included N losses from the production and transportation of materials entering the farm and could show lower numbers if these upstream losses were excluded. Moreover, these farms were primarily composed of cattle bred for meat, which could have generated lower N footprints than farms comprising all animal categories. The system boundary for the England study did not consider upstream losses but included farms practicing grazing. Also, the emission factors used to estimate N losses from grazing were higher than confined feeding systems (IPCC 2019a), which could explain the N footprint being higher than our result. These studies showed similar contributions from each loss source; volatilization and leaching comprised 50 and 15 percent in the United States production system, while England reported 57 and 19 percent and Korea 68 and 22

percent, respectively. The N footprints for beef production in Finland (436 g N/kg carcass weight; Joensuu et al. 2019), EU (500 g N/kg carcass weight; Leip et al. 2014), and Japan (363 g N/kg carcass weight; Mori et al. 2020) were not calculated by dividing the aggregated N losses by the functional unit as done by Korea, United States, and England, but by dividing the difference between N input and N output by the functional unit. While the study in Finland (Joensuu et al. 2019) considered only the N in inorganic fertilizer as the input, the study in the EU (Leip et al. 2014) included inorganic and organic fertilizers, atmospheric deposition, and biological fixation, and Japan (Mori et al. 2020) the N from inorganic and organic fertilizers, and biological fixation. Due to the difference in estimation methods, we could not compare the contributions between each loss source for these studies. Moreover, our Hanwoo N footprint estimation may have yielded a different result if we had adopted the difference between N input and output, and included inputs from atmospheric deposition and biological fixation. It must be noted that studies that used carcass weight as the functional unit would show lower N footprints if they were to be converted to live body weight.

Mitigation scenarios boost N reduction potential in Korean beef cattle production

While more pronounced reductions have been demonstrated by simulating mitigation practices on dairy farms in China (32 percent; Ledgard et al. 2019), New Zealand (25 percent; Ledgard et al. 2019), and the United States (42 percent; Veltman et al. 2018), the scenarios proposed in this study possess the capacity to further reduce N footprints of Korean beef cattle production beyond the estimated 12.1%. The effect of modifying the CP and RUP levels of feed was simulated only on animal categories used for fattening. With prior studies (Bougouin et al. 2016; Montes et al. 2013) validating its effect on reducing volatilization, additional reductions are expected to occur by expanding its use to other animal categories. However, this expansion must be coupled with research on synchronizing dietary changes with animal nutrient requirements using Hanwoo beef cattle to preclude protein deficits (Hristov et al. 2011). The capacity of microbes to remove nitrogenous compounds from manure infused agricultural wastewater

(Mankiewicz-Boczek et al. 2017) indicates the potential for expanded utilization of microorganisms to mitigate losses from leaching in crop fields. Although replacing synthetic fertilizers with manure was shown to be the least effective, it must be noted that manure is recycled within the farm while the production of synthetic fertilizers entails further environmental impacts (Gaidajis & Kakanis 2021). Thus, if the system boundary is extended to encompass upstream processes, this scenario may prove beneficial especially in Korea, which recorded the highest N surplus in crop cultivation (157 and 147 kg N/ha from organic and synthetic fertilizers) among the Organization for Economic Co-operation and Development (OECD) countries (Lim et al. 2021). The conducive effects of biochar on attenuating environmental impacts and increasing crop productivity have been illustrated in several studies (Liu et al. 2019; Singh et al. 2022; Wang et al. 2021). Coupled with the abundance of crop residues in Korea such as rice straw, barley straw, and reed straw, the application of straw-derived biochar possesses high potential for extensive future implementation. However, applying a combined set of mitigation scenarios to all beef-producing farms in the ROK might not be feasible. The diverse range of farm management practices has led to significant variations among provinces in the contribution of nitrogen loss sources. For instance, volatilization rates range from 57.2 to 70.1 percent, while leaching varies from 12.8 to 31.8 percent. Given these discrepancies, tailoring mitigation scenarios to account for the specific characteristics of each farming system within different regions could prove to be a more effective approach in targeting the primary nitrogen loss sources. Overall, the scenarios proposed in this study bear strong merits for feasibility in that they do not require expenditure for installing additional equipment nor changes in farm management practices. These merits may facilitate the widespread adoption among Korea beef producers.

Limitations

The current study carries some limitations including the system boundary delineation, uncertainty associated with emission factors, and methods for mitigation scenarios analysis that should be expanded upon to conduct more accurate evaluation in future research.

Exclusion of upstream and downstream N losses in the system boundary

The system boundary excluded upstream losses from N fertilizer production as well as downstream losses from exported manure. Although N_2O losses occur during ammonia oxidation to nitrate in the absence of catalysts, the opacity of transactions between farmers and suppliers made it impossible to track the sources of fertilizer production, or whether it was domestic or imported. Therefore, this process was excluded to prevent exacerbating the uncertainty of the results from speculating the proportion of domestic or imported input, and associated losses from transportation and production. Although excluding losses from exported manure led to skewed results where farms that used their own manure had higher N footprints than those that didn't, this process was excluded for two reasons; i) Manure transported to treatment facilities was disregarded since it was turned into a commercial product by a different entity which escapes the boundary of Hanwoo beef cattle farms; ii) There were no records on manure exported to other farms as to the amount and the type of land it was applied to. No allocations were made for rice between human consumption and animal feed, as farmers produced both whole crop and food rice: the former was used entirely for animal feed while the latter was divided into grains for human consumption and rice straw for animal feed. Thus, all N losses from rice production were included because we were unable to identify the ratio between the amounts used for human consumption and animal feed. We also deployed general emission factors although emission factors for N losses vary by the type of land applied and differences between losses from storage and field application are substantial. This deficiency of data should be considered in future research to take a more holistic approach in evaluating N footprints of agricultural production.

Emission factor uncertainties: the need to develop country specific values

The uncertainty associated with the total N footprint we generated was higher than the 7.7 percent uncertainty reported by Rotz et al. (2019), in which country specific emission factors were deployed, in contrast to our analysis where we used general IPCC emission factors. Although the unavailability of uncertainty analyses on the N footprints of additional beef cattle production systems inhibited further comparisons, the effects of emission factors uncertainties on the accuracy of the results have been elucidated in previous studies (Basset-Mens et al. 2009; Chen & Corson 2014; Flysjö et al. 2011). These studies analyzed the influence of input parameters and emission factors on the environmental impacts of dairy cattle production and concluded that the uncertainty of the result was mainly affected by emission factors uncertainties. This was validated in our sensitivity analysis where emission factors with high ranges of uncertainty had the highest contributions to the uncertainty of the resulting N footprint, highlighting the necessity to refine emission factors and develop country specific values for a more precise analysis.

Methods for mitigation scenario analyses

Certain caveats of our mitigation scenarios are attributed to deficient data on strategies that strictly target N losses from Korean beef cattle production. Feed manipulation for breeding cattle was excluded because in the current system, they are fed a bare minimum of energy and protein to maintain pregnancy, not gain weight. Thus *in-vivo* studies to reduce excess N excretion from Hanwoo breeding cattle using RUP were very insufficient. However, it must be noted that our scenario considers feed manipulation of breeding cattle after they are transitioned at a certain parity from breeding purposes to fattening purposes. The mitigation capacity of adopting EM carries uncertainty since the EM product easily accessible through regional agricultural centers vary in terms of proportion and taxonomy of microorganisms and are not identical to the treatments used in cited studies. Further studies on the mitigation capacity of EM products available in Korea are necessary to develop a more accurate country specific scenario.

Conclusion

The findings of this study establish a solid baseline for future evaluations and scenario analyses in Korean beef cattle production by identifying regional hotspots of N loss and offering feasible, beneficial strategies, along with their respective effects on each province.

The stark difference between the mitigation potentials of the combined scenario and the individual scenarios highlights the need to target all possible pathways of N loss. Although our result was lower than the average N footprints generated from other international studies, we recognize the need to downscale the current intensive N input in field application to increase the N use efficiency of crop production and reduce possible water pollution from leaching and runoff. Future studies are recommended to expand the system boundaries to include N losses from upstream processes and exported manure so that N footprints are not skewed towards farms that produce feed using their own manure, and that stakeholders can weigh the environmental benefits between importing and domestically producing feed and fertilizers for beef cattle production.

Declarations

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