Evaluating the nitrogen footprint of Korean native beef cattle farms: Uncertainty analysis and mitigation scenarios

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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 Hanwoo beef cattle production in Korea at the farm gate through a life cycle assessment approach. Field surveys conducted on 106 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 lost/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 was averaged 132.8(± 61.9) 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 68.4, 21.4, and 10.1 percent of the N footprint. The contribution of fuel combustion was marginal. The uncertainty of the result was found to be 46.6 percent and was highly associated with emission factor uncertainties. We devised four feasible mitigation scenarios that are cost effective and do not penalize productivity, and evaluated their capacity for reducing N footprint: dietary modifications to decrease animal N excretion rates, microorganism additives to reduce volatilization from housing and manure storages recycling manure within the farm to replace synthetic fertilizers, and distributing biochar to the field after fertilizer application to curtail losses from crop production. Combining these scenarios demonstrated the potential to reduce 12.3 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 driver component in agriculture which is responsible 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, 2019b). Ammonia (NH_3) and nitrogen oxide (NO_x) are precursors to 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 wetlands, 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% to net greenhouses gases emissions (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 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 & 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 activities data and output, and finally to simulate mitigation scenarios to reduce 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 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 R statistical software (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 a smaller population (Fig. 1). The survey included information on the production purpose, farms size, cropping practices, fertilizer application rate, number and animals' categories, productivity, feeding practices, manure management system, and fuel and electricity usage. 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.

Insert Fig. 1

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, on-farm organic and synthetic fertilizer application to the field for feed production, and agricultural machinery. Annual N losses were estimated as the sum of emissions from denitrification, volatilization, leaching, and fuel combustion. Upstream emissions occurring from producing, transporting, and distributing N inputs used in the farm were excluded. The functional unit was 1kg 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 or composting in manure treatment facilities were not considered (Fig. 2).

Insert 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, 2006, 2019a, 2019b) and aggregated to determine the annual N loss (Table 1).

Nitrogen excretion from animals

Annual amount of N excretion (Nex) 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. However, 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. 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. Digestible energy of the feed (DE) was also required to find the supply of NE for maintenance and growth. Since commercial feed in ROK does not provide energy content in DE units, this was approximated using the total digestible nutrient (TDN) contents and dry matter intake (DMI) acquired from field surveys as proposed by (Ibidhi et al., 2021). In the estimation of $N_{retention}$ the amount of milk production was ignored as this only applies to dairy cattle. 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). Nex was calculated for each animal category for every farm accordingly.

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, Nex, and the emission factor of 0.01 for direct N_2O 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, Nex, 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 Nex 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 ($Frac_{LEACH-(H)}$).

N losses from agricultural machinery

N losses from agricultural machinery such as tractors, forklifts, and fork cranes were determined by estimating the amount of N_2O emissions generated from fuel combustion. Diesel was the single source of fuel and the default emission factor of 28.6 for N_2O emissions from off-road agricultural mobile sources (EF_j) was applied. Since EF_j was expressed as kg N_2O per terajoule (TJ) of fuel and the surveyed amount of diesel consumed was expressed in liters, the energy content of 35.2 megajoule (MJ) per liter of diesel was applied using country specific values from the Ministry of Trade, Industry, and Energy (MOTIE, 2017). The resulting value was multiplied by 28/44 to quantify the amount of N lost as N_2O.

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	$N_{intake} = GE/18.45 \times CP\%/100/6.25$	(IPCC, 2019a)
Daily N retention rates	kg N/animal/day	$N_{retention(T)} = [Milk \times Milk\ PR\%/100]/6.38 + [WG \times (268 - (7.03 \times NE_G))/WG]/1000/6.25$	(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, 2019[a])
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 Nex	$Frac_{N2(N2O)} = R_{N2(N2O)} \times EF_{3(S)}$	(IPCC, 2019a)
Losses from N field application[b]			
Annual N_2O emissions from denitrification	kg N_2O/yr	$N_2O-N_{N\ inputs} = [(F_{SN} + F_{ON} + F_{CR} + F_{SOM}) \times EF_1] + [(F_{SN} + F_{ON} + F_{CR} + F_{SOM})_{FR} \times EF_{1FR}]$	(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)
Losses through agricultural machinery[b]			
Annual N_2O emissions from diesel combustion	kg N_2O/yr	$Emissions = \sum_j (Fuel_j \times EF_j)$	(IPCC, 2006)

[a] N excretion was calculated using the tier 2 approach.
[b] All subsequent N emissions and losses were calculated using default emission factors.

Insert Table 1.

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, 2006, 2019a, 2019b) were deployed for the uncertainties of emission factors. 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 simulation, the probability distribution functions (PDF) of all input variables were estimated using the Anderson-Darling goodness-of-fit method (Anderson & Darling, 1952) and were identified as either normal or log-normal (Table 2). Subsequently, 50000 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 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)
Losses through agricultural machinery	EF_j	28.6	kg N_2O-N / TJ diesel	14.3–85.8	Log-normal	(IPCC, 2006)

Insert Table 2.

Mitigation scenarios

Four potential mitigation scenarios to reduce N losses were simulated for all farms. All scenarios were checked with the farmers for feasibility to ensure that they did not affect productivity nor require initial expenses for equipment installment. The 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 Nex. 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 (> 22months), steers (14 ~ 21months), and growing males (6 ~ 13months) 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 (> 22months).

To curtail N losses from housing and manure storages, microorganism additives such as EM (Effective Microorganisms) were applied to all farms (Fig. 2). 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).

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).

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 (> 22months) and fattening cows – 13% CP, 51.5% RUP Steers (14 ~ 21months) – 14% CP, 44.6% RUP Growing males (6 ~ 13months) – 15% CP, 45.8% RUP	Decrease in Nex 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^-)	

Insert Table 3.

Results and discussion

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 were responsible for 35.5% of the total rice production in Korea (KOSIS, 2020). 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. 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. The N input from organic and synthetic fertilizers in this survey recorded 434 and 96 kg N/ha, which was more intense than the average input of 157 and 147 kg N/ha N from organic and synthetic fertilizers used for crop cultivation in ROK (Lim et al., 2021).

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

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)
Synthetic fertilizer	192	107	44	32	74	116	55	79	139
Energy consumption									
Diesel (L/head)	24	16	12	25	17	22	74	30	36
Electricity (kWh/head)	541	689	246	409	687	1055	774	613	415

Insert Table 4.

International and regional comparison of nitrogen footprints of the beef industry

The total N footprint of beef production was 132.8 g N/kg LBW. Volatilization was the dominant source of N losses and was responsible for 68.4 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. Losses through fuel combustion as N_2O were marginal. The result of this study was different from those found for the beef production system in the midsouth United States (138 g N/kg carcass weight; Rotz et al., 2015), the entire United States (160 g N/kg carcass weight; Rotz et al., 2019), and the United Kingdom (210 g N/kg live weight gain; Angelidis et al., 2022). The 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 are excluded. Moreover, converting their functional unit from carcass weight to live body weight could lead to a decrease in footprints. However, farms in the United States studies 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 United Kingdom study did not consider upstream losses but included farms practicing grazing. The emission factors used to estimate N losses from grazing were higher than confined feeding systems (IPCC, 2019a), which could be the explanation for the higher N footprint. All studies showed similar contributions from each loss source; volatilization and leaching comprised 50 and 15 percent in the United States production system, while the United Kingdom reported 57 and 19 percent and Korea 68 and 22 percent. The contributions of volatilization and leaching reported from the United States are assumed to be higher if upstream losses are not considered.

The N footprints were presented by activity source for all regions in Table 5. The total N footprint of beef cattle production ranged from 88.6 to 243.4 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 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 (> 22months) 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 farmgate 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 (> 22months) and fattening cow to breeding cow ratio practiced breeding with relatively high parity. Thus, our results indicate that regions with farms producing calves with lower-parity breeding cows were more likely to record lower N footprint.

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. The N footprints in agricultural machinery in total N footprints showed little regional variances.

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			Agricultural machinery	Total N footprint
	Denitrification		Volatilization	Denitrification	Volatilization	Leaching	Fuel combustion	
	N_2O	N_2	$NH_3 + NO_x$	N_2O	$NH_3 + NO_x$	NO_3^-	N_2O	
Region								
Chungcheongbuk	3.8	11.5	84.4	3.2	63.1	77.3	0.1	243.4
Chungcheongnam	3.6	10.7	78.6	1.2	29.3	34.5	0.1	158.0
Gangwon	2.4	7.2	53.2	1.5	30.4	35.0	0.0	129.7
Gyeonggi	3.1	9.5	69.4	0.9	20.7	23.8	0.1	127.5
Gyeongsangbuk	2.3	7.2	52.7	0.5	11.9	14.0	0.0	88.6
Gyeongsangnam	2.9	8.6	63.4	0.8	16.1	21.0	0.1	112.9
Jeju	3.6	10.9	79.9	1.1	15.5	26.7	0.2	137.9
Jeollabuk	3.1	9.3	68.1	1.1	28.4	34.2	0.1	144.3
Jeollanam	4.2	12.6	92.2	1.8	37.8	47.3	0.2	196.1
National	3.1	9.2	67.6	1.1	23.3	28.4	0.1	132.8

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

Insert Table 5.

Uncertainty and sensitivity analyses

The uncertainty analysis generated represents 46.6 percent of the total N footprint of Hanwoo beef production. This was higher than the 7.7 percent uncertainty reported by (Rotz et al., 2019), where country specific emission factors were deployed. 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. Leaching was the primary contributor, followed by volatilization, denitrification, and fuel combustion (Fig. 3). Although the unavailability of uncertainty analyses on the N footprints of beef cattle production inhibited further comparisons, the effects of emission factor uncertainty on the preciseness of the results have been elucidated by (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 factor uncertainties. This highlights the necessity to refine emission factors and develop country specific values for a more precise analysis.

Insert Fig. 3

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

The effects of the four 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 scenario that decreased the total N footprint by 4.7 percent. Consistent with prior studies (Bougouin et al., 2016; Montes et al., 2013), its effect on volatilization was the most prominent. Further reductions are expected with expanding its use to other animal categories, but additional research on synchronizing dietary changes with animal nutrient requirements using Hanwoo beef cattle are necessary to preclude protein deficits (Hristov et al., 2011). The application of microorganism additives to housing and manure storages showed an overall reduction of 3.7 percent. 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. 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. However, it must be noted that manure is recycled within the farm as organic fertilizers 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 agricultural production among the Economic Co-operation and Development (OECD) countries (Lim et al., 2021). 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. 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). The abundance of crop residues in the ROK such as rice straw, barley straw, and reed straw indicate a high potential for future use of straw-derived biochar. These four scenarios were combined which led to an overall N footprint reduction by 12.3 percent. This combination was shown to have effects on all loss sources, excluding volatilization from N field application. More robust 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). However, 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, which may facilitate the widespread adoption among Korea beef producers.

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			Agricultural machinery	Total N footprint
	Denitrification		Volatilization	Denitrification	Volatilization	Leaching	Fuel combustion	
	N_2O	N_2	$NH_3 + NO_x$	N_2O	$NH_3 + NO_x$	NO_3^-	N_2O	
Mitigation scenarios								
Baseline	3.0	9.1	66.5	1.1	23.4	28.7	0.1	131.8
Scenario 1[a]	2.9	8.6	63.1	1.0	22.4	27.6	0.1	125.6
PC[f]	-5.0	-5.2	-9.2	-4.0	-4.1	-3.9	0.0	-4.7
Scenario 2[b]	3.0	9.1	60.4	1.1	24.0	29.3	0.1	127.0
PC	0.0	0.0	-9.2	+ 1.8	+ 2.4	+ 2.3	0.0	-3.6
Scenario 3[c]	3.0	9.1	66.5	1.1	23.1	28.1	0.1	131.0
PC	0.0	0.0	0.0	0.0	-1.1	-2.1	0.0	-0.6
Scenario 4[d]	3.0	9.1	66.5	0.9	24.8	22.6	0.1	127.0
PC	0.0	0.0	0.0	-16.7	+ 6.2	-21.3	0.0	-3.7
Combined[e]	2.9	8.6	57.3	0.9	24.2	21.9	0.1	115.8
PC	-5.0	-5.2	-13.9	-18.5	+ 3.7	-23.8	0.0	-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

Insert Table 6.

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. Deploying the combination of mitigation scenarios to all beef producing farms in ROK may not be attainable. Tailoring these scenarios to reflect the distinctions in farming systems could be an efficacious approach to target major N loss sources of each region.

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			Agricultural machinery	Total N footprint
		Denitrification		Volatilization	Denitrification	Volatilization	Leaching	Fuel combustion	
		N_2O	N_2	$NH_3 + NO_x$	N_2O	$NH_3 + NO_x$	NO_3^-	N_2O	
Province									
Chungcheongbuk	B[a]	3.8	11.5	84.4	3.2	63.1	77.3	0.1	243.4
	M[b]	3.8	11.4	75.8	2.6	73.0	62.0	0.1	228.7
	PC[c]	0.0	-0.9	-10.2	-18.8	+ 15.7	-19.8	0.0	-6.0
Chungcheongnam	B	3.6	10.7	78.6	1.2	29.3	34.5	0.1	158.0
	M	3.5	10.6	71.0	1.0	30.9	27.5	0.1	144.7
	PC	-2.8	-0.9	-9.7	-16.7	+ 5.5	-20.3	0.0	-8.4
Gangwon	B	2.4	7.2	53.2	1.5	30.4	35.0	0.0	129.7
	M	2.4	7.2	48.3	1.2	35.5	28.4	0.0	123.0
	PC	0.0	0.0	-9.2	-20.0	+ 16.8	-18.9	0.0	-5.2
Gyeonggi	B	3.1	9.5	69.4	0.9	20.7	23.8	0.1	127.5
	M	2.9	8.7	57.8	0.7	22.3	18.5	0.1	111.0
	PC	-6.5	-8.4	-16.7	-22.2	+ 7.7	-22.3	0.0	-12.9
Gyeongsangbuk	B	2.3	7.2	52.7	0.5	11.9	14.0	0.0	88.6
	M	2.3	6.8	45.2	0.4	12.3	10.8	0.0	77.8
	PC	0.0	-5.6	-14.2	-20.0	+ 3.4	-22.9	0.0	-12.2
Gyeongsangnam	B	2.9	8.6	63.4	0.8	16.1	21.0	0.1	112.9
	M	2.8	8.3	55.3	0.7	17.0	16.3	0.1	100.5
	PC	-3.4	-3.5	-12.8	-12.5	+ 5.6	-22.4	0.0	-11.0
Jeju	B	3.6	10.9	79.9	1.1	15.5	26.7	0.2	137.9
	M	3.2	9.6	63.7	0.8	14.1	16.4	0.2	108.0
	PC	-11.1	-11.9	-20.3	-27.3	-9.0	-38.6	0.0	-21.7
Jeollabuk	B	3.1	9.3	68.1	1.1	28.4	34.2	0.1	144.3
	M	3.0	8.9	59.0	0.9	26.2	25.8	0.1	123.8
	PC	-3.2	-4.3	-13.4	-18.2	-7.7	-24.6	0.0	-14.2
Jeollanam	B	4.2	12.6	92.2	1.8	37.8	47.3	0.2	196.1
	M	3.9	11.8	78.7	1.4	35.7	33.6	0.2	165.3
	PC	-7.1	-6.3	-14.6	-22.2	-5.6	-29.0	0.0	-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

Insert Table 7.

Conclusion

This study provides an assessment of the N footprint of Korean beef cattle production and elucidates how regional differences in farming systems contributed to the disparity between the 9 provinces. The N footprint averaged 132.8 g N/kg LBW, where N volatilization and leaching were the major contributors. Regional variations were shown to be related to animal categories, manure management and cropping practices. The uncertainty and sensitivity analyses highlighted the necessity to establish country specific emission factors to attain a more precise output. Mitigation scenarios were divided with the aim to target animal diet, animal housing and manure storage, and cropping fields, in which the combined effects reduced N losses by 12.1. The output of this study can serve as a baseline for future evaluations on both regional and national scales. It also presents beneficial scenarios and their effects on each of the provinces, which may help facilitate the decision-making of agricultural stakeholders in heading towards sustainable beef production in Korea.

Declarations

Authors Contribution

R.I and KHK conceptualized and designed the study. Material preparation was done by J.B, T.K and R.I and data collection by J.B and T.K. All analyses were performed by J.B and T.K. The first draft of the manuscript was written by J.B and T.K and all authors commented on the previous versions of the manuscript. All authors revised, read, and approved the final manuscript.

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Conflict of Interest

The authors stipulate that none have a conflict of interest in submission of this manuscript.

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Figures

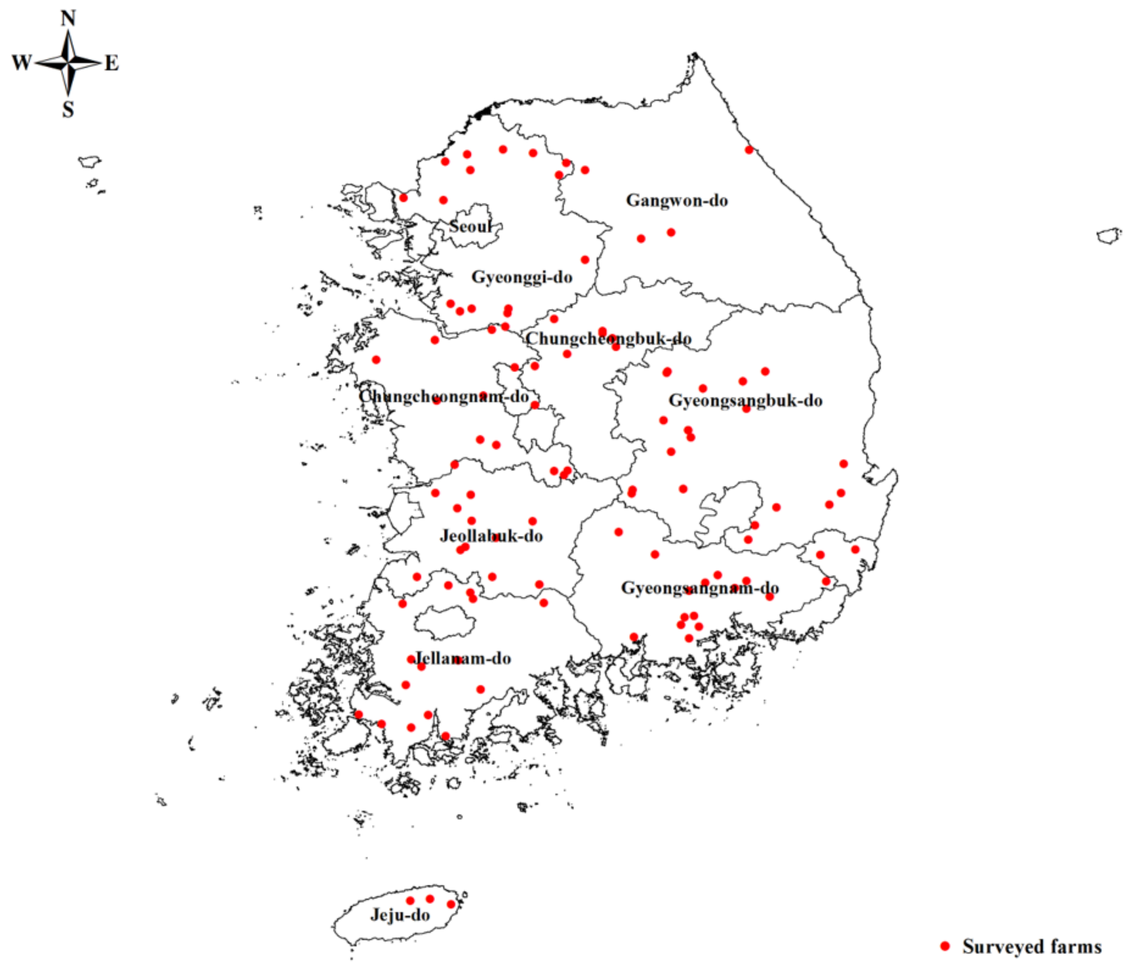

Figure 1

Spatial distribution of the 106 surveyed Hanwoo beef farms in the Republic of Korea.

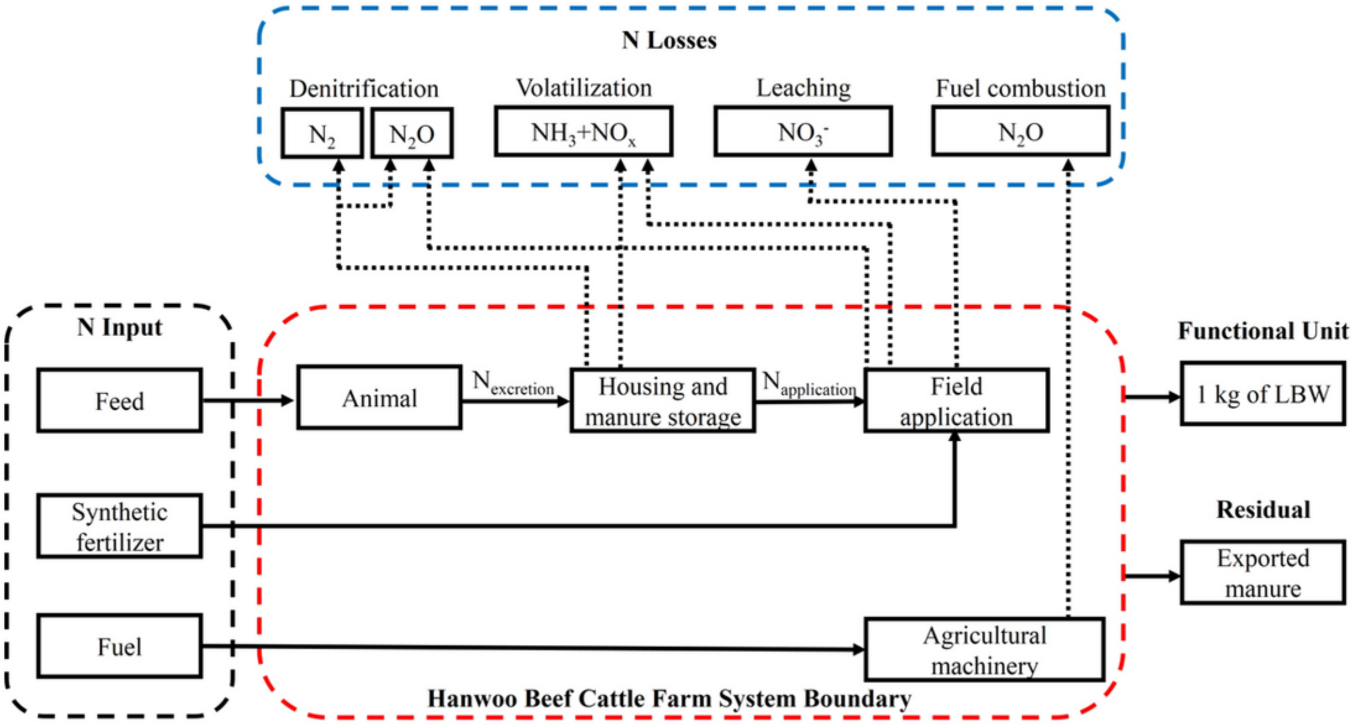

Figure 2

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.

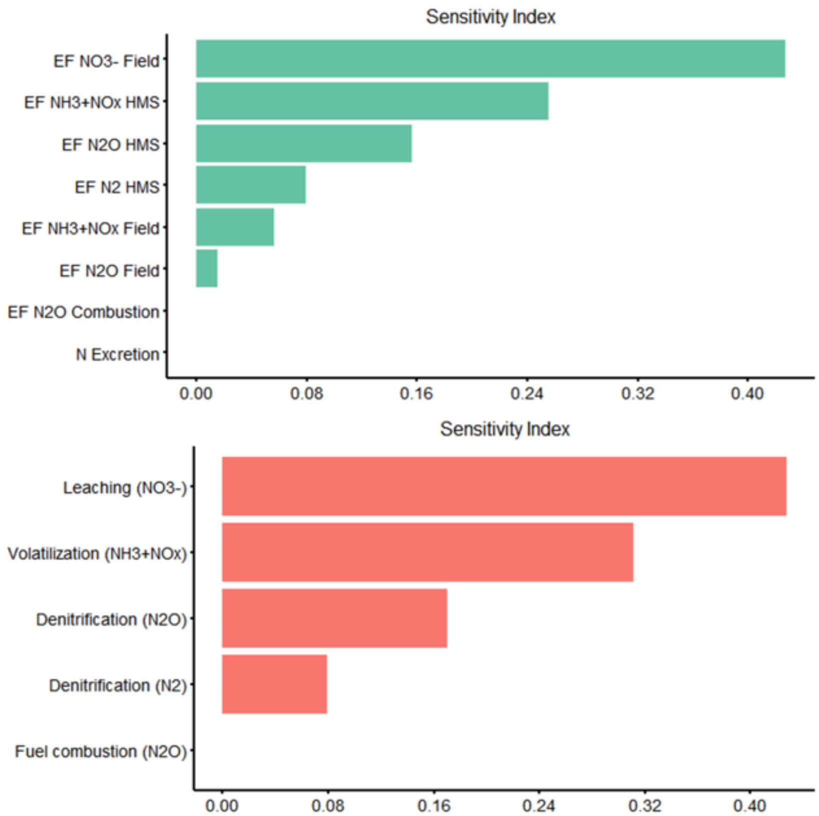

Figure 3

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