Master's Thesis of Science in Agriculture

Evaluating the nitrogen footprint of Hanwoo beef farms: uncertainty analysis and mitigation strategies

대한민국 한우 농가 질소 발자국 분석: 불확도 평가과 감축 전략 제시

February 2023

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Evaluating the nitrogen footprint of Hanwoo beef farms: uncertainty analysis and mitigation strategies

A thesis

submitted in partial fulfillment of the requirements to the faculty

of Graduate School of International Agricultural Technology

for the Degree of Master of Science in Agriculture

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February 2023

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for the Degree of Master of Science in Agriculture

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Abstract

Evaluating the nitrogen footprint of Hanwoo beef farms: uncertainty analysis and mitigation strategies

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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 N losses from Hanwoo beef cattle production in Korea at the farm gate through a life cycle assessment approach. Field surveys conducted on 106 farms across the 9 provinces were compiled with publicly accessible data to identify regional distinctions in farming systems and evaluate total losses from beef production. Emission factors from the IPCC guidelines were used to calculate the results, which were expressed as N footprints (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 average N footprint was determined to be 132.8 g N/kg LBW and varied between provinces based on animal composition, manure management, field area and fertilizer application rates. Volatilization was the primary source of N losses, followed by leaching and denitrification, each contributing 68.4, 21.4, and 10.1 percent. Losses through fuel combustion were 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 strategies that are cost-effective and do not penalize productivity, and evaluated their capacity for reducing N losses: dietary modification (Rumen undegradable protein; RUP) 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 strategies demonstrated the potential to reduce 12.3 percent of the total N footprint. The extents of mitigation differed by province (ranging from 5.2 to 21.7 percent) and were shown to be contingent on feeding practices and type of crop cultivated. Overall, this study provides an universal metric that can be utilized to communicate the environmental impacts of Korean beef production with the global agricultural community. The analyses indicate that more precise results could be achieved with future endeavours toward developing country-specific emission factors. The mitigation potentials of the presented strategies propose possibilities for practical and sustainable beef production in Korea.

Keywords: Beef production, Hanwoo beef farms, Nitrogen losses, Life cycle assessment, Mitigation strategies, Uncertainty analysis

Student Number**:** 2021-23169

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Abbreviations

AA: Amino acids

AWMS: Manure management system

B: Baseline

C: Carbon

CC-E: Complex bacterial community

CH_4: Methane

CO_2: Carbon dioxide

Combustion: Fuel combustion

CP: Crude protein

CS: Combined mitigation strategies

DE: Digestible energy

DM: Dry matter

EF: Emission factor

EF_1: Emission factor for direct N2O emissions from application of organic and synthetic fertilizers to field

EF_{1FR}: Emission factor for direct N2O emissions from application of organic and synthetic fertilizers to flooded rice

EF3: Emission factor for direct N_2O emissions from manure management

EF_j: Emission factor for direct N_2O emissions from off-road agricultural mobile sources

EM: Effective microorganisms

EMEP: European Monitoring and Evaluation Programmed

FAO: Food and Agricultural Organization

F_{CR}: Amount of nitrogeon in crop residues

Field: N field application

F_{ON}: Amount of nitrogen applied as organic fertilizers

$Frac_{GASF}$: Fraction of N volatilized from synthetic fertilizers

$Frac_{GASM}$: Fraction of N volatilized from organic fertilizers

$Frac_{GASMS(S)}$: Fraction of nitrogen lost from volatilization in manure management

$Frac_{LEACH-(H)}$: Fraction of N lost from leaching

$Frac_{N2MS(S)}$: Fraction of nitrogen lost as N_2

F_{SN}: Amount of nitrogen applied as synthetic fertilizers

F_{SOM}: Amount of nitrogen mineralized in mineral soils

GE: Gross energy

GHG: Greenhouse gas

GLEAM: Global Livestock Environmental Assessment Model

HAB: Hyper-ammonia producing bacteria

HMS: Housing and manure storage

IFSM: Integrated farm system model

IPCC: Intergovernmental Panel on Climate Change

ISO: International Organization for Standardization

LCA: Life cycle assessment

LEAP: Livestock Environmental Assessment and Performance

MC: Monte Carlo

MJ: Megajoule

N: Nitrogen

N_2: Dinitrogen

N_2O: Nitrous Oxide

NE: Net energy

NE_g: Net energy for gain

Nex: Amount of nitrogen excretion

NH_3: Ammonia

NH_4^+: Ammonium

N_{intake}: Nitrogen intake rates

NO: Nitric Oxide

NO_2^-: Nitrite

NO_2: Nitrous Oxide

NO_3^-: Nitrate

NO_x: Nitrogen oxide

N_r: Reactive nitrogen

$N_{retention}$: Nitrogen retention rate

NUTE: Nitrogen utilization efficiency

OECD: Economic Co-operation and Development

PDF: Probability distribution function

PPB: Proteolytic and peptidolytic bacteria

RDP: Rumen degradable protein

REPRO: Reproduction of soil fertility model

ROK: Republic of Korea

RUP: Rumen undegradable protein

SF: Separate feeding

SIMSDAIRY: Sustainable and integrated management systems for dairy production

TDN: Total digestible nutrient

TJ: Terajoule

TMR: Total mixed ration

UB: Ureolytic bacteria

WG: Weight gain

1. Introduction

Nitrogen (N) is a focal component in agriculture which is responsible for sustaining the global nutritional demands. In the process of producing agricultural products, N is lost in the form of reactive N (N_r), entailing various environmental risks to the surrounding environment (Galloway et al., 2003). In the context of N_r lost through the atmosphere, nitrous oxide (N_2O) is a greenhouse gas having a global warming potential of 265, far surpassing that of methane (IPCC, 2014). 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 methane sinks (Steudler et al., 1989). N_r is also lost through water as leached nitrate (NO_3^-) which gives rise to eutrophication in the wetlands, consequently declining biodiversity (Smolders et al., 2010). While advances in agricultural technology have enabled lower N_r 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 in the international food supply chain (Erisman et al., 2018; Leip et al., 2014; 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 emissions (GIR, 2021). The Hanwoo beef cattle industry is an essential domain in Korean agriculture and comprises a complex system integrating both livestock production and agronomy. This indicates the necessity to perform a comprehensive assessment of N lost during beef cattle production be conducted to reflect the diverse agricultural 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 (LEAP) Partnership (FAO, 2018) identified the N footprint as a valid index of N emissions from livestock systems and developed guidelines using a life cycle assessment (LCA) approach to quantify N flows and determine the impacts of livestock production.

N lost during cattle production and crop cultivation for feed was found to far surpass that of the consumption chain (Chatzimpiros & Barles, 2013; Joensuu et al., 2019). Therefore, assessment of N losses on a farm level is representative of the losses occurring in beef supply chains. The aim of this study was to evaluate the N footprint of Hanwoo beef farms at the farm gate in ROK on a national scale through a partial LCA approach, analyze the uncertainties of the output, and devise mitigation strategies to establish sustainable farming practices.

2. Literature Review

2.1. Nitrogen metabolism and excretion in the ruminant

All GHG emissions from manure management originate from animal urine and fecal matter. Thus, it is crucial to understand how N is processed and excreted from the ruminant body. N metabolism in the ruminant can be classified into three divisions: ruminal, urea recycling, and post-ruminal. In the ruminal section, input N (dietary, recycled, endogenous) undergo a series of protein degradation and microbial protein synthesis. Dietary N enters the rumen in the form of ruminal degradable protein (RDP) and rumen undegradable protein (RUP). Ruminal microbials adhere to feed particles in the rumen, and those with proteolytic enzymes degrade the RDP into peptides and amino acids (AA). These are then conveyed to inside the microbial cell where peptides are further broken down into AA, which serve as the ingredients for microbial protein synthesis.

If the microbial is deficit of energy, AA is not incorporated into protein synthesis but rather catabolized, so that its carbon skeleton can be fermented into VFA. Surplus AA is excreted from the cell as ammonia, transferred to the liver, and discharged in the urine as urea through the kidneys. Undegraded and microbial protein exit the rumen and proceed to the remaining gastrointestinal tract (Bach et al., 2005). The liver plays a pivotal role in urea recycling as it directs the portion of urea which is not transported to the kidney towards the rumen. The urea is channelled through the blood to either the epithelial tissues of the rumen or the saliva, which subsequently is used for microbial protein synthesis. The portion of urea recycled was observed to be in inverse proportion to dietary protein intake (Reynolds & Kristensen, 2008).

Proteolytic and peptidolytic bacteria (PPB), ureolytic bacteria (UB), and hyper-ammonia producing bacteria (HAB) are the three types of ruminal microbials with special significance in N metabolism (Tan et al., 2021). PPB degrade proteins and peptides from dietary and bacterial proteins while UB utilizes both dietary and recycled urea. HAB generates volatile fatty acids and NH_3 in the rumen by deaminating amino acids. In the post-ruminal section, undegraded dietary protein, microbial protein, residual ammonia, and endogenous protein derived from sloughed cells in the rumen progress sequentially into the abomasum, duodenum, and ileum. Proteins are degraded by abomasal, pancreatic and mucosal proteases inside these tracts where the absorption of AA occurs concomitantly. AA are further assimilated in the caecum and colon, and excess AA are transported to the liver in all segments of the post-ruminal section (Lindsay & Armstrong, 1982). Undegraded dietary and microbial N, along with metabolic fecal N, exit the animal body as feces.

Increasing N utilization efficiency (g N in product/g N in feed; NUTE) is fundamental in enhancing productivity and minimizing environmental impacts. NUTE of ruminants range between 22 to 27 percent, which falls far behind from that of swine and poultry (Huhtanen & Hristov, 2009; Kohn et al., 2005; Xue et al., 2016). The extent of ruminant NUTE is regulated by the synchrony of microbial protein synthesis, ruminal protein degradation, urea recycling, and N utilization in the muscles and the mammary gland (Calsamiglia et al., 2010). Feeding practices that amplify the efficiency of one compartment may entail negative effects on another. Identifying techniques to curtail N excretion and increase N retention is imperative in achieving optimum NUTE.

2.2. The nitrogen cycle in manure storages and agricultural soil

N excreted as manure is exposed to a myriad of aerobic and anaerobic microbials that convert it into its various oxidation states (Figure 1) (Maeda et al., 2011; Stein & Klotz, 2016). This process is known as the N cycle and all manure-derived nitrogenous emissions are products of this sequence (Figure 2). Manure N ($R-NH_2$) is mineralized into ammonia (NH_3) or ammonium (NH_4^+), which are then oxidized by aerobic bacteria in a process called nitrification to produce nitrogen dioxide (NO_2) and nitrate (NO_3^-). Consequently, anaerobic bacteria reduce the oxidized matter in a process called denitrification and generate nitric oxide (NO), nitrous oxide (N_2O), and dinitrogen (N_2). Nitrogen loss occurs before the cycle is completed, as 19 to 77 percent of the initial manure N is discharged as N_2 or NH_3, and 0.2 to 9.9 as N_2O (Maeda et al., 2011). The intermediates of the N cycle all contribute to nitrogenous GHG emissions in the livestock sector. N_2 alone stays stable in the atmosphere and is not considered a GHG.

Reduced

Molecule	Name	Oxidation state
NH_3, NH_4^+	Ammonia, Ammonium	-3
N_2	Dinitrogen	0
N_2O	Nitrous oxide	1
NO	Nitric oxide	2
NO_2^-	Nitrite	3
NO_2	Nitrogen dioxide	4
NO_3^-	Nitrate	5

Oxidized

Figure 1. Oxidation states of nitrogen adapted from (Stein & Klotz, 2016).

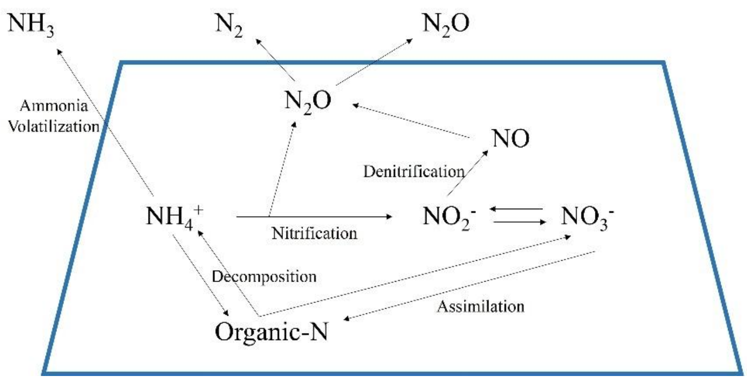

Figure 2. The nitrogen cycle in manure adapted from (Maeda et al., 2011).

2.3. Nitrogenous emissions from the farm

2.3.1. Nitrous oxide

Nitrous oxide is released from manure storage and agricultural soils through the process of nitrification and denitrification. While manure is the sole contributor to N_2O emissions in storage systems, emissions from soils stem from synthetic fertilizers, manure, and crop residues after harvest. Environmental factors affect the extent of N_2O emissions in both storage and soil. Initial carbon, nitrogen and water contents of the manure and storage temperature were observed to be positively correlated with N_2O production. It was presumed that an ample supply of carbon provided a favourable environment for denitrification bacteria, while semi-humid conditions prompted the simultaneous existence of both aerobic and anaerobic regions (Ba et al., 2020a). Soil characteristics, climate, and N application methods were shown to influence emissions from agricultural soils. High precipitation, high pH, clay and organic soils, and soil compaction had positive effects on N_2O emissions (Bouwman et al., 2002). Subsurface manure application and the use of raw manure reported higher N_2O emissions than surface application or treated manure. Previous studies suggest that increased contact between the soil and manure, lower NH_3 volatilization beneath the soil surface, and organic compounds more susceptible to degradation within untreated manure served as the cause (Zhou et al., 2017).

2.3.2. Ammonia

Ammonia is a by-product of the N cycle and indirectly contributes to GHG emissions as a precursor to N_2O. The proportion of total N fed to cattle lost as NH_3 reaches up to 55 percent. This volatilized NH_3 either bonds with atmospheric acids to form fine particulate matters or is deposited to the land, where soil acidification or its transition to N_2O ensue (McGinn et al., 2007). Contrary to N_2O emissions, studies indicate that manure storage and soil application techniques that minimize the exposure to air were observed to be negatively related to NH_3 volatilization (Hou et al., 2015). The absence of aerobic environments is known to impede the release of NH_3 into the air.

2.3.3. Nitrate

Nitrate is produced from the nitrification of organic N and lost through a process known as leaching. The compound is dissolved in the soil through percolating water and travels below the rooting zone of the vegetation to groundwaters. In this process, nitrate mobilizes sulphate, which ultimately induces phosphate eutrophication in adjacent wetlands (Smolders et al., 2010b). A marginal portion of the leached nitrate is transmuted into N_2O and deposited to the ground (IPCC, 2006b). The degree of leached N is impacted by soil characteristics, type of N applied to the soil, and climate. Higher clay level in soils, the utilization of manure opposed to mineral N, and low precipitation were found to be connected to lower leaching rates (Broeke & de Groot, 1998; Demurtas et al., 2016; Simmelsgaard, 1998; Webb et al., 2005).

2.4. Manure management methods

Manure management encompasses the collection, storage, treatment, transport, and application of manure to the land (Pain & Menzi, 2011). The magnitude of GHG emissions and the types of nitrogenous effluence were found to vary substantially between different storage, treatment, and application systems (Owen & Silver, 2015; Webb et al., 2010; Zhou et al., 2017). Understanding the concept of each system is essential in identifying the optimal GHG mitigation strategy.

2.4.1. Manure storage

The IPCC and EMEP established different terms for categorizing manure storage types (Table 1). Although the EMEP presents term equivalents between the two guidelines, slight discrepancies do exist between the definitions provided. Terms used to elucidate types of storage systems in one guideline may not be available in another.

Table 1. Term equivalents between IPCC and EMEP guidelines

IPCC	EMEP
Liquid/Slurry	Lagoons
Definition unavailable	Tanks
Solid storage	Heaps
Pit storage below animal	In-house slurry pit
confinements	In-house deep litter
Cattle and swine deep bedding	Crust

Liquid/slurry, cover	Cover
Solid storage – covered	Composting, passive windrow
Composting, static pile	Forced-aeration composting
Composting, in-vessel	Definition unavailable
Composting, intensive windrow	Definition unavailable
Composting, passive windrow	Biogas treatment
Anaerobic digester	Slurry separation
Definition unavailable	Acidification
Definition unavailable	Definition unavailable
Dry lot	Definition unavailable
Uncovered anaerobic lagoon	Definition unavailable
Aerobic treatment	

The EMEP defines lagoons as storages with a high surface area to depth ratio, generally constructed by making shallow excavations in the soil. The liquid or slurry term used by the IPCC differs, as it indicates manure stored with or without minimum addition of water and stored in tanks or earthen ponds. This is then divided into three subcategories: with natural crust cover, without natural crust cover, and cover.

The term tank is identified by the EMEP as cylindrical storage systems with low surface area to depth ratio commonly composed of steel or concrete. Albeit no specific equivalent is provided by the IPCC, the expression ‘tanks or earthen ponds outside the housing' used to supplement liquid or slurry storages bears similarity to tanks.

Heaps are specified as piles of solid manure by the EMEP, while the IPCC further explicates its counterpart, solid storage. The term solid storage refers to a system where manure is stored in unconfined piles or stacks for months. The stacking of manure is facilitated by the presence of ample bedding material or moisture evaporation.

The definition of in-house slurry pits according to the EMEP is storages set below the confined livestock containing a combination of animal excreta and bedding. This is in line with the IPCC term pit storage below animal confinements, in which manure is collected and stored with little or no water underneath a slatted floor in a livestock confinement station.

In-house deep litter is a term used by the EMEP to depict a system where excreta and bedding are cumulated on the floor of livestock housing. Cattle and swine deep bedding is its term equivalent provided by the IPCC and identified as accumulated manure continuously absorbing moisture over a production cycle of 6 to 12 months. The GHG emission capacity differs on whether the bedding was mixed or not.

The crust and cover systems as defined by the EMEP, are storages where a layer is incorporated to seal the openings. The former refers to the covering of slurry so that gasses discharge to the atmosphere are minimized. The latter is the complete separation of manure from water or gasses. While the extent of shielding excreta from exterior substances may vary, the IPCC terms liquid/slurry with cover and solid storage – covered are correspondent to the EMEP classifications.

The EMEP identifies the composting passive windrow and forced-aeration composting systems as aerobic decomposition of manure without and with enforced ventilation. Analogous terms presented by the IPCC are composting static pile and composting in-vessel. The definition of static piles deviates from passive windrow in that piles are composted with forced aeration, but no mixing occurs. In-vessel composting involves forced aeration and constant mixing inside an enclosed container.

Composting – passive or intensive windrow are classifications used by the IPCC to indicate systems where manure is composted in windrows with infrequent or consistent mixing and aeration. No term equivalents exist in the EMEP.

Biogas treatment refers to the anaerobic fermentation of slurry or manure as defined by the EMEP. The IPCC equivalent is anaerobic digester and is delineated as a storage system built for waste management through microbial reduction of organic compounds to CH_4 and CO_2. The produced gasses are consequently captured and burnt or utilized as ingredients for fuel.

According to the EMEP, the slurry separation system is where the liquid and solid elements of the slurry is divided. The acidification system is specified as the reduction of manure pH through the supply of strong acids. No term equivalents exist in the IPCC.

The dry lot, uncovered anaerobic lagoon, and aerobic treatment are management systems catalogued only in the IPCC. In the dry lot system, manure is removed to an open confinement area absent of vegetation. Uncovered anaerobic lagoon is a system able to function as both a waste stabilization facility and a storage. Water produced from this system may be recycled for irrigation to fertilize the fields. Aerobic treatment refers to the practice of biological oxidation of liquid manure with forced or natural aeration. The process is dependent on photosynthesis and thus prone to turn anoxic with a dearth of sunlight.

2.4.2. Manure application

Types of manure application methods are not categorized in the forementioned guidelines, but common terms depicting similar techniques were found in numerous studies (Beltran et al., 2021; Hou et al., 2015; van der Weerden et al., 2021; Webb et al., 2010). The application methods can be classified into broadcast, trail hose, trail shoe, open slot or shallow injection, and closed slot or deep injection (Tamm et al., 2016). Manure is incorporated through machines by using plows, tines, discs, or harrows.

The broadcast method is a practice that spreads manure on the soil surface. Since the manure is not incorporated into the soil, high amounts of N can be lost through NH_3 volatilization and run-off. Mineralization of organic N to inorganic N is also obstructed due to less contact with the soil.

Manure is injected closer to the ground than the broadcasting system through hoses during trail hose application. While the amount of NH_3 volatilized may be lower, it is still susceptible to N loss since manure is not incorporated into the soil.

The trail shoe system is similar to the trail hose system but differs in that a fixed shoe supplies the manure beneath the herbage and above the soil surface. The portion of N lost is lower than the previously mentioned application methods because the manure is closer to the roots. An even distribution of manure is made possible since the shoe remain fixed.

Through open slot or shallow injection, manure is directed into 5 cm deep slots cut into the soil with knives or discs. The intensity of injection is regulated so that an overflow of manure out of the slots do not occur. Although less NH_3 is discharged by utilizing this technique, open slots are still exposed to risks of N loss through volatilization and run-off.

The closed slot or deep injection method incorporates manure 10 to 15 cm beneath the soil surface. Slots are cut with discs and pressure wheel or rolls subsequently seal the openings. Occluding the slots deter N loss through NH_3 and run-off but manure must be injected to adequate depths to preclude nitrate leaching.

2.5. Terminologies for evaluating nitrogen interplay in livestock production

Numerous terminologies have been developed to evaluate the interplay between different N bodies in the livestock production system. Although all relevant studies aim to improve the efficiency of N utilization and mitigate environmental impacts, it is essential that a thorough understanding of each terminology be established to effectively communicate discoveries from research. The nitrogen flow, nitrogen flux, nitrogen budget, nitrogen balance, nitrogen use efficiency and nitrogen footprint are the most commonly used terms, where the latter five are techniques deployed to assess the nitrogen flow over a certain spatial or temporal boundary.

2.5.1. Nitrogen flow

Nitrogen flow is a concept used to explicate the transit of nitrogen between different N pools over time. The flows occur as reactive N and must be presented in the identical unit, e.g. in kg of N per year (FAO, 2018). N pools are vessels to store quantities of N and can be classified into environmental (e.g. atmosphere, soil), societal (e.g. humans and settlements), and economic (e.g. agriculture, industry) sectors (UNECE, 2012). Establishing the flow of N in a certain system boundary is the cornerstone for elucidating concepts such as flux, balance, use efficiency, budget, and footprint.

Once a system boundary is defined, the input, output, loss, and recycling flows must be identified (Figure 3). Input flows consist of material from previous stages or outside the boundaries. Output flows can be divided into co-products, which transfer burden to the next stage, and residuals, which have further use but do not convey burden to other systems. Loss flows are comprised of emission flows and waste flows. The former refers to the losses of resources lost to the environment, while the latter indicates flows with potential for additional emissions and burden allocated to co-products. Recycling flows are re-captured emissions and waste products of a resource and can also be divided into co-products and residuals. The border between loss flows and recycling flows are not yet fully demarcated. Stock changes of the pool relates to nutrients in the soil. The flow output can be expressed as the combination of emission, waste, residuals, and co-products or the difference between input flows and stock changes of the pool.

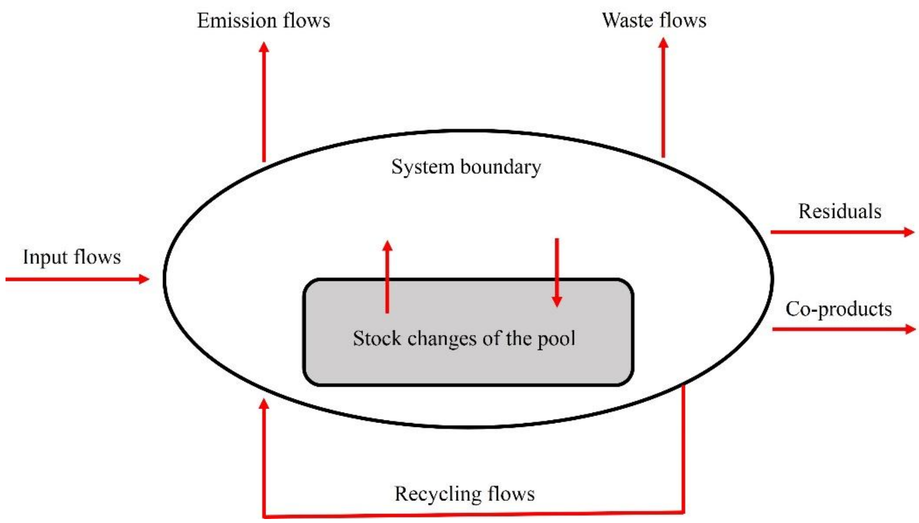

Figure 3. System boundary to track the N flow in agricultural production systems.

This notion can be tailored to illustrate the N flow in cattle production inside farm boundaries. The system boundary embraces both agronomic and bovine production illustrated in numerous prior studies (Figure 4) (Cameron et al., 2013; FAO, 2018; Ouatahar et al., 2021; C. A. Rotz, 2018). The input flow is comprised of N sources outside the cattle farm system, such as biological N fixation, animal feed, manure and mineral fertilizers, N resulting from fuel and electricity production, bedding material, and atmospheric deposition. The output flow consists of animal products (e.g. meat, milk), harvested crops, and a mix of manure and bedding material that can be further processed and utilized in the following system. Nitrogen compounds lost in forms of volatilization (e.g. NH_3, NO_x), leaching and run-off (e.g. NO_3^-), and denitrification (e.g. N_2O, N_2) were considered loss flows. Harvested crops used as animal feed inside the system, manure and bedding material used as sources for fertilization, and the fluctuation of soil carbon stocks constituted the recycling flow.

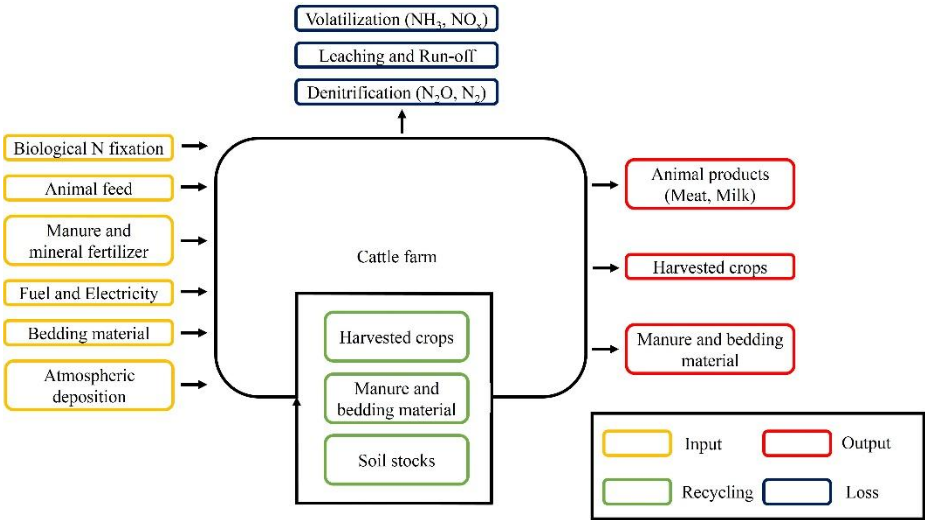

Figure 4. System boundary to track the N flow of beef and dairy production systems.

2.5.2 Nitrogen flux

The term nitrogen flux represents the flow density over an area for a certain period of time (e.g. gram of N per square meter) (FAO, 2018). This concept could be used to either quantify the flow of N using analytical instruments or model the shift of N within a system boundary. Won et al. assessed the movement of N released from manure chambers by analyzing gas samples through gas chromatography through the following equation. (Won et al., 2020)

$$\text{Flux} = FR \times (C_{out} - C_{in})_{TGA} \times P \times M / T \times R / A$$

FR is the air flow rate through the chamber (m^3/s), A indicates the surface area of emitting materials in the chamber (m^2), $(C_{out} - C_{in})_{TGA}$ shows the difference in concentration measured using gas chromatography (ppm), p symbolizes the atmospheric pressure (Pa), M indicates the molecular weight of nitrous oxide (N_2O = 44.01 (g/mol)), T is the average temperature of the analyzed air, and R shows the universal gas constant (8.314 J/mol K).

To expand this concept onto the whole farm, N pools and flows must be identified to evaluate the net N lost from the system. (West & Marland, 2002) established an equation to estimate the net carbon (C) flux in an agricultural ecosystem.

Absolute net C flux = $\int_0^t f(\text{C emissions - C sequestration})\, dt$

Here, the t indicates a designated period of time. If the amount sequestrated is higher than the emissions, the system acts as a sink, while the opposite would be considered a source. (Küstermann et al., 2010) and (de Vries et al., 2001) have furnished more intricate models to examine the N flux within a whole farm system by cataloguing the input, loss, and the interaction between pools (Figure 5). The relationship between the three different pools, N inputs, and outputs are based on linear equations.

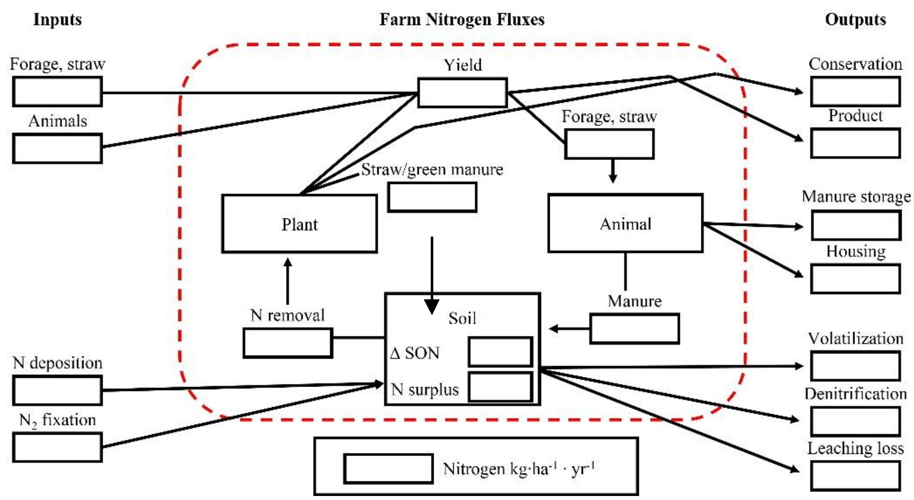

Figure 5. N flux of an agricultural production system. Adapted from **(**Küstermann et al., 2010**).**

This model could be adjusted to fit various parameters and system boundaries. The net flux is the sum of outputs expressed as kg per hectare per year.

2.5.3. Nitrogen budget

Nitrogen budgets are used to quantify the flow of N within and out of a designated system boundary in a given period. The movement of N between pools inside the system is also recorded. They can be formulated for geographic entities of all sizes, ranging from the regional level (e.g. Asia) to a single farm (FAO, 2018). Three forms of budgets have been established: farm-gate, soil surface, and soil systems budgets (Oenema et al., 2003) (Figure 6). The farm-gate budget is representative of environmental burdens, and thus considered the most appropriate environmental performance index. It documents the surplus and deficits based on the difference between the inputs and outputs at farm-gate. Soil surface budgets are apt for recording the accumulative input into the soil where input nutrients enter the soil through the surface and leave through crop uptake. The soil surface budget is an intricate method that incorporates all inputs, outputs, and recycling within the system as well as losses and changes in the soil. The methods are analogous to the economic input-output (EIO), biological input-output (BIO), and transfer recycle input-output (TRIO) budgets discussed by (Watson & Atkinson, 1999). Budgets are illustrated in tables in which the quantities of inputs and outputs of the nitrogen are displayed. The elements in the table differ for each type of budget, and the surplus and deficiency are presented in the balance entry.

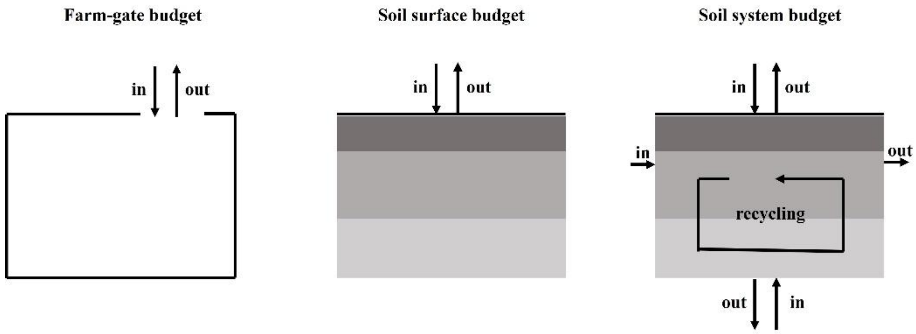

Figure 6. The three types of N budgets to quantify the N flow of agricultural systems: Farm-gate budget, soil surface budget, and soil system budget. Adapted from (Oenema et al., 2003).

Table 2. N budget calculation sheet to assess the N flow of agricultural systems

Inputs[d]	Outputs[d]
Purchased fertilizer[a]	Exported milk[a]
Purchased feed[a]	Exported cattle[a]

Purchased manure[a]	Exported animal manure[a]
Purchased cattle[a]	
Purchased bedding material[a]	
Biological N fixation[abc]	Harvested crops[b]
Atmospheric deposition[abc]	Volatilization from applied manure[c]
Applied fertilizer[bc]	Volatilization from crops[c]
Applied animal manure[bc]	Denitrification[c]
Recycled forage losses[bc]	Leaching and runoff[c]
	Net immobilization in soil[c]
	Unaccounted for[c]
	Balance (surplus)
Total	Total

[a]Inputs and outputs used for the farm gate budget

[a]Inputs and outputs used for the soil surface budget

[a]Inputs and outputs used for the soil system budget

[d]Different types of budgets can use the same input and output parameters

2.5.4. Nitrogen balance

A nitrogen balance is a set of records quantifying all nitrogen flows across system boundaries and the change of N within the pools. It is different from nitrogen budgets in that flows inside the system are not considered. The balance equation is expressed as 'Output + Changes in pools – Input = 0' (UNECE, 2012). They can also be categorized into farm-gate, soil surface, and soil systems balances (Öborn et al., 2003). Balance sheets are used to visualize the net inputs and outputs of N and their differences (Schröder et al., 2003). The Dutch mineral accounting system (MINAS) is the quintessential balance system that is used to track the environmental impacts of farms at a national level. A calculation sheet to evaluate the N balance of cattle production systems is illustrated in Table 3.

Table 3. N budget calculation sheet to assess the N balance of beef and dairy systems

Inputs	Outputs
Imported manure	Exported manure
Imported feeds	Exported animal products
Imported animals	Exported crops
Imported seeds, etc.	Gaseous losses from housing and storage
Mineral fertilizer	
Biological N fixation	
Mineralization	
	Balance (surplus)
	Gaseous losses from spreading
	Accumulation/depletion
	Denitrification
	Leaching
	Correction for defects and errors
Total	Total

2.5.5. Nitrogen use efficiency

Nitrogen use efficiency (NUE) is employed to mark the conversion efficiency of N input to output in a system boundary. Three levels of NUE are provided as indicators for a typical cattle farm: feed NUE, manure-fertilizer NUE, and whole-farm NUE (Powell et al., 2010). Estimating the NUE is generally concomitant with elucidating the N flow and establishing the balance sheet of a system so that corresponding factors for each level of efficiency could be selected (Domburg et al., 2000; Erisman et al., 2018b; Foskolos & Moorby, 2018; Powell et al., 2010; Reinsch et al., 2021).

Feed NUE = (N in animal products / N consumed as feed by cattle) × 100

Manure-fertilizer NUE = (N uptake by crops / N applied as manure-fertilizer) × 100

Whole-farm NUE = (sum of N exported annually off-farm / sum of N imported on to the farm) × 100

2.5.6. Nitrogen footprint

The nitrogen footprint can be defined as the aggregate of emissions generated from the production of one unit of the final product, scaling processes such that the quantity of intermediate products produced equals the quantity required in the subsequent supply chain (Heijungs & Suh, 2002). Emissions are allocated to various co-products produced throughout the supply chain (FAO, 2018). N footprints are frequently utilized as indicators of gross environmental pressure caused by agricultural products (Leach et al., 2012; Mazzetto et al., 2020; A.

Rotz et al., 2021; C. A. Rotz et al., 2019; Veltman et al., 2018; Zhang et al., 2021). The term is associated with the life cycle assessment (LCA) method and would be expressed as kg N per kg of animal product in a typical livestock production system (Figure 7).

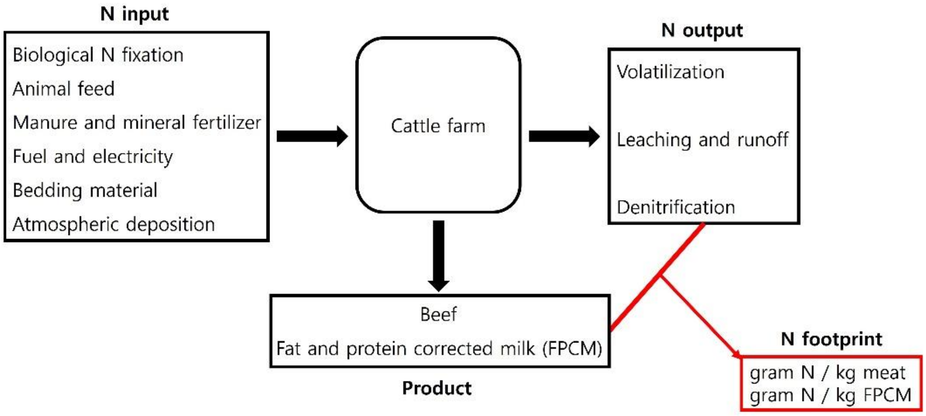

Figure 7. N footprint assessment system of beef and dairy cattle production

2.6. N loss quantification methodologies for the livestock sector

Several experimental techniques to measure and estimate N losses from livestock production exist, ranging in different scales from the single animal to the whole farm. Respiration chambers and manure storage chambers are utilized to measure losses from fresh manure, pots and field lysimeters measure losses from the field after manure application, and towers equipped with the eddy covariance technique are deployed to calculate the amount of nitrogenous compounds released into the air across an expansive area (Hristov et al., 2019). However, the application of these methods accompanies temporal and monetary expenses. To avoid the restraints of actual measurements, many models have been developed by collating data produced from experimental techniques. With sufficient input variables, models can provide accurate estimations for N losses from individual farms.

2.6.1. Intergovernmental Panel on Climate Change Reporting Protocols

The first IPCC guideline for calculating national GHG inventories was published in 1997. Revised and updated versions were subsequently published in 2000, 2003, 2006, and 2019, encompassing all industrial sectors (e.g., energy, industrial processes and product use, agriculture and forestry, and waste).

In the context of livestock production, the guidelines enabled the assessment of national emissions from activity data, such as animal population, feed intake rates and nutrient contents, fertilizer application rates, land use change, and energy consumption, integrated with emission factors for each activity. Default values are provided to reflect the vast diversity of farm operations which allow sectoral comparisons to be made within and among countries. The robustness of these inventories is contingent on the accuracy of the activity data and emission factors. Hence, estimations using the guidelines are conducted on three levels or tiers, and differ in accuracy based on the input database established by individual countries. The simplest is the tier 1 approach where calculations are dependent on only default values. Tiers 2 and 3 require country specific data and emission factors which are verified with complex models and experimental measurements. For example, when estimating nitrous oxide emissions from the manure storage, default animal N excretion rates and emission factors for the storage type are the only variables required for a tier 1 approach. The tier 2 method necessitates either the country specific emission factors or N excretion rates relative to feed digestibility and nutrient content. For the tier 3 approach, both animal specific excretion rates and country specific emission factors must be acquired from extensive research (IPCC, 2019a).

The merits of utilizing the IPCC guidelines are that easily accessible default values can be used for various farm operation types, and national inventories can be established from relatively incomprehensive databases. Numerous studies have been conducted using these guidelines which have facilitated the communication within and between nations on the environmental impacts of livestock production. However, the sector-based structure of the IPCC methodology poses limits on analyzing N losses from integrated agricultural systems. To elaborate, even if different sectors are compiled to make up a whole farm, losses occurring from upstream processes such as industrial processes in producing items to be used in the farm, and downstream processes such as the waste treatment of agricultural products after leaving the farm, are not considered. Thus, system analysis models have been developed to address this issue. System analysis models are generally classified into whole farm models or life cycle assessment (LCA) models.

2.6.2. Whole farm models

Whole-farm models were developed to assess GHG emissions, identify nutrient flows, and facilitate the simulation of mitigation strategies in agricultural production. Each model requires different input parameters and has distinct calculation procedures. While there is no model tailored specifically to evaluate N losses in beef and dairy production, sub-components of the models provide information on N_2O, NH_3, or the whole N flow which could be utilized to analyze the N losses. Concise descriptions of the existing models and how they could be used to assess N losses are presented in this section.

IFSM

The integrated farm system model (IFSM) was developed to estimate GHG emissions, and phosphorus, carbon and N flows in dairy-beef-crop integrated farms in the United States of America (Rotz et al., 2012). This model requires detailed information on animal category and population, type of crop and pasture cultivated, amount harvested, feeding practices, manure handling, and energy consumed to operate agricultural machinery. Local climate information such as precipitation, temperature, and wind velocity are also incorporated to provide a more accurate prediction.

The IFSM tracks N losses from housing, manure storage, and N field application. All processes begin from the amount and nutrient contents of animal feed which is directly related to the amount of feces and urine excreted. The type of housing and methods for manure collection is used to estimate losses in forms of N_2O and NH_3. To track losses in forms of N_2O and NH_3 from manure storages, the type, volume, and ambient temperature of the storage as well as the moisture content of the manure and storage period are required. Estimating N losses from field application requires the soil profile, type of crop cultivated, N application rates, and the amount of residue after harvest. With these information, N_2O, NH_3, and leaching (NO_3^-) losses are calculated.

All imports, exports, and flows of N into and within the farms are recorded and can be expressed as losses per product at farm gate. Therefore, the output of the model can be used for comparison between systems which encompass N losses from both the upstream and production processes.

DairyWise

DairyWise was designed by amalgamating existing models of integral farm subsystems into a single whole farm model to perform environmental and financial simulations of dairy farms (Schils et al., 2007). The major subsystems are categorized into the FeedSupply, DairyHerd, GrassGrowth, Nutrient cycling, and GHG emission models. Information on animal category and feeding practices, farm management, soil profile, cropping practices, grass and forage management, and buildings and machinery are required to predict productivity, GHG emissions, and the nutrient flows of the farm.

The DairyHerd sub-model is used to determine the energy and nutrient requirements of the individual cattle. N excreted as feces and urine were each estimated from the undigested fraction of feed N and the digested fraction of feed N that was not utilized to meet the animal requirements provided by model. The Nutrient cycling sub-model quantifies N losses from volatilization and leaching. Losses as NH_3 from housing and manure storages were dependent on the ambient temperature, manure N content, and the height and roof type of the storage. Losses from N application from the field as NO_3^- were quantified based on the soil N content, fertilizer type and application rate, and the application method. Direct N_2O emissions from denitrification is estimated with the GHG emissions sub-model. The calculation process is coupled to manure management, excreted N during grazing, manure application, fertilizer use, crop residues, mineralization from peat soils, grassland renewal, biological N fixation, soil profile, and groundwater level.

Using the DairyWise model, N losses can be predicted from diverse farming operations as the model takes account of a broad spectrum of parameters. The losses can also be expressed per product, and financial simulations could facilitate the identification of strategies to increase N use efficiency while mitigating environmental impacts.

FarmGHG

The FarmGHG was designed to model carbon and N flows in dairy farms in Europe and quantify direct and indirect gaseous emissions of CH_4 and N_2O produced from the farms (Olesen et al., 2006). The model requires information on animal category and population, feeding practices, type of manure and manure storage, type of crop cultivated, and crop N demand. Calculations are based on IPCC equations and experimental data from Danish farms.

This model can be deployed to evaluate N losses from upstream processes to the farm gate. Losses from producing material that enter the farm are estimated, and the N entering the farm from those materials, along with the N from atmospheric deposition and soil fixation, are traced. Like the IFSM, the FarmGHG predicts the amount of manure excreted based on feed intake and nutrient content. The model defines four different types of manure storages, each with different calculation processes for quantifying gaseous losses such as N_2O and NH_3. The N lost from leaching is estimated after the type of crop grown in the field, N application rate, and the amount harvested are specified.

FarmGHG enables users to track N balance and evaluate N use efficiency based on surplus or deficits. However, its structure was derived from farms within a single country with homogenous climate conditions, which indicates the necessity for validation from other regions.

SIMSDAIRY

Sustainable and integrated management systems for dairy production (SIMSDAIRY) was designed in the United Kingdom by compiling integral components of the dairy farm into a modeling framework (del Prado et al., 2011). The purpose of the model is to simulate monthly interactions between management, climate, soil type and animal genetic traits and how they affect: i) N and phosphorus flows in the soil-plant-animal system, ii) GHG emissions and soil C storage, iii) animal performance and nutritional demands, iv) farm economics, v) biodiversity, food quality, soil quality, and animal welfare. The major subcomponents are SIMSManagement, SIMSFIM, SIMSManure, SIMSPsychic, SIMSNGAUGE, SIMSScore, and SIMSEconomics. Information on animal category and feeding practices, farm management, soil profile, cropping practices, grass and forage management, and genetic traits of plants and animals are entered into these submodules to generate the output.

N losses are evaluated through a series of processes in SIMSFIM, SIMSManure, SIMSPsychic, and SIMSNGAUGE. The nutritional requirements and genetic capacities of the animal are coupled with the amount of feed intake and its nutrient content to estimate N excreted as feces and urine through SIMSFIM. SIMSManure predicts losses as NH_3, N_2O, NO_x and N_2 from housing and manure storages according to the type of storage, total ammonium N content of feces and urine, and the amount of bedding applied. Losses from the field as NH_3, N_2O, NO_x, N_2 and NO_3- are simulated through SIMSPhychic and SIMSNGAUGE from fertilizer application rates and method, soil profile, precipitation, and the N requirements and genetic capacity of the plants.

SIMSDAIRY allows the evaluation of both environmental and economic indices of milk production in dairy-crop integrated farms. It enables users to identify more efficient N use strategies and provides a broader scope for product sustainability by presenting the effects of milk production on biodiversity, and soil and water quality.

REPRO

The reproduction of soil fertility model (REPRO) was formulated in Germany to evaluate and optimize the environmental effects of animal-plant integrated farming systems (Küstermann et al., 2010). It is composed of submodels which support the balancing of energy, carbon fluxes and GHG emissions, predict damages to the soil, and determine impacts on biodiversity. The model connects the soil, animals and plants through N fluxes which reflect the interactions between crop cultivation and animal production. Information on animal feed, livestock products, housing type and pasturing, harvested crop and crop residues, precipitation, and soil profile are used to estimate N balance of the livestock system and the cropping system.

N excretion from livestock is estimated based on the nutrient content of the feed and animal productivity, where subsequent simulations ensue to track the losses from both systems. Different calculations to estimate losses from the livestock system are applied to each type of housing and manure storage. Symbiotic N_2 fixation, the amount of N applied as manure, mineralization and immobilization in the soil, precipitation, and the amount of N in harvested crops are integrated to predict losses from the cropping system through denitrification and leaching.

REPRO takes account of the complex soil mechanism and provides the N balance for both the livestock and cropping systems enabling users to analyze the surplus and deficit of N. However, it is limited in identifying N losses by each nitrogenous sources and expressing the losses by the product.

ManureDNDC

ManureDNDC is a process-based model that enables users to construct a virtual farm and calculates variations of the environmental factors for each subcomponent of the farm (e.g., feedlot, manure storage, field) to simulate the biochemical reactions that lead to emissions of gaseous compounds from the manure (Li et al., 2012). With the information on feed, type of manure storage, soil profile, and climate, all GHG and nitrogenous losses from the manure are predicted on a daily basis.

The amount and property of manure is estimated from the nutrient content of the feed. Manure storage types are classified into composts, lagoons, and anerobic digesters, and environmental factors (e.g., temperature, moisture, pH, radiation, Eh) are integrated to calculate the urea hydrolysis, nitrification, denitrification, volatilization, and leaching from housing and manure storages. Each manure storage type affects the physical and chemical composition of the manure, and these effects are taken account along with soil organic matter, type of crop cultivated, and climate factors to predict the N losses from field application. The dates of harvest, manure application, irrigation, and tillage are inserted to generate a daily flux of N from the farm.

ManureDNDC provides a deep insight into the complex biochemical reactions that occur in the manure by integrating numerous environmental factors that other models to not consider. It also allows users to view the daily N losses by taking account of the timeline of all farming activities. Hence, more intricate mitigation strategies can be devised, and detailed results can be simulated from deploying such strategies.

2.6.3. Life cycle assessment

The life cycle assessment (LCA) methodology evaluates the environment impacts from the entire life cycle of products. All upstream and downstream processes from raw material procurement to the disposal of the final product are included in the life cycle (ISO, 2006a). The International Organization for Standardization (ISO) provides a framework for conducting LCA (ISO, 2006a, 2006b) which is composed of four phases: i) goal and scope definition, ii) life cycle inventory analysis, iii) impact assessment, iv) interpretation. In the goal and scope phase, the aim of the study, data requirements, system boundary, and functional unit are decided. The system boundary determines which processes will be included within the LCA. The functional unit provides a measurable reference to compare systems producing products with the same function. Depending on the function of the system, more than one functional unit can be defined. In the life cycle inventory analysis phase, data collection and calculations are performed to quantify the environmental impacts of a functional unit. If there are more than one functional unit, allocations between the functional units can be made to allot the environmental burden. In the impact assessment phase, the results are assigned to different impact categories (e.g., climate change, eutrophication, acidification) and multiplied by their characterization factor (e.g., 265 CO_2-eq/kg N_2O for climate change). The interpretation phase comprises the identification of significant issues based on the results, evaluation of completeness, sensitivity check, limitations, conclusions, and recommendations. Interpretation is iterative and accompanies the entire process of the analysis. The framework for the four phases is illustrated in Figure 8.

While LCA of most products is termed a ‘cradle to grave analysis’ and includes all the environmental impacts until the end of the products' life, the term for agricultural products is a 'cradle to gate analysis'. This is because the scope of agricultural LCA is focused on the commodity produced in the farm, which is then processed to enter subsequent systems and ultimately for consumption. Thus, evaluation is made on the product at the farm gate, taking account of the processes in furnishing raw materials to be delivered to the farm and activities within the farm. This makes the LCA methodology is an effective technique to compare and communicate the environmental impacts of agricultural products because it provides the means to demarcate the production system and express the results as impact per product (Casey & Holden, 2006). The benefits of using LCA have prompted a wide array of studies on identifying the N losses from livestock products worldwide (Joensuu et al., 2019; Ledgard et al., 2019; Leip et al., 2014; C. A. Rotz et al., 2019; Veltman et al., 2018).

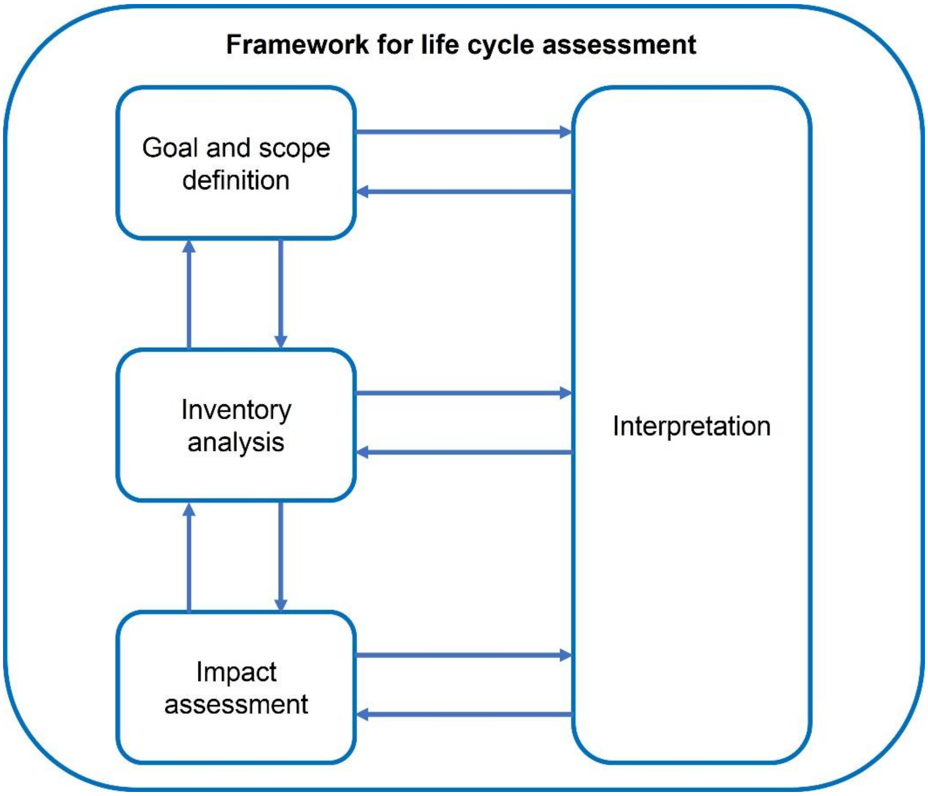

Figure 8. The ISO framework for the four phases of conducting life cycle assessments.

GLEAM

The Global Livestock Environmental Assessment Model (GLEAM) is a GIS framework that simulates the biophysical processes and activities along livestock supply chains under a LCA approach. It was formulated by the Food and Agricultural Organization (FAO) in 2010 to quantify production and use of natural resources in the livestock sector and to identify environmental impacts of livestock to contribute to the assessment of adaptation and mitigation scenarios to move towards a more sustainable livestock sector (FAO, 2017). It is composed of submodules each representing the herd, manure, feed, system, allocation, and post-farm impacts. Information on feed, animal composition, manure management, system boundaries, function units, and activities beyond the farm gate are simulated through these submodules to provide the environmental impacts of a livestock product. Environmental impacts are calculated using the guidelines provided by the IPCC and are allocated to the products based on the function of the system. Gerber et al. (2013) established guidelines to adapt this model to ruminant supply chains, allowing comparisons between cattle production systems with similar system boundaries.

These guidelines were further developed to assess the N losses from livestock production (FAO, 2018). This enables users to identify all N flows relevant to the entire life cycle of a livestock product such as beef or milk. Data regarding the type of housing and manure storage, atmospheric deposition and biological fixation of N, mineral and organic fertilizer application rates, irrigation, soil profile, crop residue, and energy consumption rates are all utilized to quantify the losses within the farm. Losses are allocated to the products, and manure exported from the farm can be expressed as a co-product if sold on the market as fertilizer or energy source, or a residual if it holds no market value. The system boundary can be expanded to a 'cradle to primary processing analysis', where losses from wastewater and animal residues such as bones and intestines are considered. A further expansion to a 'cradle to grave analysis' incorporates the losses from transportation to the consumer stage, and food waste.

This model can be adapted to express the N losses from livestock production as a N footprint. This allows stakeholders to set the system boundaries according to the purpose of the analysis and provides a measurable metric to compare the N losses of production systems with similar functions. Simulations can be conducted without intricate input parameters, as default equations are provided to process relatively crude data. Thus, GLEAM facilitates the communication of the environmental impacts of livestock production on a global scale using the LCA approach, encompassing all types of production systems.

3. Material and methods

3.1. Data collection

Initial steps were taken to construct a database based on accessible public data from various government institutions. All farm information required to estimate the N footprint excluding the number of cattle and production purposes were inaccessible due to privacy issues. The unavailability of data necessitated field visits to collect information from Hanwoo beef cattle farms on a national scale. Activity data were collected between July 2021 and July 2022 using field surveys to assess the year-round N flow of 106 farms in the year 2020. Farms were selected using a random sampling algorithm with R statistical software (v4.1.2; R Core Team 2021) on a list of 3000 beef cattle farms affiliated with the Hanwoo Association. The number of farms surveyed for provinces with a relatively larger Hanwoo population were higher than those with a smaller population. The locations of the farms within the provinces were spatially distributed to reflect the representative farming systems of all major production sites (Figure 9). The survey included information on the production purpose, size of farms, cropping practices, fertilizer application rate, number of cattle, productivity, feeding practices, manure management, and fuel and electricity usage. All farms were categorized into three production purposes: fattening farms, breeding farms, and mixed farms, to reflect the conventional Korean operation systems. Fattening farms raised only steers and fattening cows produced for meat, while breeding farms raised only fattening cows and breeding cows for meat and producing calves. Mixed farms raised both steers and 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). Farmers were requested to access government institutions and agricultural union homepages to acquire credible information in accordance with the items in the field survey. Unavailable data were procured from individual farm records and assumptions based on existing data; the live body weight (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.

Table 4. Source of data acquired from field surveys

Survey category	Source
Animal	
Number of cattle by growth stage	Korea Federation of Livestock Cooperatives
Carcass weight	Korea Federation of Livestock Cooperatives
Feeding practices	
Amount fed (as-fed basis, kg/animal/day)	Individual farm records
DM, TDN, CP, Ash content of TMR (%)	Individual farm records, feed company

DM, TDN, CP, Ash content of concentrate (%)	Feed company
DM, TDN, CP, Ash content of forage (%)	Standard table of Korean feed ingredients (2017)
Farm size	
Housing and manure storage area	National Agricultural Products Quality Management Service
Field area	National Agricultural Products Quality Management Service
Cropping practices	
Type of crop	National Agricultural Products Quality Management Service
Amount produced	National Agricultural Products Quality Management Service
Fertilization application rate	
Organic fertilizer	Individual farm records
Synthetic fertilizer	Individual farm records
Manure management	
Proportion of manure sent to facility, shared with other farms, or applied to field	Individual farm records
Energy consumption	
Electricity usage	Korea Electric Power Corporation
Fuel usage (diesel)	NongHyup Agribusiness Group Inc.

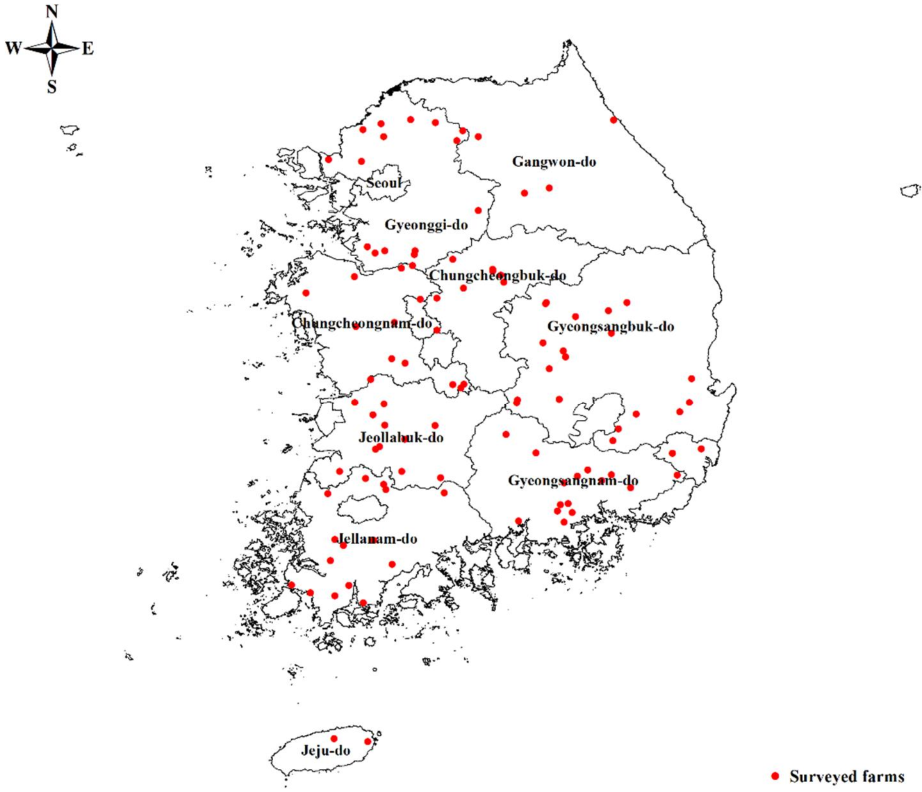

Figure 9. Spatial distribution of 106 surveyed Hanwoo beef farms in the Republic of Korea used to identify the N footprint.

3.2. Modeling procedure

A cradle-to-farm gate partial LCA was deployed to determine the annual N losses in accordance with guidelines provided by the Livestock Environmental Assessment and Performance partnership (FAO, 2016). The system boundary encompasses 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 losses 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 (Figure 10).

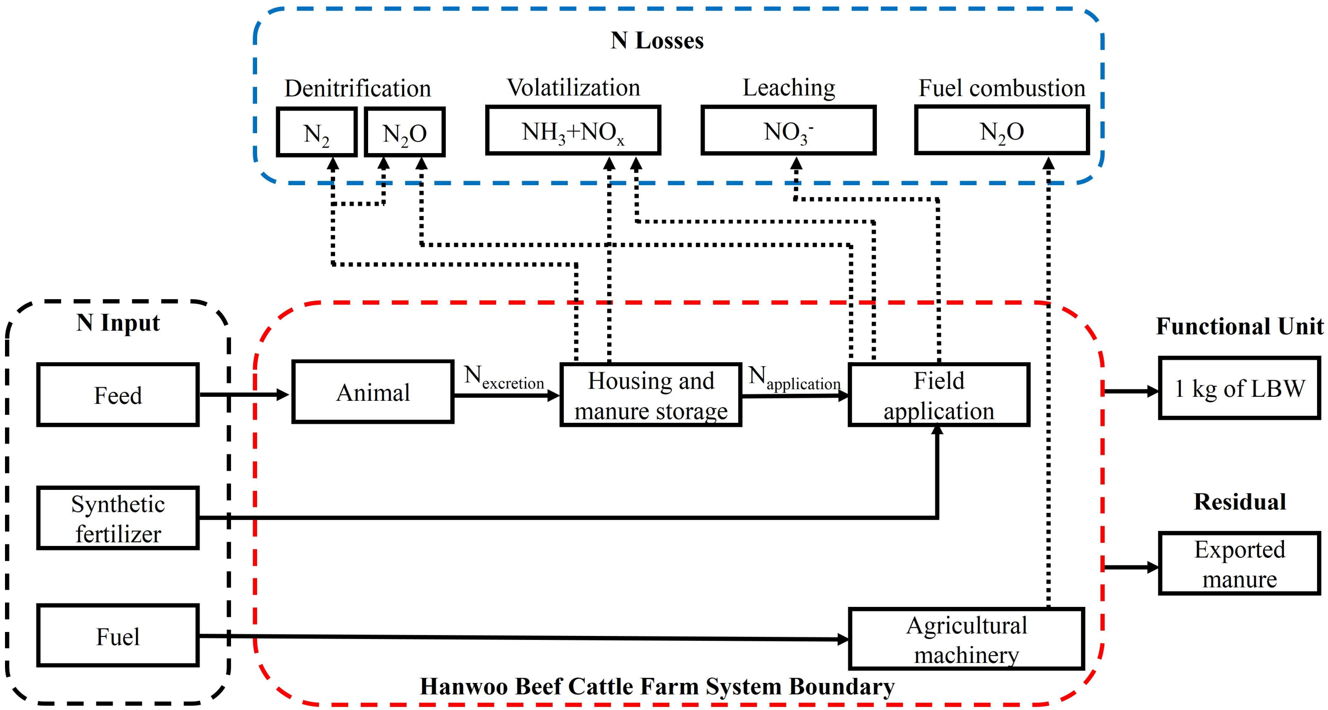

Figure 10. N loss sources for a partial life cycle assessment of the nitrogen footprint of Hanwoo beef cattle farm systems. The red dotted line represents the system boundary, items in the black dotted line are additional N inputs, and items in the blue dotted line are emission sources contributing to N loss. The functional unit is 1 kg of LBW at farm gate and manure exported from the farm is considered a residual.

3.3. Nitrogen losses

Activity sources for N loss were classified as animal housing and manure storage, N field application, and agricultural machinery. Emissions from each source were estimated following the IPCC guidelines (IPCC, 2006a, 2019a, 2019b) and aggregated to determine the annual N loss (Table 6). The process of losses from each activity source is depicted in Figure 11.

3.3.1. 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 as the amount of net energy (NE) required for activity, growth, lactation, maintenance, and pregnancy on the basis of LBW and default coefficients. NE for activity and lactation were disregarded due to confined feeding practices and marginal milk production. LBW of animals raised for beef production were assumed from carcass weights 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 amount of feed supplied 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. Carcass weights 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.

3.3.2. N losses from housing and manure storage

All surveyed farms housed cattle in confinement and stacked manure in adjacent storages with metal covers and concrete floors. The manure management system was identified as 'solid storage – covered/compacted' and default emission factors were deployed to calculate N losses. Emission sources were N_2O and N_2 from denitrification, and NH_3 and NO_x from volatilization. N lost as NO_3^- from leaching was not considered. 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 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 was 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.

3.3.3. 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 collected data. Emission sources were N_2O from denitrification, NH_3 and NO_x from volatilization, and NO_3^- from leaching. The resulting value was multiplied by 28/44 to quantify the amount of N lost as N_2O. 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 default value of 0.21 and 0.11 was 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 ($Frac_{LEACH-(H)}$).

3.3.4. 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 TJ of fuel and the surveyed amount of diesel consumed was expressed in liters, the energy content of 35.2 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.

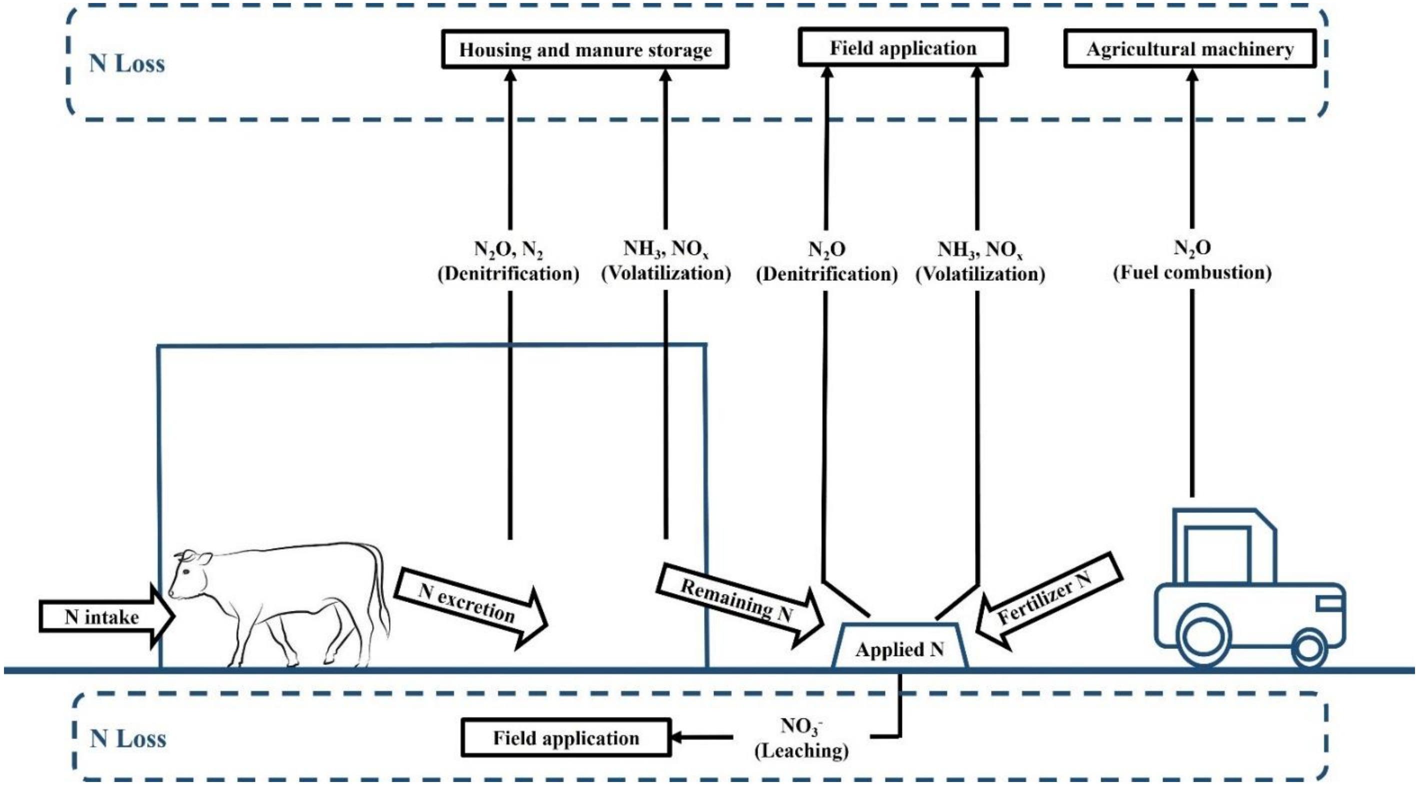

Figure 11. N loss process in a beef cattle production [변1]system.

Table 5. Methodologies used to estimate N losses from the system boundary

Activity sources	Unit	Methodology	Reference
N excretion[a]			
Daily N intake rates	kg N/animal/day	$N_{intake(T)} = GE/18.45 \cdot CP\%/100/6.25$	IPCC (2019)
Daily N retention rates	kg N/animal/day	$N_{retention(T)} = [Milk \cdot (Milk\ PR\%/100)]/6.38 + [WG \cdot [268 - (7.03 \cdot NE_g)/WG]/1000/6.25$	IPCC (2019)
Annual N excretion rates	kg N/animal/yr	$Nex_{(T)} = (N_{intake(T)} - N_{retention(T)}) \cdot 365$	IPCC (2019)
Losses from housing and manure storage[b]			
Annual N_2O emissions from denitrification	kg N_2O/yr	$N_2O_{D(mm)} = [\Sigma_S[((N \cdot Nex) \cdot AWMS_{(S)})] \cdot EF_{3(S)}] \cdot 44/28$	IPCC (2019)
Annual amount of N lost from volatilization of	kg N/yr	$N_{volatilization\text{-}MMS} = \Sigma_S[[((N \cdot Nex) \cdot AWMS_{(S)})] \cdot Frac_{GasMS(S)}]]$	IPCC (2019)
Fraction of N lost as N_2	fraction of Nex	$Frac_{N2MS(S)} = R_{N2(N2O)} \cdot EF_{3(S)}$	IPCC (2019)
Losses from N field application[b]			
Annual N_2O emissions from denitrification	kg N_2O/yr	$N_2O\text{-}N_{N\ inputs} = [(F_{SN} + F_{ON} + F_{CR} + F_{SOM}) \cdot EF_1] + [(F_{SN} + F_{ON} + F_{CR} + F_{SOM})_{FR} \cdot EF_{1FR}]$	IPCC (2019)
Annual amount of N lost from volatilization of	kg N/yr	$(F_{SN} \cdot Frac_{GASF}) + (F_{ON} \cdot Frac_{GASM})$	IPCC (2019)
Annual amount of N lost from leached NO_3^-	kg N/yr	$(F_{SN} + F_{ON} + F_{CR} + F_{SOM}) \cdot Frac_{LEACH\text{-}(H)}$	IPCC (2019)
Losses through agricultural machinery[b]			
Annual N_2O emissions from diesel combustion	kg N_2O/yr	$Emissions = \Sigma_j(Fuel_j \cdot EF_j)$	IPCC (2019)

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

3.4. Impact assessment

The N footprint was determined from the total amount of N losses that occurred inside the system boundaries on a gram N basis by the functional unit. Allocations 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.

3.5. Uncertainty and sensitivity analysis

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, 2006a, 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 7). 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 production purpose 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 6. Average and referenced values and uncertainties of input parameters and emission factors

Activity sources	Unit	Methodology	Reference
N excretion[a]			
Daily N intake rates	kg N/animal/day	$N_{intake(T)} = GE/18.45 \cdot CP\%/100/6.25$	IPCC (2019)
Daily N retention rates	kg N/animal/day	$N_{retention(T)} = [Milk \cdot (Milk\ PR\%/100)]/6.38 + [WG \cdot [268 –$	IPCC (2019)
Annual N excretion rates	kg N/animal/yr	$Nex_{(T)} = (N_{intake(T)} – N_{retention(T)}) \cdot 365$	IPCC (2019)
Losses from housing and manure storage[b]			
Annual N_2O emissions from denitrification	kg N_2O/yr	$N_2O_{D(mm)} = [\Sigma_S[((N{\cdot}Nex) \cdot AWMS_{(S)})] \cdot EF_{3(S)}] \cdot 44/28$	IPCC (2019)
Annual amount of N lost from volatilization of	kg N/yr	$N_{volatilization\text{-}MMS} = \Sigma_S[[((N{\cdot}Nex_{()} \cdot AWMS_{(S)})] \cdot Frac_{GasMS(S)}]]$	IPCC (2019)
Fraction of N lost as N_2	fraction of Nex	$Frac_{N2MS(S)} = R_{N2(N2O)} \cdot EF_{3(S)}$	IPCC (2019)
Losses from N field application[b]			
Annual N_2O emissions from denitrification	kg N_2O/yr	$N_2O\text{-}N_{N\ inputs} = [(F_{SN} + F_{ON} + F_{CR} + F_{SOM}) \cdot EF_1] + [(F_{SN} + F_{ON} + F_{CR} + F_{SOM})_{FR} \cdot$	IPCC (2019)
Annual amount of N lost from volatilization of	kg N/yr	$(F_{SN} \cdot Frac_{GASF}) + (F_{ON} \cdot Frac_{GASM})$	IPCC (2019)
Annual amount of N lost from leached NO_3^-	kg N/yr	$(F_{SN} + F_{ON} + F_{CR} + F_{SOM}) \cdot Frac_{LEACH\text{-}(H)}$	IPCC (2019)
Losses through agricultural machinery[b]			
Annual N_2O emissions from diesel combustion	kg N_2O/yr	$Emissions = \Sigma_j(Fuel_j \cdot EF_j)$	IPCC (2019)

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

3.6. Mitigation strategies

Four potential mitigation strategies to reduce N losses were evaluated for all farms. All strategies were validated with the surveyed farms for feasibility to ensure that they did not harm productivity nor require initial expenses for equipment installment. The strategies were farm-specific and targeted three farm constituents: animal feed, housing and manure storage, and N field application (Table 8).

The dietary mitigation strategy focused on decreasing the amount of CP but increasing the proportion of rumen undegradable protein (RUP) of feed for steers and fattening cows to reduce Nex while maintaining productivity. 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). The same strategy for steers (>22months) was employed to fattening cows since feeding practices did not differ between the two animal categories. Feed adjustments were applied to a total of 62 farms that supplied feed with CP contents above the modified levels. It was assumed that the decrease in Nex would diminish the amount of all subsequent N losses from animal excreta.

To curtail N losses from housing and manure storages, microorganism additives such as CC-E (complex bacterial community) and EM (Effective microorganisms) were applied to all farms. These microorganisms were expected to reduce volatilization by 9.15 percent by mineralizing organic N to ammonium N (NH_4^+), which was then incorporated into their bodies as microbial protein (Ba et al., 2020). For farms that utilized organic fertilizers in their fields, the amount of N applied was assumed to increase by the amount of N preserved from volatilization.

Two mitigation strategies were considered for N field application: replacing synthetic fertilizers with organic fertilizers and deploying biochar. A preliminary step was taken to identify the 29 farms that exported manure but also utilized synthetic fertilizers. For those farms, synthetic fertilizers were replaced with exported manure that had the equal amount of N as the fertilizers. 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 both field crops and rice cultivation were expected to decrease by 26.8 and 28.9 percent (Xia et al., 2017). Straw derived biochar was added once after N application in low amounts (10~20t/ha) to all farms that practiced crop cultivation. This was presumed 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 7. Mitigation strategies and expected effects on N losses by activity source

Strategy	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., 2020b)
N Field application			
Replacing organic fertilizers with synthetic 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) Increase in volatilization by 14% for field crops (NH_3+NO_x)	(Liu et al., 2019)

	Decrease in leaching by 20.8% for field crops (NO_3^-)

4. Results and discussions

The analyses on the N footprints of Hanwoo beef farms are presented in four sections. The first section is a presentation of the farm management characteristics of the surveyed farms and their regional distinctions. The second section is an explanation of how the difference in farm characteristics contributed to the variance of N losses and footprints across regions. The third section describes the total N footprint and its uncertainty and provides comparisons with existing studies for validation. In the final section, the effects of mitigation practices and their implications for application to a wider scale are discussed.

4.1. Farm presentation

A wide range of Hanwoo farm management characteristics was reported, with each province having distinct feeding practices, cropping practices, manure management systems, and energy utilization (Table 5). As Hanwoo farms have been conventionally categorized into fattening, breeding, and mixed production systems, this surveyed included all three categories of farms dispersed across Korea. The proportions (12.2, 9.6, 9.2, 37.6, 10.9, 9.6, 10.9 percent) of the number of animals for each category (steers over 22 months, steers between 14 and 21 months, growing males, fattening and breeding cows, heifers, growing males, and calves) for the total surveyed farms showed minimal difference from the actual proportions (9.9, 8.5, 10.6, 37.0, 12.4, 10.0, 11.5 percent) provided by the Ministry of Agriculture, Food and Rural Affairs (MAFRA, 2020).

However, these numbers showed variance across provinces as the ratio of cattle raised for fattening (steers and fattening cows) were more prominent in Gangwon, Gyeonggi, Gyeongsangbuk and Gyeongsangnam, while cattle for breeding (breeding cows and heifers) were the major components in Chungcheongbuk, Jeollabuk and Jeollanam. LBW exported from the farms was consistent with number of cattle raised from fattening among provinces.

All cattle were raised in confinement and fed in feedlots. Feeding practices across provinces varied in terms of total mixed ration (TMR) and separate feeding (concentrate and forage), and on average, the proportion of TMR (36 percent) was higher than the 25 percent reported by Bharanidharan et al., (2021) . Concentrates were supplied from feed mill companies and TMR were formulated by farm owners mixing a combination of commercial concentrates and forages cultivated withing system boundaries. The crude protein (CP) content of the feed is a pivotal factor in predicting N excretion from cattle and showed marginal variability across provinces due to the homogeneity of the CP content in commercial concentrates. The average CP content of feed in this survey is consistent with previous records for feed fed to steers, in which the CP content gradually decreased from 16 to 12 percent in accordance with growth (Bharanidharan et al., 2021), and those for breeding cows and heifers, which were maintained at around 12 percent (NIAS, 2017). While the amounts of supplied feed recorded by individual farms were distributed across a wide range (Figure 12), their averages did not deviate from the amount recommended by the Korean Feeding Standards (NIAS, 2017). The recorded amount of N intake also displayed variance, which subsequently contributed to the variance in estimated N excretion rates (Figure 13). Such variations could be attributed to farms keeping records of only the amount of feed given to the animals, while not measuring the residue. However, it should be noted that most of the data for the amounts of feed supplied were located within the first and third quantile. This signifies that the numbers presented in this study could be representative of national feeding practices.

The southern regions of Korea such as Gyeongsangnam, Jeju, Jeollabuk and Jeollanam have expansive lands for cropping and the 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 practiced conventional tillage.

Manure in all farms was stored in solid storages with a concrete floor and metal ceiling. After leaving the storage, manure was applied to fields for feed production or sent out of the system boundary to be either shared with other farms or processed in resource recovery 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).

The net amount of diesel consumed in the farm was proportionate to the number of machineries used to cultivate and harvest crops. This explains the higher usage of diesel per cattle in Jeju, Jeollabuk and Jeollanam as larger fields require more machineries. Electricity was mainly used to operate fans or insulation to maintain ideal temperatures for animal production and function TMR machines. Consumption rates varied hugely due to differences in climate and feeding practices. Gangwon maintains a year-round cool temperature and showed the lowest consumption of electricity because farms were able to operate fans on a minimum basis. Jeju is exposed to extreme sunlight and consumed the highest amount by constantly operating fans to alleviate the heat. Gyeongsangnam also used a high amount of electricity to power TMR machines and fans.

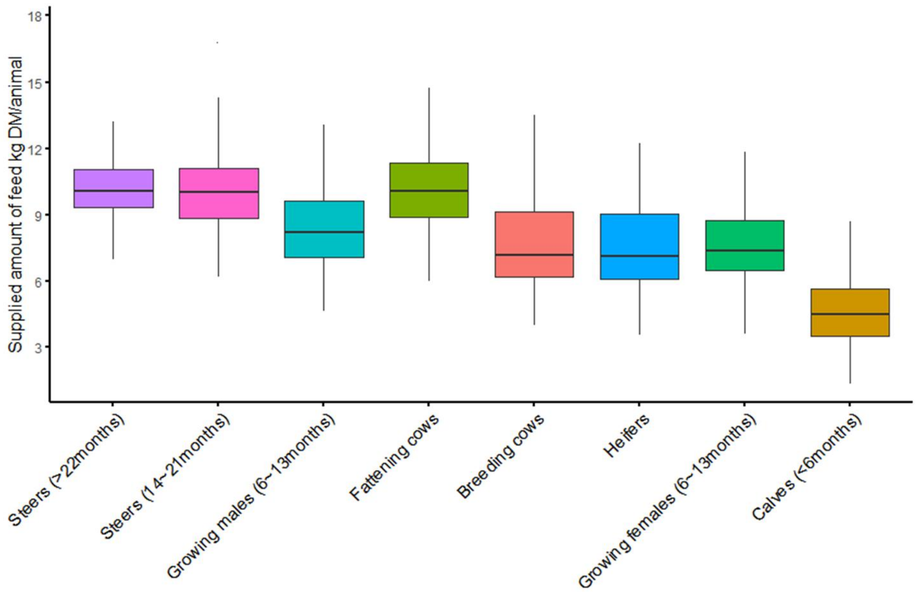

Figure 12. Boxplot of amount of feed supplied for each animal category.

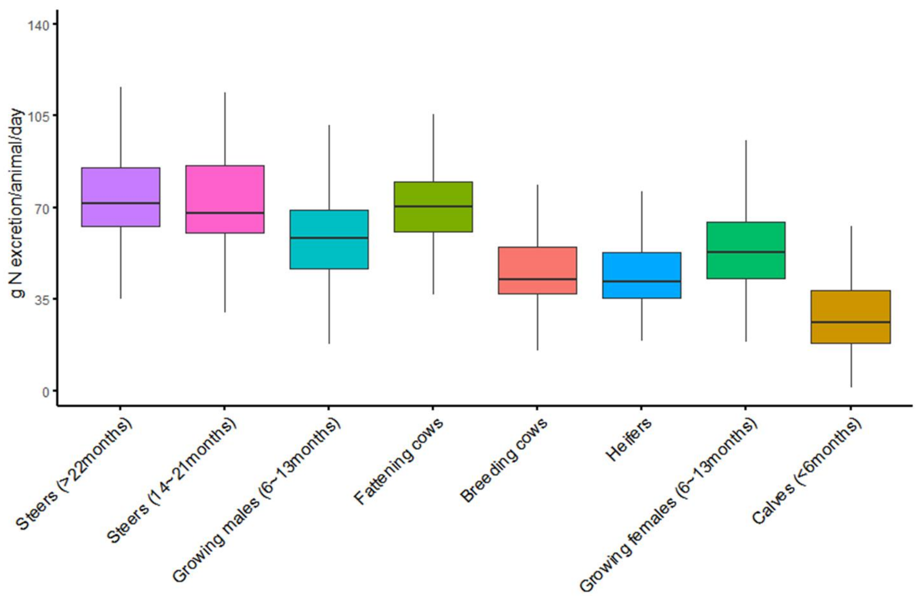

Figure 13. Boxplot of N excretion rate for each animal category.

Table 8. Characteristics and resource use parameters of Hanwoo farm systems for the 9 provinces and total surveyed farms

Region	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
Total surveyed animals (head)	1323	1464	1232	4528	4712	4140	404	2280	4320	24372	
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	12.2	9.9
Steers (14~21months)	7.9	7.4	8.1	10.2	13.3	10.0	6.7	6.3	8.1	9.6	8.5
Growing males (6~13months)	6.3	9.0	13.3	8.8	11.7	8.7	18.1	5.8	9.6	9.2	10.6
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	37.0
Heifers	11.6	10.7	11.0	10.2	12.1	11.3	6.2	12.6	8.1	10.9	12.4
Growing females (6~13months)	11.1	12.3	12.7	9.2	9.3	8.3	9.9	9.5	11.1	9.6	10.0
Calves (<6months)	16.4	16.3	1.6	11.0	8.5	12.2	15.8	14.2	9.6	10.9	11.5
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	72	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										
Field area for feed production (ha)	6.2	2.1	3.3	4.0	4.3	10.4	61.2	13.5	16.9	9.2
Field area for rice cultivation (ha)	0	1.0	0	1.4	2.1	5.1	0	13.0	11.4	4.7
Manure management										
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										
Organic fertilizer (kg N/ha)	1178	1118	2424	1205	741	267	23	292	361	434
Synthetic fertilizer (kg N/ha)	192	107	44	32	74	116	55	79	139	96
Energy consumption										
Diesel (L/head)	24	16	12	25	17	22	74	30	36	25
Electricity (kWh/head)	541	689	246	409	687	1055	774	613	415	609

4. 2. Validation of the N footprint and regional variances as affected by farming system

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 miniscule. The result of this study was similar to 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 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 was 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 relative contributions of each loss source to the total N losses are presented in Figure 14 for the 9 provinces and the total surveyed farms, showing that the proportion of losses from leaching varied by province. These differences were associated with the field area, manure management, and N field input. The contributions from leaching were highest in Chungcheongbuk and Gangwon. Although the field areas of Chungcheongbuk and Gangwon were relatively small (6.2 and 3.3 ha), these regions applied large portions of manure to the field (96 and 70 percent) and recorded high N field input (1370 and 2468 kg N/ha) as shown in Table 5. The proportion of losses through the field was the lowest in Gyeongsangbuk. While the amount of N applied to the field was higher than the national average (815 kg N/ha), farms in this region possessed small field area (4.3 ha) and applied only 30 percent of the manure to their fields. The results demonstrated that manure utilization decided the role of leaching total N losses; it was closely related to the portion of manure recycled within the farm for crop cultivation and the amount of N applied to the field.

The N footprints were presented by activity source for all regions in Table 9. The total 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. Footprints were higher in regions that recorded lower LBW at farmgate per animal, such as Chungcheongbuk and Chungcheongnam. This was because N losses from housing and manure storage in these regions were divided by a relatively lower denominator to be expressed as footprints. Likewise, Gangwon and Gyeongsangbuk recorded lower footprints due to higher LBW at farmgate. The ratio of steers (>22months) and fattening cows to breeding cows was another contributing factor. Although Chungcheongnam showed lower LBW at farm gate compared to Chungcheongbuk, it had a higher steers and fattening cows to breeding cows ratio which generated lower footprints. Gangwon 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 composition 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 footprints.

The intensity of footprints in N field application was influenced by the same factors, 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 followed but utilized 44 percent of its manure for field application, resulting in a difference of 56.7 g N/kg LBW between Chungcheongbuk. Gangwon also distributed a high portion of its manure to the field (70 percent) and ranked the thirst highest. 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 despite the differences in diesel consumed per head.

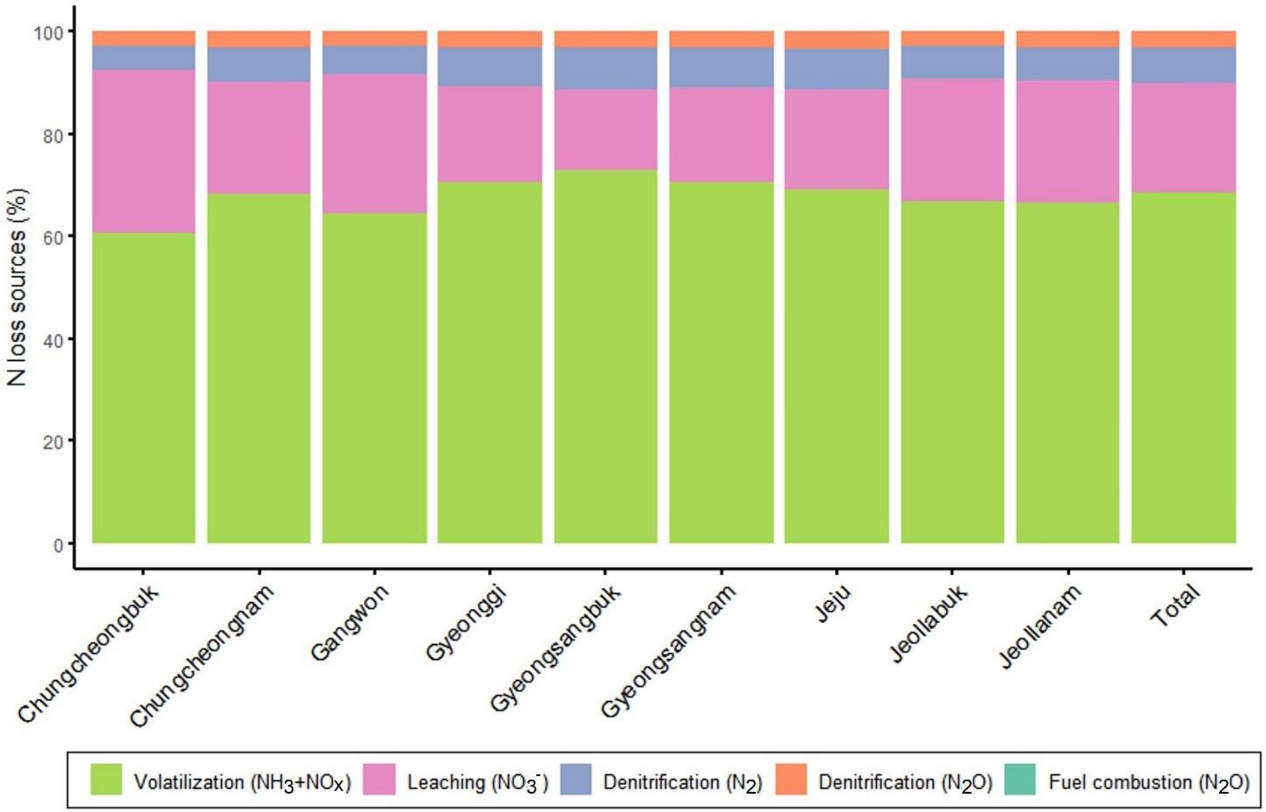

Figure 14. Relative contribution of different loss sources to total N loss for the 9 provinces and total surveyed farms.

Table 9. Nitrogen footprints by activity source for the 9 provinces and total surveyed farms

Activity sources (g N/LBW/year)	Housing and manure storage			N field application			Agricultural machinery	Total 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
Total	3.1	9.2	67.6	1.1	23.3	28.4	0.1	132.8 ± (46.6%)

4. 3. Uncertainty and sensitivity analyses

The uncertainty analysis generated 46.6 percent for the total N footprint of beef production. This was higher than the 7.7 percent uncertainty reported by Rotz et al. (2019), where country specific emission factors with uncertainties of 20 percent were deployed. Emission factor uncertainties were shown to be related to the uncertainty range of the N footprint; the sensitivity analysis presented in Figure 15a indicated that the emission factors were the key drivers of high uncertainty, while the contribution of N excretion was marginal. Accordingly, footprints of each loss source simulated through the MC approach exhibited wide dispersions (Figure 16). Leaching was the primary contributor, followed by volatilization, denitrification, and fuel combustion (Figure 15b). 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 precision of the results have been elucidated by Basset-Mens et al. (2009), Chen & Corson, (2014), and 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 underscores the necessity to refine emission factors and develop country specific values for a more precise analysis.

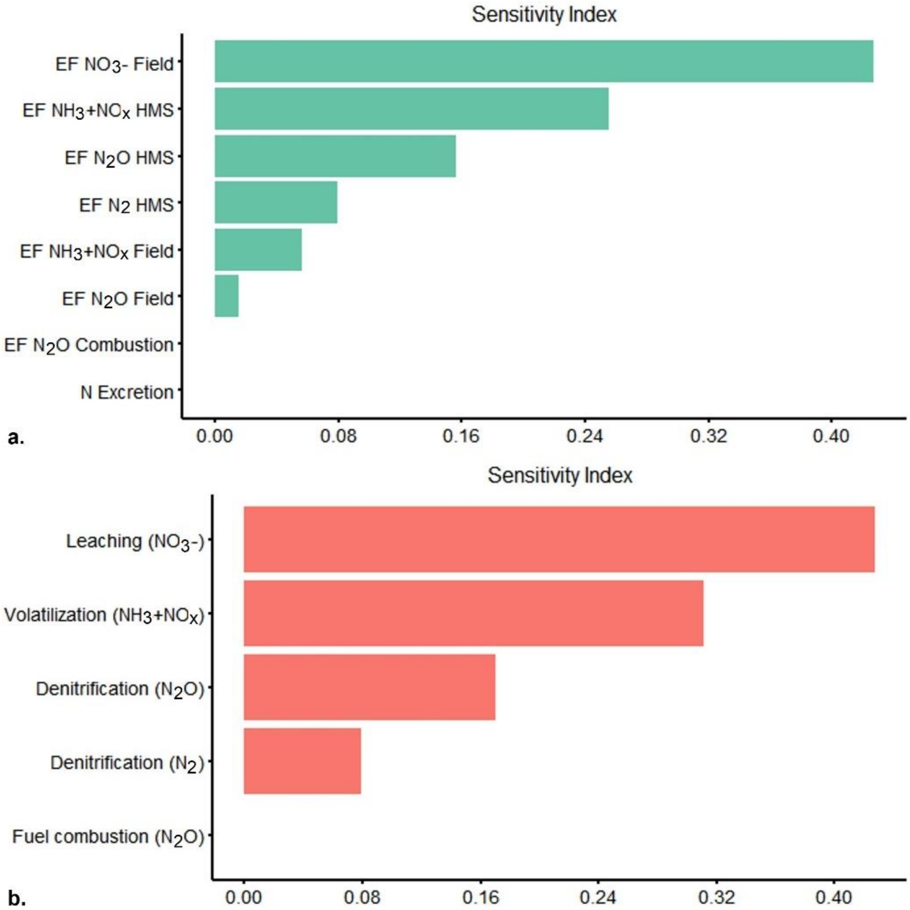

Figure 15. Sensitivity indices by input parameters and N loss sources. EF represents emission factor. HMS, Field, and Combustion indicates that the emission factors were used to calculate losses from housing and manure storage, N field application, and fuel combustion, respectively.

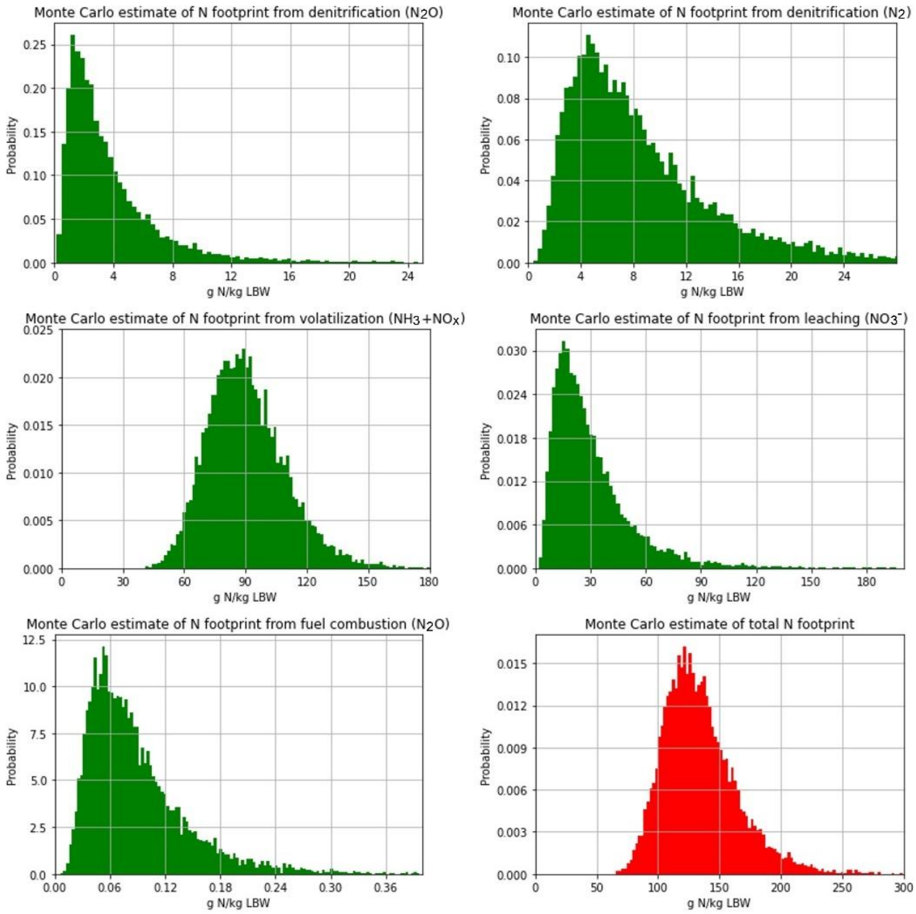

Figure 16. Probability distribution functions of N footprints by denitrification (N_2O and N_2), volatilization (NH_3+NO_x), leaching (NO_3^-), fuel combustion (N_2O), and total losses after 50000 MC simulations.

4. 4. Effects of mitigation strategies

The effects of four mitigation strategies were modelled to evaluate the potential for reducing N footprints of beef production for each loss source (Figure 18). Modifying the content of CP fed to steers and fattening cows using RUP was the most efficient strategy and 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 (Table 10). 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, but losses from N field application increased. This was because of the assumption that the amount of organic N applied increased by the amount of N preserved from volatilization. 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 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 strategy 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 footprint by 3.6 percent. Losses from denitrification and leaching decreased, but an increase in losses from volatilization was seen. This was because the rise in volatilization from crop fields was 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 numerous studies (Liu et al., 2019; Singh et al., 2022; Wang et al., 2021). The abundance of crop residues in Korea such as rice straw, barley straw, and reed straw indicate a high potential for future use of straw-derived biochar.

These four strategies were combined which and 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 strategies 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.

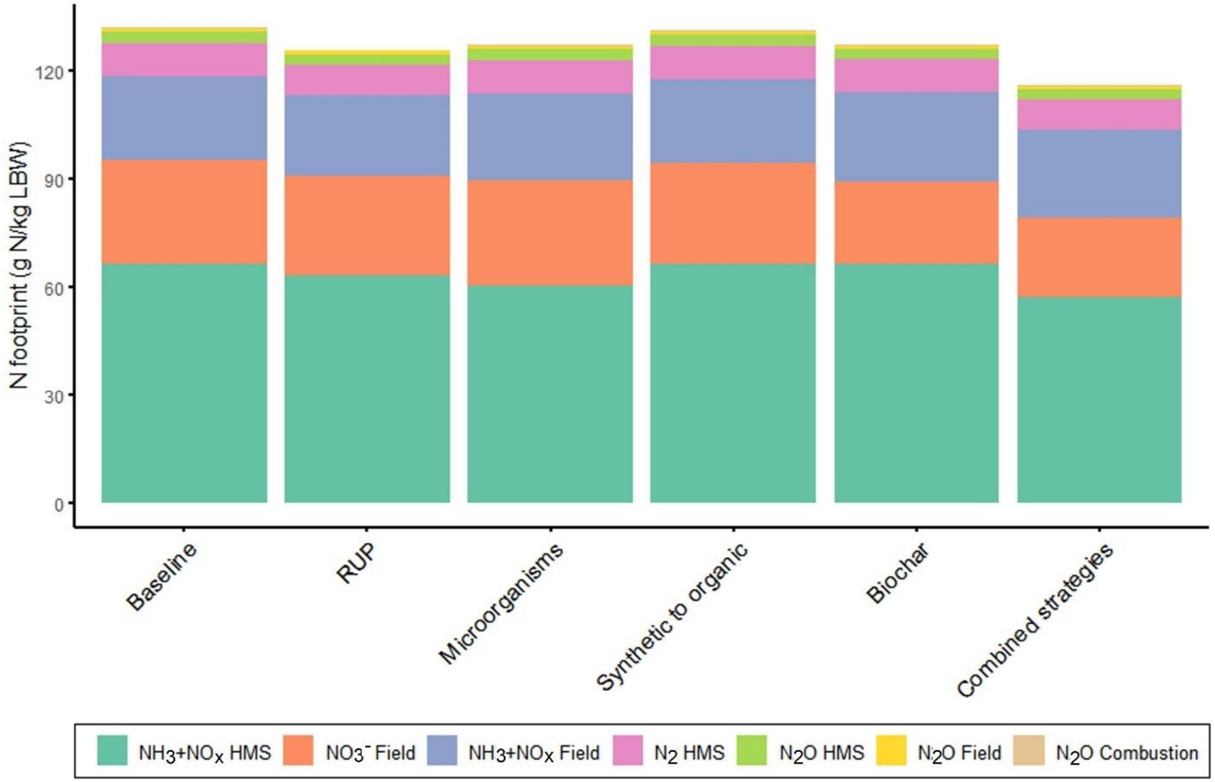

Figure 17. Effects of mitigation strategies on N footprints by loss source for the total surveyed farms. HMS is housing and manure storage, Field is N field application, and combustion is fuel combustion.

Table 10. Effects of mitigation strategies on N footprints by loss source for the total surveyed farms

Activity sources (g N/kg LBW)	Housing and manure storage			N field application			Agricultural machinery	Total 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 strategies								
Baseline	3.1	9.2	67.6	1.1	23.3	28.4	0.1	132.8
RUP	2.9	8.7	64.0	1.0	22.3	27.3	0.1	126.5
	(-6.5%)[a]	(-5.f%)	(-5.3%)	(-9.1%)	(-4.3%)	(-3.9%)	(0%)	(-4.7%)
Microorganisms	3.1	9.2	61.4	1.1	23.9	29.1	0.1	127.9
	(0%)	(0%)	(-9.2%)	(0%)	(+2.6%)	(+2.5%)	(0%)	(-3.7%)
Synthetic to organic	3.1	9.2	67.6	1.1	23.1	27.8	0.1	132.0
	(0%)	(0%)	(0%)	(0%)	(-0.9%)	(-2.1%)	(0%)	(-0.6%)
Biochar	3.1	9.2	67.6	0.9	24.7	22.4	0.1	128.0
	(0%)	(0%)	(0%)	(-18.2%)	(+6.0%)	(-21.1%)	(0%)	(-3.6%)
Combined strategies	2.9	8.7	58.2	0.9	24.1	21.6	0.1	116.6
	(-7.5%)	(-5.4%)	(-13.9%)	(-19.6%)	(+3.4%)	(-23.9%)	(0%)	(-12.3%)

[a] Percentage of N loss reduced compared to baseline losses

The mitigation effects of the combined strategies were modelled for each of the provinces as shown in Figure 19. Effects were highest in Jeju (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 (Table 11). Decreases in losses as denitrification from housing and manure storage in Chungcheongbuk, Chungcheongnam, and Gangwon were relatively low, signifying that these farms surveyed in these provinces fed steers and fattening cows with feeds of low CP. 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 and Gangwon did not practice rice cultivation and did not benefit from biochar application. Farms in Jeju had exceptionally expansive field areas and consequently showed the highest reduction in losses from N field application. Deploying the combination of mitigation strategies to all beef producing farms in Korea may not be attainable. Tailoring these strategies to reflect the distinctions in farming systems could be an efficacious approach to target major N loss sources of each region.

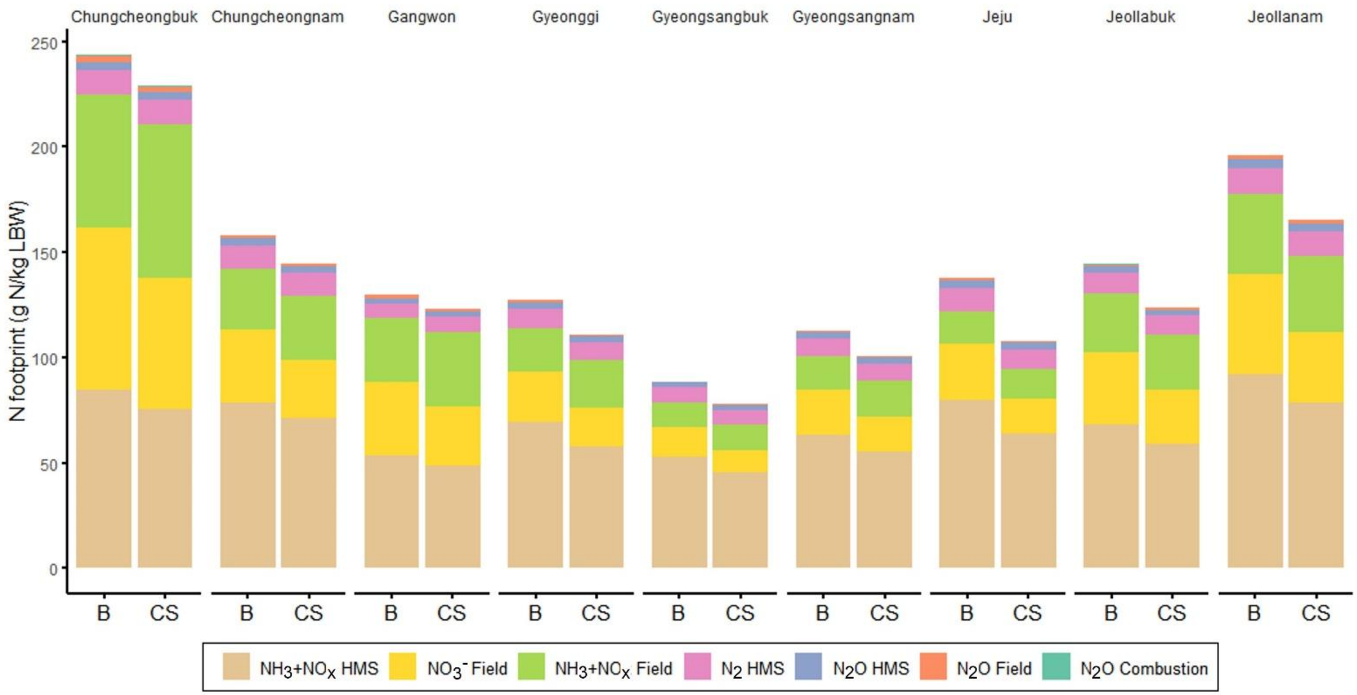

Figure 18. Effects of combined strategies on N footprints by loss source for the 9 provinces. B is the baseline footprint and CS is the footprint after combined mitigation strategies were applied. HMS is housing and manure storage, Field is N field application, and combustion is fuel combustion.

Table 11. Effects of combined strategies on N footprints by loss source for the 9 provinces.

Activity sources (g N/kg LBW)		**Housing and manure storage**			**N field application**			**Agricultural machinery**	**Total 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
	CS[b]	3.8	11.4	75.8	2.6	73.0	62.0	0.1	228.7
		(0%)[c]	(-0.9%)	(-10.2%)	(-18.8%)	(+15.7%)	(-19.8%)	(0%)	(-6.0%)
Chungcheongnam	B	3.6	10.7	78.6	1.2	29.3	34.5	0.1	158.0
	CS	3.5	10.6	71.0	1.0	30.9	27.5	0.1	144.7
		(-2.8%)	(-0.9%)	(-9.7%)	(-16.7%)	(+5.5%)	(-20.3%)	(0%)	(-8.4%)
Gangwon	B	2.4	7.2	53.2	1.5	30.4	35.0	0.0	129.7
	CS	2.4	7.2	48.3	1.2	35.5	28.4	0.0	123.0
		(0%)	(0%)	(-9.2%)	(-20.0%)	(+16.8%)	(-18.9%)	(0%)	(-5.2%)
Gyeonggi	B	3.1	9.5	69.4	0.9	20.7	23.8	0.1	127.5
	CS	2.9	8.7	57.8	0.7	22.3	18.5	0.1	111.0
		(-6.5%)	(-8.4%)	(-16.7%)	(-22.2%)	(+7.7%)	(-22.3%)	(0%)	(-12.9%)
Gyeongsangbuk	B	2.3	7.2	52.7	0.5	11.9	14.0	0.0	88.6
	CS	2.3	6.8	45.2	0.4	12.3	10.8	0.0	77.8
		(0%)	(-5.6%)	(-14.2%)	(-20%)	(+3.4%)	(-22.9%)	(0%)	(-12.2%)
Gyeongsangnam	B	2.9	8.6	63.4	0.8	16.1	21.0	0.1	112.9
	CS	2.8	8.3	55.3	0.7	17.0	16.3	0.1	100.5
		(-3.4%)	(-3.5%)	(-12.8%)	(-12.5%)	(+5.6%)	(-22.4%)	(0%)	(-11.0%)
Jeju	B	3.6	10.9	79.9	1.1	15.5	26.7	0.2	137.9

	CS	3.2	9.6	63.7	0.8	14.1	16.4	0.2	108.0
		(-11.1%)	(-11.9%)	(-20.3%)	(-27.3%)	(-9.0%)	(-38.6%)	(0%)	(-21.7%)
Jeollabuk	B	3.1	9.3	68.1	1.1	28.4	34.2	0.1	144.3
	CS	3.0	8.9	59.0	0.9	26.2	25.8	0.1	123.8
		(-3.2%)	(-4.3%)	(-13.4%)	(-18.2%)	(-7.7%)	(-24.6%)	(0%)	(-14.2%)
Jeollanam	B	4.2	12.6	92.2	1.8	37.8	47.3	0.2	196.1
	CS	3.9	11.8	78.7	1.4	35.7	33.6	0.2	165.3
		(-7.1%)	(-6.3%)	(-14.6%)	(-22.2%)	(-5.6%)	(-29.0%)	(0%)	(-15.7%)

[a] Baseline N footprint

[b] N footprint after application of combined mitigation strategies

[c] Percentage of N loss reduced compared to baseline losses

5. Conclusion

This study provides an assessment of the N footprint of Korean beef cattle production and elucidated how regional differences in farming systems contributed to the disparity between the 9 provinces. The average footprint was determined to be 132.8 g N/kg LBW, with volatilization and leaching as the major contributors. Regional variations were shown to be related to animal composition, 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. We devised mitigation strategies targeting animal diet, housing and manure storage, and cropping fields, in which the combined effects attained 12.14 percent overall reduction. Our results can serve as a baseline for future evaluations in both regional and national scales. It also presents beneficial strategies 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.

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요약 (국문초록)

대한민국 한우 농가 질소 발자국 분석: 불확도 평가과 감축 전략 제시

축산물 생산에 있어서 질소는 필수적인 영양소이지만, 최근에는 생산성 증대를 위해서 투입량이 증가하면서 온실가스, 하천 부영영화, 토양 오염 등의 여러 환경적인 문제가 발생하고 있다. 본 연구의 목표는 한우 농장의 사육과정에서 투입되는 사료량, 가축분뇨 배출량, 그리고 가축분뇨 처리과정과 퇴비 시용 과정에서 손실되는 질소를 전과정 평가(Life cycle assessment) 방법을 이용하여 평가하는데 있다. 연구에 필요한 자료는 전국의 지역별(도) 한우 농가 분포를 반영하는 총 106 개소의 한우 농장을 현장 조사하여 2020 년 기준의 공공자료와 농장 자체 기록들을 사용했다. 질소 손실량은 해당 자료들을 기후변화에 관한 정부 간 패널 (IPCC)에서 발행하는 지침서에 따라서 계산했고, 출하 kg 생체중(비육우와 송아지 판매)기준 g 질소 손실량이라는 질소 발자국 형태로 나타냈다. 또한 결과값의 정밀도와 결과에 기여한 요인들을 밝히기 위해 불확도와 민감도 평가를 진행했다. 결과적으로 질소 발자국은 132.8 g 질소/kg 생체중으로 평가되었고 사양단계별 구성, 가축분뇨 처리과정, 경작지 면적, 그리고 퇴비 시용량에 따라 지역별 차이가 나타났다. 손실된 경로로는 휘발된 비율이 68.4%로 가장 컸으며, 침출과 탈질화에 의해 손실된 비율은 각각 21.4%,

그리고 10.1%로였다. 연료 연소로 인해 손실된 질소량은 미미했다. 불확도 평가의 결과 46.6%라는 다소 높은 수치가 도출됐고 이 값은 계산과정에서 사용된 배출계수들의 불확도와 높은 상관관계를 보였다. 한우 생산과정에서 질소 손실 저감을 위해 생산성과 수익을 저하시키지 않는 네가지 감축전략들이 구상됐다. 구체적으로는 한우 질소 배출량을 줄이기 위한 반추위 비분해 단백질 급여, 우사와 분뇨 저장고에서 휘발되는 질소양을 줄이기 위해 미생물제 투여, 화학비료를 우사에서 나온 퇴비로 대체, 그리고 경작지에서 손실되는 질소를 줄이기 위해 비료시비 후 바이오차 살포이다. 모의 실행(simulation)을 통해 조사된 106 개의 한우농장에 네가지 전략이 모두 적용되면 질소 발자국을 12.3% 줄일 수 있다는 것을 밝혀냈다. 다만 지역별로 감축 정도가 다르게 나타났으며 (최소 5.2%에서 최대 21.7%) 사료 급여형태와 경작된 작물의 종류에 따라 상이했다. 궁극적으로, 본 연구는 대한민국 쇠고기 산업이 환경에 끼치는 영향을 국제 농업 사회에 알릴 수 있는 질소 발자국이라는 지표를 제시했다. 또한 불확도에 영향을 주는 요인들을 분석함으로써, 국가 고유의 배출계수 개발을 통해 더 정밀한 결과값을 도출해낼 수 있다는 것을 알아냈다. 이 연구에서 구상된 질소 손실 감축전략들은 대한민국이 지속가능하고 실현가능한 한우 산업으로 도약할 수 있는 가능성을 제시한다.

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주요어: 쇠고기 생산, 한우 농가, 질소 손실, 전과정 평가, 감축 전략, 불확도 평가

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