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Impacts of guidelines transition on greenhouse gas inventory in the livestock sector: a study case of Korea

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Abstract

The Paris Agreement signatories have committed to limit global average temperature increase above pre-industrial levels to below 2℃. Reporting of the greenhouse gas (GHG) inventory is regulated by the United Nations Framework Convention on Climate Change. Currently, countries are transitioning from the Measurement, Reporting, and Verification reporting system to the Enhanced Transparency Framework (ETF) reporting system. Under the ETF, countries are required to use the 2006 guidelines (GL). This study explored how replacing the 1996 GL with the 2006 GL or the 2019 Refinement impacts the overall GHG inventory from the livestock sector, with Korea as a case study. The result affirmed that changes in guideline led to changes in total estimated emissions. Moving from the 1996 GL to the 2019 Refinement resulted in more significant differences in estimated emissions than moving to the 2006 GL in terms of source-based emissions, annual inventory, or trend. Notably, guidelines' changes also impacted the proportion of each source's contribution to total estimated emissions. While applying the most recent guidelines is expected to produce more accurate estimations, consistency with the previous inventory calculated with previously used guidelines should be maintained. Additionally, the changes in the contribution of each source clarifies that although enteric fermentation is the largest contributor of GHGs, relevant mitigations are likely less feasible compared to those related to manure management. This is because of naturally occurring biological processes. Thus, mitigations in manure management are suggested.

Keywords: Greenhouse gas emission, Livestock sector, IPCC guidelines, 2019 Refinement, Greenhouse gas inventory

INTRODUCTION

The goal of the Paris Agreement to limit the increase of global surface temperature to well below 2℃ and further 1.5℃ above pre-industrial level [1] has increased the scrutiny on the role of all sectors in

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climate change mitigation. This includes the agricultural sector, which accounts for 9.71% of total greenhouse gas (GHG) emissions without land use, land-use change, and forestry (LULUCF) [2]. However, some key principles are, apparently, overlooked. For example, how the impacts of methane (CH_4) and nitrous oxide (N_2O)—the major GHGs emitted from agricultural production—are mutually distinct, and, in particular, from that of carbon dioxide (CO_2). CH_4 is a more potent GHG than CO_2, has a shorter lifetime in the atmosphere, and is a significant contributor to short-term global warming [3,4]. However, N_2O has higher global warming potential (GWP) than CH_4 and CO_2 [5]. Furthermore, Intergovernmental Panel on Climate Change (IPCC) predicts that over the next 10 to 20 years, both CH_4 and CO_2 will have similar global warming impacts [5].

GHGs are produced both directly from livestock (enteric fermentation and manure management) and indirectly from the production of livestock feed, energy use in fertilizer manufacture, farm operations, and post-production transportation, processing, and retailing [6]. Livestock accounts for 4.95% of total GHG emissions and 32% of total anthropogenic CH_4 emissions [7]. Nonetheless, the livestock sector has the potential to reduce emissions by up to 14%, if certain mitigation measures are taken [8]. Additionally, the livestock sector supports climate change mitigation and adaptions through circular bioeconomy, that is, as a natural energy source, as well as contributes to the improvement of food security and nutrition [9].

The GHG inventory is a measure of the emissions and removals occurring within national (including administered) territories and offshore areas over which countries have jurisdiction [10]. It is an instrument to report GHG emissions under international agreements, including the Paris Agreement, and is significant for several reasons: scientific understanding of the link between environmental pollution and effects to sources of pollution, as well as to monitor progress toward policy goals.

An international agreement to limit climate change must set emission limits/ targets/ goals and monitor progress in an open and transparent manner, which necessitates reliable and internationally accepted methods and guidelines. Furthermore, standard methods of calculating inventories facilitate comparisons between countries and regions [11]. This is facilitated by the IPCC Guidelines (GL) as the standard tool to calculate GHG emissions for the GHG inventory. The IPCC GL were first published in 1996 [10]; a revised version was published in 2006 [12]; and a refinement of the 2006 GL was published in 2019 (2019 Refinement) [13]. The guidelines use national data and employ different approaches (tiers): Tier 1 is based on default values, Tier 2 is based on country-specific values, and Tier 3 is based on the most-detailed values (e.g., models).

Currently, the United Nations Framework Convention on Climate Change (UNFCCC) is transitioning from the Measurement, Reporting, and Verification (MRV) system to the Enhanced Transparency Framework (ETF). The countries have started reporting under the ETF since 31 December 2024, and the GHG inventories in the ETF requires all countries to follow the 2006 IPCC GL, while the use of the 2019 Refinement is voluntary [14]. Hence, guideline changes will impact the national GHG inventory, especially for countries currently using the 1996 GL for their GHG inventories.

Korea is classified as a non-Annex I country and has ratified the Paris Agreement [15]. The country follows the 1996 GL to estimate its national GHG inventory and the 2006 GL for a few categories, e.g., rice cultivation, forestland and wetland, others in waste sector [16]. The GHG inventories from the livestock sector are calculated by following the 1996 GL with the Tier 1 method [17]. Through its Nationally Determined Contribution (NDC), Korea has set a definite carbon neutrality goal for 2050 and coordinates sectoral strategies aligned with policy directions for each sector, including agriculture and livestock [16].

The changes in the recent IPCC GL are considered to provide more accurate estimates than

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earlier guidelins owing to the improved values and calculation method. However, concerns regarding how the changes may affect the inventory remain unknown. This study assesses the difference among the guidelines to show how guidelines improvement impacts the GHG inventory.

MATERIALS AND METHODS

The estimation of GHG emissions from livestock was conducted using the 1996 GL, 2006 GL, and 2019 Refinement for baseline year 1990 and recent year 2020. Korea was chosen as a study country because it is currently following the 1996 GL for its GHG inventory, which encompasses relevant livestock categories as well as the country's manure management system. The emissions included in the study are: CH_4 emissions from enteric fermentation, CH_4 emissions from manure management, and direct N_2O emissions from manure management. It is noteworthy that N_2O emissions from manure management comprises direct and indirect N_2O; however, owing to the unavailability of data, and the fact that this study is in accordance with Korea's GHG inventory, indirect N_2O emissions from manure management was not estimated. Furthermore, as Korea is currently using the Tier 1 method for all livestock categories, the same was applied in this study. Default values from each guideline were derived based on the determined characteristics. The calculation for each emission followed the equations provided by the guidelines [10,12,13]. The GWP was based on the IPCC 2nd Assessment Report with the values of 21 (CH_4) and 310 (N_2O) for the calculation with 1996 IPCC GL, and based on the IPCC 5th Assessment Report with the values of 28 (CH_4) and 265 (N_2O) for the calculation with 2006 IPCC GL and 2019 Refinement. The result was divided by 10^6 for total emissions expressed with kg/year to derive the result for Gg/year. Therefore, the total emission of each gas was shown as Gg CO_2-eq/year.

Activity data and emission factors

This study compares the 1996 GL, 2006 GL, and 2019 Refinement and demonstrates the effects of changes in the guidelines. Therefore, the same set of activity data (animal numbers and manure management system) was applied in all guidelines to to avoid biases and to maintain consistency throughout the calculation using different guidelines (Table 1-Table 3). However, owing to the unavailability of data on manure management system in 1990, the manure mangement system in 1990 used the data from 2011 (the earliest available data). Moreover, because of the differences in the climate characteristics among the guidelines, the climate characteristics were determined as follows: "cool" for the 1996 GL based on Korea's GHG inventory [17], "cool climate 12" for the 2006 GL based on the typical annual temperature by the Korea Meteorological Administration

Table 1. Korea's livestock population in 1990 and 2020

Animal Category	Population (head)	
	1990	2020
Dairy cattle	499,689	408,243
Hanwoo cattle*	1,502,768	3,190,768
Beef cattle*	76,230	161,855
Swine	4,412,206	11,184,873
Chicken layer	40,127,223	73,541,183
Chicken broiler	24,049,628	97,557,487
Duck	716,871	8,676,228

Data from KOSIS [18] and Ministry of Agriculture, Forestry, and FIsheries [19].

*No divided categories for beef cattle and Hanwoo in 1990, using the proportion in year 2020 to divide Hanwoo and beef cattle

Table 2. Typical manure treatment characteristic in Korea

1996 GL	2006 GL	2019 Refinement
Solid storage and dry lot	Solid storage	Solid storage
	Composting-in vessel (*for swine*)	Composting-in vessel
Liquid system	Liquid/slurry with natural crust	Liquid/slurry with natural crust > 6 months
	Pit storage below confinement > 1 month (*for swine*)	Pit storage below confinement > 6 months (*for swine*)
	Liquid/slurry without natural crust (*for poultry*)	Liquid/slurry without natural crust > 6 months (*for poultry*)
Other	Aerobic treatment-forced aeration system	Aerobic treatment-forced aeration system

*Manure treatment characteristic is adjusted for each guideline

Table 3. Manure treatment system in Korea

Animal Category	2011*			2020		
	Solid storage and dry lot	Liquid system	Other	Solid storage and dry lot	Liquid system	Other
Dairy cattle	0.862	0.001	0.137	0.666	0.004	0.330
Hanwoo cattle	0.923	0.003	0.074	0.754	0.004	0.243
Beef cattle	0.810	0.017	0.172	0.667	0.003	0.329
Swine	0.456	0.162	0.382	0.173	0.050	0.777
Chicken layer	0.704	0.005	0.291	0.579	0.001	0.420
Chicken broiler	0.671	0.002	0.327	0.524	0.001	0.475
Duck	0.678	0.006	0.316	0.508	0.004	0.488

Data from KOSIS [18].

*The earliest available data for management system is from 2011, thus, this data is used to estimate GHG emissions from manure management.

[20], and "warm temperate, moist" for the 2019 GL based on the mapping of the IPCC climate zone in Figure 10A.1 of 2019 Refinement [13]. The regional characteristics and climatic zones of Korea were based on each of the guidelines (Table 4) in accordance with Korea's GHG inventory [17], and default values derived from the three IPCC GLs were used to estimate Korean GHG emission in this study (Tables 5-Table 8). Manure treatment system (MS) classification followed 2023 GHG inventory in accordance with 1996 GL: "solid storage and dry lot", "liquid system", and "other". In order to maintain consistencies in the calculation throughout the guidelines, the values related to MS in other guidelines (2006 GL and 2019 Refinement) was adopted based on the closest definition in each guideline for each MS and each livestock category.

Calculation of greenhouse gas emissions

CH_4 emission from enteric fermentation

CH_4 emissions from enteric fermentation for the 1996 GL, 2006 GL, and 2019 Refinement are calculated as follows: total annual CH_4 emission by one head animal (Emission Factor [EF]) multiplied by the annual number of each livestock category (Population). Therefore, CH_4 emission from enteric fermentation was calculated using the following equation:

$$CH_{4-\text{ enteric fermentation}} = \sum \frac{EF \times N}{10^6}$$

where CH_4 is the total CH_4 emission (Gg CH_4/year), EF is the emission factor for each livestock category (kg CH_4/head/year), and N is the annual population of each livestock category (head).

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Table 4. Regional characteristic and climate zones to estimate GHG emissions from livestock sector in Korea

Source of emission	Animal category	Region characteristic			Climate zone		
		1996 GL	2006 GL	2019 Refinement	1996 GL	2006 GL	2019 Refinement
CH_4 (enteric fermentation)	Dairy cattle	North America	North America	North America	Not applicable		
	Hanwoo cattle	North America	North America	North America			
	Beef cattle	North America	North America	North America			
	Swine	Developed country	Developed country	High productivity system			
	Chicken layer	-	-	-			
	Chicken broiler	-	-	-			
	Duck	-	-	-			
CH_4 (manure management)	Dairy cattle	North America	North America	North America, high productivity	Cool	Cool 12°	Warm temperate, moist
	Hanwoo cattle	North America	North America	North America, high productivity			
	Beef cattle	North America	North America	North America, high productivity			
	Swine	East Europe	Eastern Europe	Eastern Europe			
	Chicken layer	Developed country	Developed country	Eastern Europe			
	Chicken broiler	Developed country	Developed country	Eastern Europe			
	Duck	Developed country	Developed country	All region			
N_2O (manure management)	Dairy cattle	North America	North America	North America, high productivity	Cool	Cool 12°	Warm temperate, moist
	Hanwoo cattle	North America	North America	North America, high productivity			
	Beef cattle	North America	North America	North America, high productivity			
	Swine	East Europe	Eastern Europe	Eastern Europe			
	Chicken layer	East Europe	Eastern Europe	Eastern Europe			
	Chicken broiler	East Europe	Eastern Europe	Eastern Europe			
	Duck	East Europe	Eastern Europe	All region			

Data from IPCC [10], IPCC [12], and IPCC [13].

Table 5. Emission factor (EF) to calculate CH_4 emissions from enteric fermentation

Animal Category	EF (kg CH_4/head/year)		
	1996 GL	2006 GL	2019 Refinement
Dairy cattle	118	121	138
Hanwoo cattle	47	53	64
Beef cattle	47	53	64
Swine	1.5	1.5	1.5
Chicken layer	0	0	0
Chicken broiler	0	0	0
Duck	0	0	0

Data from IPCC [10], IPCC [12], and IPCC [13].

CH_4 emission from manure management

CH_4 emissions from manure management for the 1996 GL and 2006 GL are calculated as follows: the amount of CH_4 emitted by one head animal in a year (EF) multiplied by the annual number of each livestock category (Population). Therefore, CH_4 emission from manure management was

Table 6. Emission factor (EF), default volatile solid rate (VS_{rate}), default average body weight (ABW) to calculate CH_4 emissions from manure management

Animal Category	1996 GL	2006 GL	2019 Refinement					
	EF (kg CH_4/head/year)	EF (kg CH_4/head/year)	VS_{rate} (kg VS/1000 kg animal mass/day)	ABW (kg)	VS (kg/animal/year)	EF (g CH_4/kg VS)*		
						Solid storage	Liquid system	Other
Dairy cattle	36	53	9.3	650	2,206.43	6.4	59.5	-
Hanwoo cattle	1	1	7.6	407	1,129.02	5.1	47.1	-
Beef cattle	1	1	7.6	407	1,129.02	5.1	47.1	-
Swine	3	3	4.9	59	105.52	1.5	111.6	-
Chicken layer	0.078	0.03	9.4	1.9	6.52	10.5	96.7	-
Chicken broiler	0.078	0.02	16	1.1	6.42	9.6	89.2	-
Duck	0.078	0.01	7.4	2.7	7.29	5.1	47.1	-

Data from IPCC [10], IPCC [12], IPCC [13].

*Emission factors in 2019 Refinement depends on typical manure treatment for each livestock category based on default MCF and B_0, using equation MCF*B0*0.67.

Table 7. Nitrogen excretion (N_{ex}) and average body weight (ABW) to calculate N_2O emissions from manure management

Animal Category	1996 GL	2006 GL			2019 Refinement		
	N_{ex} (kg N/head/year)	N_{rate} (kg N/1000 kg animal mass/day)	ABW (kg)	N_{ex} (kg N/head/year)	N_{rate} (kg N/1000 kg animal mass/day)	ABW (kg)	N_{ex} (kg N/animal/year)
Dairy cattle	100	0.44	604	97.002	0.60	650	142.4
Hanwoo cattle	70	0.31	389	44.015	0.40	407	59.4
Beef cattle	20	0.31	389	44.015	0.40	407	59.4
Swine	0.60	0.55	50	10.038	0.77	59	16.6
Chicken layer	0.60	0.82	1.80	0.539	0.81	1.9	0.6
Chicken broiler	0.60	1.10	0.90	0.361	1.12	1.1	0.4
Duck	0.60	0.83	-	-	0.83	2.7	0.8

Data from IPCC [10], IPCC [12], and IPCC [13].

Table 8. Emission factor (EF_3) to calculate N_2O emissions from manure management

1996 GL		2006 GL		2019 Refinement	
Manure treatment system	EF_3 (kg N_2O-N/kg N)	Manure treatment system	EF_3 (kg N_2O-N/kg N)	Manure treatment system	EF_3 (kg N_2O-N/kg N)
Solid storage and dry lot	0.02	Solid storage	0.005	Solid storage	0.01
		Composting-in vessel (*for swine*)	0.006	Composting-in vessel	0.006
Liquid system	0.001	Liquid/slurry with natural crust	0.005	Liquid/slurry with natural crust > 6 months	0.005
		Pit storage below confinement > 1 month (*for swine*)	0.002	Pit storage below confinement > 6 months (*for swine*)	0.002
		Liquid/slurry without natural crust (*for poultry*)	0	Liquid/slurry without natural crust > 6 months (*for poultry*)	0
Other	0.005	Aerobic treatment-forced aeration system	0.005	Aerobic treatment-forced aeration system	0.005

Data from IPCC [10], IPCC [12], and IPCC [13].

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calculated as follows:

$$CH_{4-\text{ manure management ('96,'06)}} = \sum \frac{EF \times N}{10^6}$$

where CH_4 is the total CH_4 emission (Gg CH_4/year), EF is the emission factor for each livestock category (kg CH_4/head/year), and N is the annual population of each livestock category (head).

The calculation approach for CH_4 emission from manure management in the 2019 Refinement has been improved as follows:

$$CH_{4-\text{ manure management ('19)}} = \sum \frac{N \times VS \times MS \times EF}{1000}$$

where CH_4 is the total CH_4 emission (kg CH_4/year), N is the annual population of each livestock category (head), VS is the annual volatile solid excretion (kg VS/animal/year), MS is the fraction of typical manure treatment system for each livestock category (dimensionless), and EF_{19} is the emission factor for each livestock category (g CH_4/head/kg VS).

N_2O emission from manure management

N_2O emissions from manure management for the 1996 GL and 2006 GL are calculated as follow: the amount of nitrogen emitted by one head animal in a year (N_{ex}) multiplied the annual number of each animal category for each MS (Population). N_2O from manure management in this study includes only direct N_2O emissions; therefore, the N_2O emissions from manure management using the 1996 GL, 2006 GL, and 2019 Refinement were calculated as follows:

$$N_2O_{\text{manure management}} = \sum [N \times N_{ex} \times MS \times EF_3] \times \frac{44}{28}$$

where N_2O is the total N_2O emission (kg N_2O/year), N is the annual population of each livestock category (head), N_{ex} is the annual average nitrogen excretion (kg N/animal/year), MS is the fraction of typical manure treatment system for each livestock category (dimensionless), EF_3 is the emission factor for direct N_2O emissions from manure management system (kg N_2O-N/kg N manure management system), and 44/28 is the conversion of (N_2O-N) emissions to N_2O emissions.

RESULT

Changes in estimated emissions from sources

Fig.1 shows the GHG emissions from enteric fermentation, manure management, and total emissions expressed in CO_2-eq estimated with the 1996 GL, 2006 GL, and 2019 Refinement. CH_4 emissions from enteric fermentation increased by approximately 40% when switching from the 1996 GL to 2006 GL; by approximately 70% when switching from the 1996 GL to 2019 Refinement; and by approximately 17% when 2006 GL was replaced by 2019 Refinement.

Nonetheless, the estimated GHG emissions, either CH_4 or N_2O, from manure management following different guidelines seem to be different. CH4 emission from manure management was 2 times higher in the 2006 GL compared to the 1996 GL. In contrast, the emission decreased by approximately 5% and 30% when 1996 GL is replaced with 2006 GL for year 1990 and 2020, respectively. Further, when 2006 GL is changed to 2019 Refinement, emission from manure

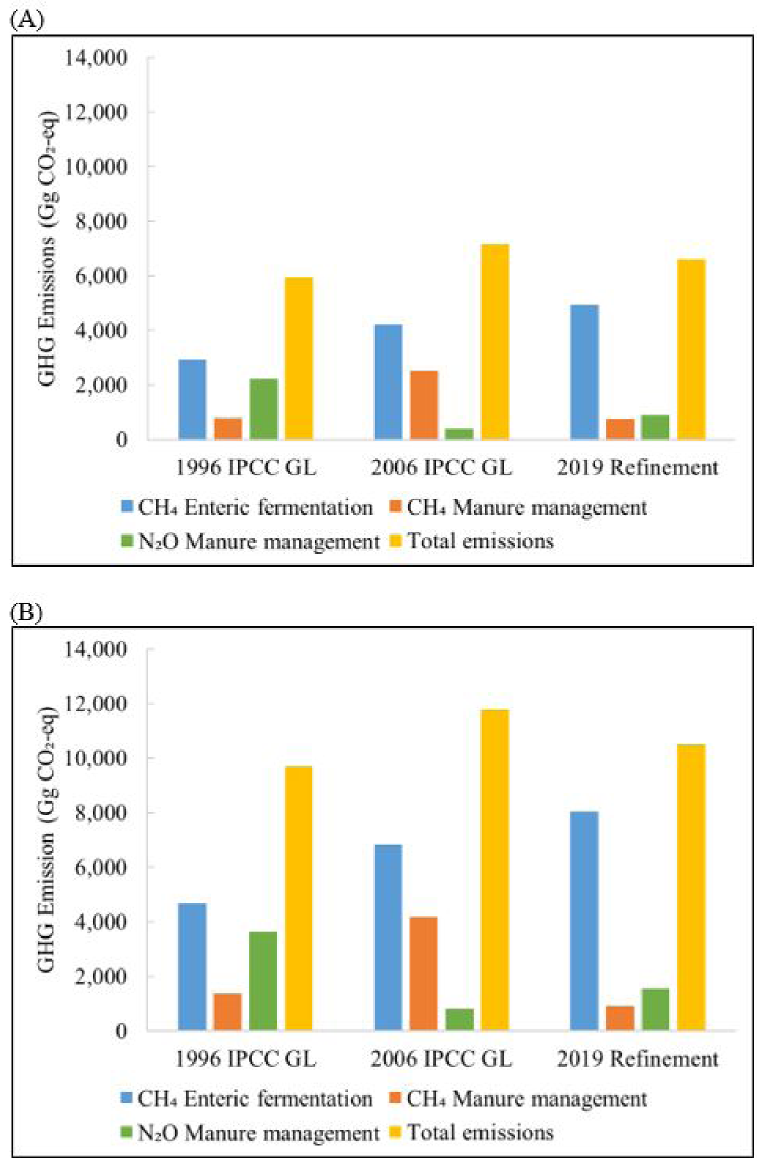

Fig. 1. GHG emissions from livestock sector in Korea from different IPCC guidelines; (A) Emissions in 1990; (B) Emissions in 2020. IPCC, Intergovernmental Panel on Climate Change; GL, guidelines; GHG, greenhouse gas.

management showed approximately 70% reduction.

Direct N_2O emission showed a decreased in both 2006 GL and 2019 Refinement compared to 1996 GL by approximately 80% and 58%, but showed an increase by 120% and 90% for year 1990 and 2020 respectively when 2006 GL is replaced with 2019 Refinement.

N_2O emission from manure management also varied depending on the guidelines followed (Fig.1). The main factor affecting N_2O emission is nitrogen excretion (N_{ex}). Default N_{ex} in the 2019 Refinement is the highest among all guidelines and N_{ex} in the 1996 GL is the lowest among all the guidelines. When the 2006 IPCC GL is compared to the 2019 Refinement, although the calculation to determine N_{ex} is the same, in these two mentioned guidelines, N_{ex} is affected by the rate of nitrogen excretion (N_{rate}) and typical animal mass (TAM). The default values of N_{rate} and TAM in the 2019 Refinement are relatively higher for all animal category than the ones in the

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2006 IPCC GL, resulting in higher N_2O emissions from manure management.

Comparison of emission trends

Table 9 shows the trend comparison of estimated emissions from baseline year 1990 and current year 2020 calculated with three guidelines. The trend of CH4 emissions from enteric fermentation generally unchanges when the guidelines are compared. Both ratio and annual increase of CH_4 emission from manure management showed sharp reduction in 2019 Refinement.

The trend of direct N2O emissions are close in 1996 GL and 2019 Refinement. The consequential difference in both emission ratio and annual emission increase is due to a different approach to estimate CH_4 emission from manure management in the 2019 Refinement from other guidelines. Previously, in the 1996 GL and 2006 GL, CH_4 emission was calculated by multiplying EF (kg CH_4/head/year) and the annual number of livestock (head). However, in the 2019 Refinement, the calculation approach has been improved by considering VS excretion as the main factor of CH_4 emission in the form of changing unit of the EF (g CH_4/ kg VS). In previous guidelines (1996 and 2006), VS was a factor to determine EF for CH_4 emission from manure management, while in the 2019 Refinement, VS is an independent factor in the equation. With this change in equation, although calculated with the same activity data of population (Table 1) as 1996 GL and 2006 GL, the proportion of MS for each livestock category becomes a significant factor. Thus, when compared to other guidelines, 2019 Refinement showed the noticeable percentage change.

Differences in the contribution of sources

Fig. 2 shows the relative contribution of different emission sources. It is clear that source

Table 9. Comparison of Korean estimated GHG emissions from years 1990 and 2020 using 1996 GL, 2006 GL, and 2019 Refinement

Emission source		Year	1996 GL	2006 GL	2019 Refinement
CH4 enteric fermentation	Emission (Gg CO_2-eq)	1990	2,935.69	4,221.50	4,945.68
		2020	4,673.00	6,828.19	8,055.12
	Trend	2020/1990 Ratio	1.6	1.6	1.6
		Annual change (%)	1.6	1.7	1.7
CH4 manure management	Emission (Gg CO_2-eq)	1990	795.19	2,518.52	753.73
		2020	1,378.16	4,169.72	901.44
	Trend	2020/1990 Ratio	1.7	1.7	1.2
		Annual change (%)	1.9	1.7	0.6
N2O manure management	Emission (Gg CO_2-eq)	1990	2,218.32	401.42	898.14
		2020	3,651.82	795.03	1,549.06
	Trend	2020/1990 Ratio	1.6	2.0	1.7
		Annual change (%)	1.7	2.3	1.8
Total emission	Emission (Gg CO_2-eq)	1990	5,949.20	7,141.44	6,597.55
		2020	9,702.98	11,792.94	10,505.62
	Trend	2020/1990 Ratio	1.6	1.7	1.6
		Annual change (%)	1.7	1.7	1.6

Annual emission change was estimated using Compound Annual Growth Rate (CAGR) calculation to determine the increase rate each year during the specific period.

contribution in 1996 GL and 2019 Refinement are closely identical with enteric fermentation as the major, followed by N_2O emission from manure management, and CH_4 emission from manure management. The CH_4 emitted from enteric fermentation exceeded 50% of the total GHG emissions from the livestock sector. However, the proportion of GHG emissions from manure management varied depending on the guidelines used. Regarding the estimated emission using the 1996 IPCC GL and 2019 Refinement, the contribution of CH_4 was higher than that of N_2O, but using the 2006 IPCC GL, it was lower than that of N_2O. The estimated GHG emissions from the livestock sector in Korea using the 1996 GL, 2006 GL, and 2019 Refinement indicate that changes

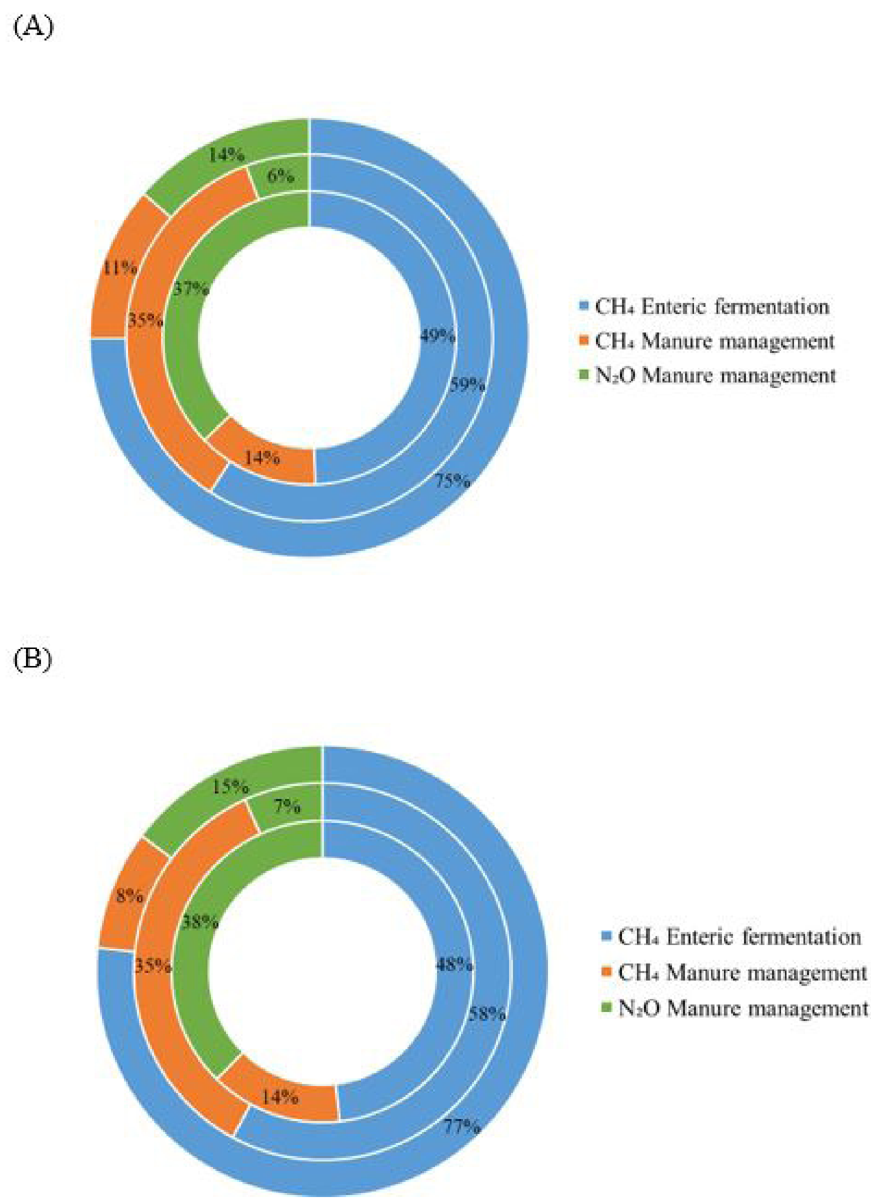

Fig. 2. Contribution of emission sources to Korea's GHG emissions from livestock sector using 1996 IPCC GL (inner layer), 2006 IPCC GL (middle layer), 2019 Refinement (outer layer); (A) Emissions in 1990; (B) Emissions in 2020. IPCC, Intergovernmental Panel on Climate Change; GL, guidelines; GHG, greenhouse gas.

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of guidelines impact GHG inventory reporting, not only in terms of the amounts of estimated emissions, but also in terms of the proportion of the source's contribution. The contribution of enteric fermentation increased when the 1996 GL was replaced with either the 2006 GL or the 2019 Refinement, while the contribution of manure management varied depending on which guideline was used. The contribution of CH_4 from manure management increased when the 1996 GL was replaced with the 2006 GL but decreased when it was replaced with the 2019 Refinement. Interestingly, although, N_2O contribution was smaller when following the 2006 GL and the 2019 Refinement than the 1996 GL, it was smaller for the 2006 GL than the 2019 Refinement. This difference may be a cause of concern. Mitigation policies are based on the inventory data, in which, if the contribution is changed because of guidelines change, there is likely to be confusion or uncertainty regarding which mitigation action should be prioritized.

DISCUSSION

Brief comparison among guidelines

The main differences among guidelines are the changes of the default EF or other default values. For instance, the EF for enteric fermentation increases from the 1996 GL to 2006 GL to 2019 Refinement. For emissions from manure management, the differences of values include differences related to CH_4 EF, nitrogen excretion, and EF_3. Additionally, regional and climatic characteristics have changed in the guidelines throughout its development. The feeding situation, average weight gain per day, and average body weight are a few factors that determine the EF [12]. The increase in the genetic merits of cows and changes in the feeding practices affect the animals' CH_4 production [21]. Manure biodegradability or the ultimate CH_4 production is a significant value for EF calculation [22].

In the 2019 Refinement, new classifications of productivity characteristic were added, namely, low productivity and high productivity. These components indicate a typical livestock category based on its usage, production level, typical feed, and typical manure management [13]. Feed intake varies among animal types, as well as among different management practices for individual animal types [23], which then impacts the EF.

The 1996 GL classified climates based on the average annual temperature, while the 2019 Refinement classified climates based on the mean annual temperature, humidity, and potential evapotranspiration. The principles calculation of CH_4 emissions using the IPCC GL is based on multiplying the EF with the total population of livestock in a category. However, the calculation of CH_4 emissions from manure management in the 2019 Refinement adopts a different approach that uses the same principle of calculation, but with modification based on independent factors such as the EF, VS of livestock, and typical MS, which indicates that the three factors have the same influence on total emissions.

Changes in inventory and its implication

For reporting purpose under the UNFCCC, Annex I countries (developed, industrialized countries) are required to use the 2006 GL [24], meanwhile, for non-Annex I countries, the report is calculated with the 1996 GL [25]. Owing to the recent transition from MRV to ETF, the understanding of this changes is critical. The transition to the 2006 IPCC GL, or further, to the 2019 IPCC GL may impact the country's policy related to setting goals and mitigation in a definite period of time. This study has demonstrated that the inventory from the same country may differ depending on the methodology and guidelines applied to calculate the estimated emissions, even though the same set of activity data was used to calculate with each methodology (guideline).

Studies by Amon et al. [26] and Petrescu et al. [27] also showed that different methodologies result in different inventories, even within the same country.

The likeliness of inaccuracy using the Tier 1 method is caused by the data origin—the data is mostly drawn from specific countries in a region. While these data sources may represent the typical regional situation or climate, they are, however, unrepresentative of specific livestock management systems in a country; for example, type of feed, breed, housing, management practices, etc. Therefore, changing from Tier 1 to Tier 2 or Tier 3 will provide more accurate and consistent inventory, better representing the circumstances and situations in a country or region. However, although the Tier 2 method uses country-specific data, the risk of inaccurate and inconsistent inventory remains. This is because in a few cases, default values are used when certain country-specific data are unavailable. Therefore, Tier 3 is encouraged because countries may create their own methodologies or EFs through direct measurement, creating accurate and consistent inventories over time. Nonetheless, in a country with limited capacity, using the Tier 1 method would help develop other systems within the country, for example, statistical data (for population, feed, MS, etc.), before moving to a higher tier.

It is noteworthy that if independent inventories fit well for a sector, that does not necessarily imply that it is closer to the actual emissions [27]. Nonetheless, consistency in methodology—including the use of tier—is essential depending on the animal categories, while improving the inventory data. Improvement of inventory guidelines is essential to ensure that countries can select the most suitable mitigation measures and demonstrate their effects in the national inventories [24].

Additionally, differences in inventories would complicate the monitoring of the progress of reducing emission by 30% in 2030 for reaching Paris Agreement goal. With many countries using different guidelines for their GHG inventory before ETF reporting, the difference between pra-ETF and post-ETF reporting may inevitably impact this climate goal. Moreover, the barrier for climate action is more political than technical—without political will, implementing concrete actions would be challenging [28]. Therefore, with the changes in inventory, there is possibility for manipulating or exploiting differences in the GHG inventory for political use.

While the Paris Agreement has created a system of pledges—albeit voluntary, it is noteworthy that these reporting requirements will produce information that can be reviewed and compared. Eventually, most climate-change policies are created and implemented by national entities. Furthermore, Tosun and Peters [29] revealed a strong and positive correlation between national and international climate policies. This implies that national-level ambitions for climate-related actions influence countries' similar ambitions at the international level. Thus, national policies would somewhat drive the overall global action to tackle climate change, and lack of well-established inventory as the baseline would adversely impact effective policy-making at the international level.

Ascertaining the significance of inventory is also necessary for prioritizing feasible mitigation. In the livestock sector, the maximum contribution to the total GHG emissions is in the form of CH_4 emissions from enteric fermentation. However, the mitigation—although effective—is challenging because of concerns related to health and animal welfare. Conversely, mitigation in manure management seems to be promising. The combinations with a high mitigation potential show a pattern of a few core mitigation measures targeting the largest emission flows combined with a wider set of other measures [30].

CONCLUSION

Presently, the global efforts for reduction of emissions to limit temperature increase are mainly focused on CO_2. However, recent evidence [8] reveals that reducing non-CO_2 emissions—

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specifically, CH_4—will help meet the emissions reduction target. Moreover, N_2O emission reduction is also significant considering its high GWP. The livestock industry is considered among the chief contributors of CH_4 and N_2O emissions; nevertheless, its significance cannot be ignored.

The GHG inventory, as the main tool to track emissions, shall maintain its Transparency, Accuracy, Completeness, Comparability, Consistency (TACCC) principles. The transition from the MRV to ETF will require all countries to apply the 2006 GL in accordance with the 2019 Refinement. However, changing the guideline impacts the estimation of emissions reported in the GHG inventory. The different default values, and specifically, the calculation approach for determining CH_4 emission from manure management in the 2019 Refinement, caused the differences between estimations based on different guidelines. Furthermore, the variations in estimated emissions impacted the proportion of contribution and GHG emissions trends. Further research is required to ascertain whether the results of this study are comparable with the results in other countries, which have different regional and climatic characteristics.

To improve the accuracy and consistency of the GHG inventory, countries are required to develop the Tier 3 method based on country-specific methodologies or EFs devised via direct measurement. The development of the Tier 3 method may experience challenges related to data availability, data confidentiality, or resources and equipment limitations. Therefore, the cooperation of researchers, governments, private companies, and other related-bodies is crucial. Countries should consider the significance of the accuracy and consistency of inventory to ensure the formulation of strategic policies and mitigation efforts. Failure to do so may result in unattained objectives, both on a domestic and global scale.

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