atmosphere

MDPI

Article

Estimation of Ammonia Emission Inventory Using Life Cycle Assessment Based on Livestock Manure Flow: A Case Study of the Manure Management Sector in Korea

Hye-Min Lee [1,2], Kyoung-Chan Kim [1], Min-Wook Kim [2], Ju-Yong Lee [1] and Hung-Soo Joo [1,*]

[1] Department of Environmental Engineering, Anyang University, Anyang-si 14028, Gyeonggi-do, Republic of Korea; hyemin7682@daum.net (H.-M.L.)

[2] Climate Change & Assessment Division, National Institute of Agricultural Sciences, Rural Development Administration, Wanju 55365, Jeonbuk, Republic of Korea

* Correspondence: hjoo@anyang.ac.kr; Tel.: +82-031-463-1292

Abstract: Ammonia is one of the precursor gases in the formation of particulate matter (PM) that reacts with nitrogen oxides and sulfur oxides in the atmosphere. Based on the Clean Air Policy Support System (CAPSS) of Korea, the annual ammonia emissions amounted to 261,207 tons in 2020 and the agricultural source (manure management sector) contributes the highest proportion of the ammonia inventory. However, the methodology for the study of ammonia emissions in Korea has some limitations regarding the representativeness of the sites selected and the reliability of the measurement method. In this study, we aimed to recalculate the ammonia emissions from the livestock industry in Korea using the UK's estimation method, which uses the life cycle assessment of livestock manure. Three major animal types, i.e., cattle (beef cattle and dairy cows), pigs and chickens, and three major processes based on the manure flow, i.e., housing, manure storage and treatment and land application processes, were considered. The total ammonia emissions were estimated to be approximately 33% higher than the official ammonia emissions stated by the CAPSS. For the manure flow, the ammonia emissions were the highest from land application processes. The ammonia emissions from dairy cow and poultry manure were much higher than those stated by the CAPSS, while the emissions from beef cattle and pig manure showed similar levels. The methodology used in this study can offer an alternative approach to the ammonia emission estimation of the manure management sector in the agriculture industry of Korea. Korean emission factors based on the manure flow should be developed and applied in the future.

Keywords: ammonia; emission inventory; livestock industry; life cycle assessment; manure flow

Citation: Lee, H.-M.; Kim, K.-C.; Kim, M.-W.; Lee, J.-Y.; Joo, H.-S. Estimation of Ammonia Emission Inventory Using Life Cycle Assessment Based on Livestock Manure Flow: A Case Study of the Manure Management Sector in Korea. *Atmosphere* **2024**, *15*, 910. https://doi.org/10.3390/atmos15080910

Academic Editor: Xuejun Liu

Received: 18 July 2024
Revised: 23 July 2024
Accepted: 26 July 2024
Published: 30 July 2024

1. Introduction

Ammonia (NH_3) emissions significantly impact the air quality and ecosystems [1,2]. Ammonia emitted from agricultural sources is considered to be a major contributor to the formation of particulate matter in the atmosphere [2–4]. Atmospheric ammonia reacts with sulfur oxides (SO_x) and nitrogen oxides (NO_x) to form particulate matter such as ammonium nitrate (NH_4NO_3) and ammonium sulfate ($(NH_4)_2SO_4$) [5]. Thereby, ammonia is recognized as a key component of secondary particulate matter, but more scientific data are needed regarding this issue. In 2020, the national ammonia emissions of South Korea (Korea) were 261,207 tons per year, and 200,206 tons (80%) of ammonia were emitted from agricultural sources [6]. Although national population and area of South Korea are smaller than those of the United Kingdom (UK), its emissions were approximately 100,000 (40%) tons higher than those of the UK [7]. In Korea, most of the ammonia emissions from the agriculture industry are produced by the manure management sector (91%), which is perceived as a livestock industry source (NAIR 2020) [6]. Ammonia emission sources and processes from the initial manure excretion in the livestock industry can be divided into three major stages as follows:

(i) Animal housing;
(ii) Manure storage and treatment facilities;
(iii) Land applications via liquefied fertilizer and compost;

In animal housing and manure storage and treatment facilities, ammonia is volatilized via the hydrolysis of urea, mainly from the urine with urease, which is plentifully produced during the degradation of feces [8,9]. In the manure land application process, ammonia is emitted via the chemical equilibrium of Henry's law from the soil in alkalic and wet conditions [10]. In these sources, variations in the structure of the animal housing, breeding and feeding, manure management and storage, meteorological parameters, fertilization methods and so on significantly influence the ammonia emissions [6,11]. Therefore, the estimation of the national ammonia emission inventory is not simple, and the predictable errors should be minimized as much as possible. The Clean Air Policy Support System (CAPSS) of Korea has been estimating the national emission inventory of air pollutants including ammonia. Ammonia emission inventory in the CAPSS is calculated by multiplying the number of animals by the individual emission factor (kg-NH_3/yr/head) [12]. The number of animal groups in the CAPSS is now 24, i.e., a dairy cow group, three groups of beef cattle (under 1 year old, 1–2 years old and over 2 years old), four groups of pigs (nursery pigs, glowing pigs and fattening pigs), two groups of poultry (laying hens and broilers) and 14 groups of other animals (ducks, geese, turkeys, sheep, lambs, horses, mules, donkeys, minks, foxes, rabbits, dogs, deer and cats) [12,13]. Most of the ammonia emissions (94%) in Korea are produced from three major types of animals, i.e., cattle, pigs and poultry [13].

In the early 2000s, Jeon et al. developed individual emission factors for beef, cattle and pigs, and these developed emission factors included emissions from animal housing, manure storage and land applications. However, these emission factors were determined under artificial conditions using a dynamic flux chamber (DFC) at a few facilities [14,15]. As for other previous studies on the development of ammonia emission factors in Korea, Lee et al. conducted a study on ammonia emissions for beef cattle and broilers [16], and Seo et al. measured the ammonia emission flux in naturally ventilated beef cattle barns [17]. However, these emission factors should be complemented considering their reliability and representativeness. In addition, for dairy cows, poultry and other animals, the emission factors of the United States Environmental Protection Agency (US EPA) or COReINventory of AIR emissions (CORINAIR) [18,19] have been applied without considering activities related to the manure flow in Korea. Therefore, complementary studies on the emission factors and activities used in Korea are needed. Indeed, various research activities related to the development of ammonia emission factors have recently been undertaken in Korea, such as government-led research projects. Most of the studies in these projects are focused on field monitoring using real-time monitoring instruments. Various studies have tried to accurately measure the ammonia emissions in many countries [20]. The ammonia emissions in the U.S. were estimated with a model based on the emission factors (EFs) developed by Battye et al. in Europe [5,19–21]. The volatilized ammonia from the total ammoniacal nitrogen (TAN) in each manure management stage is used in the estimation of ammonia emissions in Europe [22,23]. Denmark, Germany and the Netherlands use the EFs implemented in the Validated Entheses-Based Reconstruction of Activity (VERA) protocol [24,25].

In the United Kingdom (UK), the national ammonia emissions are estimated based on the nitrogen mass flow according to the ammonia emission factor (%) from the TAN in livestock manure from various manure-related processes [26]. In this methodology, the TAN mass flow, which refers to the tracking of the portion of manure in the life cycle from the initial manure excretion in the housing, plays an important role in the estimation of the ammonia emission inventory in the UK. Emission factors (%) in various manure-related processes are cited in various previous studies [27]. The total ammonia emissions of each animal type can be integrated with the emissions from various processes, and this can be reproduced using emission factors for each individual head by dividing the total ammonia emissions by the total number of heads [26]. The initial nitrogen and TAN production were calculated by multiplying the number of animal heads [10,26–28]. The UK's methodology has been applied to estimate the ammonia emissions in South Korea. This approach involves calculating the emissions based on the initial total ammoniacal nitrogen (TAN) production, emission factors (EF%) and livestock population.

In this study, the methodology of the UK was used to estimate the national ammonia emission inventory of Korea. The manure mass flow of Korea was determined according to the animal type (three major animals, i.e., cattle, pigs and poultry), and three major stages, namely housing, manure storage and land application, were applied as activities. The ammonia emission percentages from the TAN in manure in each process were applied as ammonia emission factors, and the national ammonia emissions estimated in this study was then compared with the official national ammonia emissions of Korea (CAPSS) to evaluate the approach used in this study.

2. Materials and Methods

2.1. Various Manure Processes Related to Ammonia Emissions

Figure 1 shows the livestock manure mass flow and ammonia volatilization from each process. Three major animals (i.e., cattle, pigs and poultry) and three major stages (i.e., livestock housing, intermediate treatment processes and final land application) were considered as manure-related processes in this study. The intermediate treatment processes were divided into two types, namely composting treatment processes (solid type) and liquefied fertilization processes (liquid type). The land application process was also divided into two types depending on the intermediate treatment processes. Purification was regarded as the same liquid type of treatment process as liquefied fertilization. The ammonia emissions after purification processes were not considered in this study, because liquid-type by-products from the purification process are not utilized for land application in Korea.

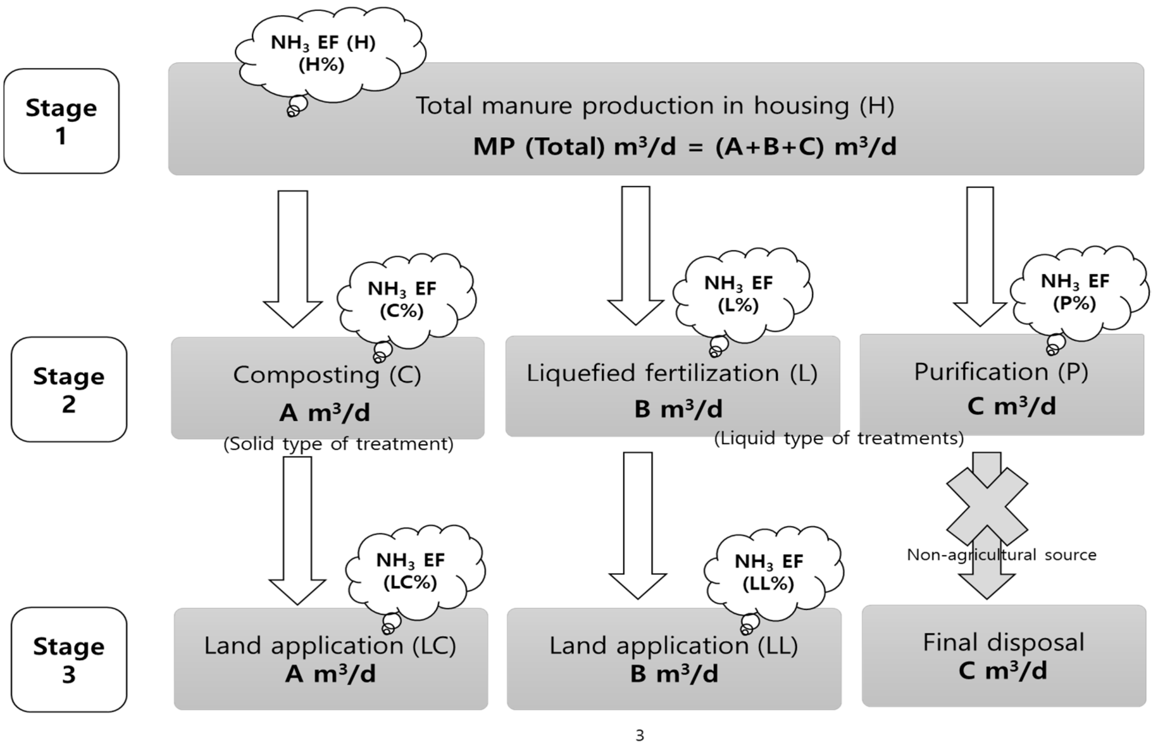

Figure 1. Livestock manure mass flow and ammonia emissions from each process.

2.2. Method Comparison

Table 1 compares the estimation methods for ammonia emissions in the manure management sector of the agriculture industry among Korea, the UK and this study. The UK's method was introduced as a basic approach in this study. The ammonia emissions were basically calculated by multiplying the activities (A) and emission factors (EFs). Although Korea and the UK have similar processes for the manure flow, the application of the ammonia emission factor was different between the two countries. The emission factor of Korea was developed based on livestock facilities, such as barns (housing), yards or buildings for composting and liquefied treatment, and their land application fields. The emission concentration of ammonia was directly measured from these individual facilities. In this method, the selection of a representative facility is critical, but this is a limitation. The method using a dynamic flux chamber (DFC) was used in the measurement of the ammonia emissions in Korea; however, this is also a limitation owing to the uncertainty about the reliability of DFC measurement. On the other hand, the emission factors of the UK were developed based on the livestock manure flow [21]. The residual nitrogen and nitrogen loss (ammonia volatilization) in manure are traced during its life cycle. The ammonia emissions increase in conditions involving high TAN content in manure; thus, the determination of the TAN is important in the estimation of ammonia emissions, especially for agricultural sources [23,29,30]. The ammonia emission factors of each stage were also presented as percentages (%) per TAN in manure. Although the UK's method indirectly measures ammonia emissions, it is a simpler and more reliable approach from the viewpoint of the ammonia loss (volatilization) from manure.

Table 1. Comparison of calculation methods for ammonia emissions.

	Korea (CAPSS)	UK	This Study
Ammonia emission (g/yr)	E * = A ** × EF	E = A × EF	E = A × EF
Consideration of life cycle analysis (LCA)	-	Manure excretion to final application	Manure excretion to final application
Target of EF	Facilities	Manure in individual processes	Manure in individual processes
Measurement (Parameter)	Direct measurement (DFC) for each facility (Ammonia emitted from manure)	Nitrogen and TAN in manure (Residual nitrogen in manure)	Nitrogen and TAN in manure (Residual nitrogen in manure)
Individual EF	Emission factors of individual facilities (g/yr/head)	Emission factors of individual processes (%)	Emission factors of individual processes (%)
Total EF (g/yr/head)	Sum of EFs of individual facilities	Total emission ÷ Heads	Total emission÷ Heads
Limitations	Selection of inclusive facility (size/type) Reliability measurement method (DFC)	Statistical data of manure mass flow (DEFRA +)	Statistical data of manure mass flow (MAFRA ++)

* Emission, ** Activity, + Department for Environment Food & Rural Affairs, ++ Ministry of Agriculture, Food and Rural Affairs.

2.3. Calculation of Ammonia Emissions

Figure 2 shows the procedure of ammonia emission. The total ammonia emissions were calculated by integrating the emissions from housing, composting processes, liquefied fertilization processes and land application. This study assumed that all by-products produced from intermediate processes (liquefied fertilization and composting) would be utilized in the land application stages via composting and liquid fertilizers. Data on the manure production (MP) and manure mass flow of cattle, pigs and poultry in Korea were used [31]. The initial TAN content [32] and emission factors of the UK [7] were used in the ammonia emission calculations.

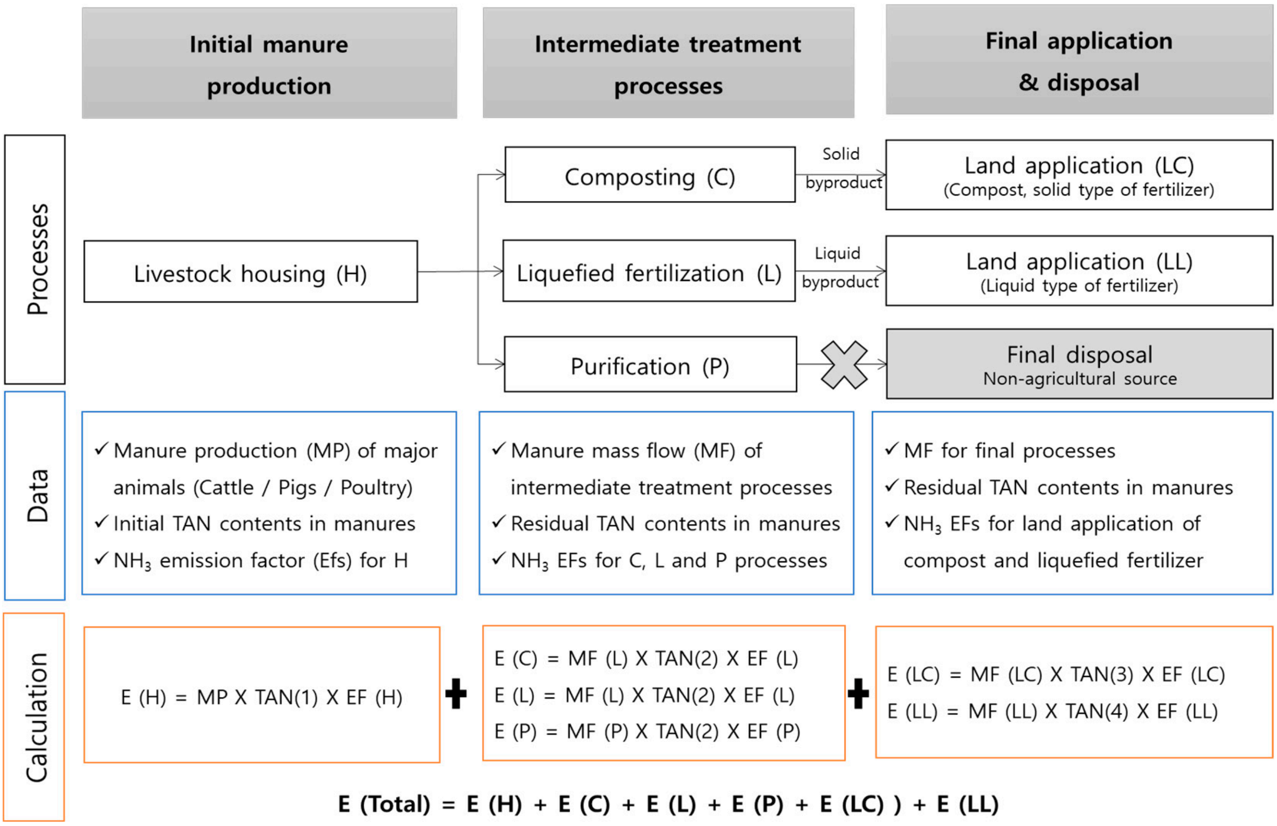

Figure 2. Estimation of ammonia emissions based on manure mass flow (MF) during the life cycle of livestock manure.

3. Results and Discussion

3.1. Ammonia Emission by CAPSS 2020

Table 2 shows the ammonia emissions from major animals in the UK (2019) and in the CAPSS 2020 of Korea, respectively. Indeed, the comparison of the ammonia emissions between Korea and the UK is not meaningful, because the geographical properties, feeding conditions, livestock manure management types and so on are different between the two countries. However, the comparison of the ammonia emissions considering the number of animals between Korea and the UK, shown in Table 2, can be helpful to understand more clearly the results of this study. The total ammonia emissions from the livestock industry in Korea were similar to those of the UK. The ammonia emissions from pigs and poultry in Korea were higher than those of the UK. In particular, the ammonia emissions from the three major animals (cattle, pigs and poultry) in Korea constituted 95% of the total ammonia emissions. The ammonia emissions of pigs in Korea were the highest (79.1 kton/yr), followed by cattle (58.1 kton/yr), poultry (35.4 kton/yr) and other animals. Compared with the number of animals (approximately two times higher in Korea), the emissions of pigs in Korea were significantly higher, approximately four times higher than those in the UK (18.5 kton/yr). Although various factors in the breeding and environmental conditions were different between the two countries, these results suggest that the ammonia emissions in Korea need to be compensated for or re-evaluated with other estimation methods, considering the limitations of the measurement methods, as mentioned earlier.

Table 2. Comparison of ammonia emissions from UK agriculture in 2019 [7,33] and Korean ammonia emissions in 2020 [34,35].

	UK (2019)		Korea (2020)	
	NH_3 Emission (kt/yr)	Animals (Head)	NH_3 Emission (kt/yr)	Animals (Head)
Total	179.10	208,844,000	181.06	215,223,879
Cattle	113.30	9,739,000	58.08	6,804,051
Sheep	12.30	17,545,000	0.23	8993
Pigs	18.50	5,078,000	79.10	11,208,400
Poultry	33.80	176,232,000	35.40	197,175,910
Horses	1.20	250,000	0.14	26,525

3.2. Manure Mass Flow (MF)

Manure production (MP) was used as an activity in this study. The manure production of Korea and the total manure production data for four types of animals in the UK in 2014 [36] are shown in Table 3. Statistical data for livestock manure production (MP) according to the treatment processes were obtained from the report of the Ministry of Agriculture, Food and Rural Affairs (MAFRA) of Korea [31]. The pig manure production in Korea was the highest, followed by beef cattle, poultry and dairy cows. The distribution of manure production among the animal types was significant. In particular, the pig manure production in Korea was significantly higher than that of the UK (19,210 ton/yr > 6040 ton/yr). On the other hand, the cattle manure production in the UK (especially dairy cow manure) was much higher than that in Korea (29,950 ton/yr > 4618 ton/yr). Beef cattle and dairy manure was mainly treated via individual (self-) treatment on the farm (> 80%), while pig and poultry manure was treated via community treatment (66% and 82%, respectively).

Table 3. Livestock manure production (ton/yr) in Korea (2022) and the UK (2019).

Treatment			Beef Cattle	Dairy Cows	Pigs	Poultry
Korea 2022	Individual treatment	Composting	14,170	3607	623	1575
		Liquefied fertilization		293	2507	
		Purification		26	3370	
	Community treatment	Composting	3179	655	6398	7160
		Liquefied fertilization			3164	
		Purification		37	3148	
	Total manure production		17,349	4618	19,210	8735
	Community treatment ratio		0.18	0.15	0.66	0.82
UK 2019	Total manure production		28,310	29,950	6040	4580

As shown in Table 2, the major treatment type in Korea was the composting process. The composting process was also a major treatment for livestock manure in the UK and some other countries [37,38]. Cattle and poultry manure was treated via a composting process (solid-state treatment) in Korea, whereas liquid-state treatment processes were more common for pig manure. In particular, in terms of individual treatment, pig manure was mainly treated via purification and liquefied fertilization (with a low portion for composting processes), and the portions that underwent community treatment were similar between solid-state treatment and liquid-state treatment. Approximately 34% (6518 ton/yr) of pig manure was treated via the purification process and was not utilized in land application.

3.3. Initial TAN and Emission Factors

In the UK's methodology, the TAN plays a crucial role in the calculation of ammonia emissions because the emission factors are defined by the nitrogen loss (%) from the TAN. The TAN is defined as the volatilized TAN (kg) from the unit manure mass (ton-manure) during the life cycle of manure. In this study, it is also defined as the initial TAN, which refers to the TAN in the initial stage of manure (housing), and it can be estimated from the excretion of manure. The TAN is not simple and is only applied for first-stage housing because it should be summated according to the volatilized ammoniacal nitrogen during all stages of the manure flow [7,33,36]. The initial TAN in housing was determined through several calculation steps based on previous studies [32,38,39], as shown in Table 4. Finally, the initial TAN values were calculated as 5.772 kg-N/ton-manure for dairy cows, 2.563 kg-N/ton-manure for beef cattle, 5.620 kg-N/ton-manure for pigs and 12.846 kg-N/ton-manure for poultry. Misselbrook et al. reported that the TAN values during land application were 0.4–1.9 kg/ton-manure for cattle slurry, 2.0–5.7 kg/ton-manure for pig slurry and 3.5–13.4 kg/ton-manure for poultry slurry [40]. The initial TAN values determined in this study were closer to or higher than the ranges reported by Misselbrook. Nevertheless, the initial TAN values in this study can be considered reasonable because they include each TAN value for all stages from housing to land application.

Table 4. The determination of the initial TAN (housing) using the statistical data of the UK.

Calculation Procedure	Dairy Cows	Beef Cattle	Pigs	Poultry	References and Calculation
(1) N excretion per animal (kg/yr/head)	110	55	10.6	0.57	Gerard et al., 2015 [36]
(2) Animals (head)	3,223,000	6,516,000	5,078,000	176,232,000	DEFRA 2019, farming statistics [33]
(3) N excretion (kton/yr)	354.53	358.38	53.83	100.45	(1) × (2)
(4) Manure production (ton/yr)	28,310,000	29,950,000	6,040,000	4,580,000	Smith et al., 2016 [39]
(5) N excretion (kg/ton-manure)	12.523	11.966	8.912	21.933	(3) ÷ (4)
(6) % TAN from N excretion (%)	0.461	0.214	0.631	0.586	Misselbrook et al., 2004 [32]
(7) Initial TAN in housing (kg/ton-manure)	5.772	2.564	5.620	12.846	(5) × (6)

The emission factor is the percentage of volatilized ammonia from the TAN in each stage. The ammonia emission factors in five processes, namely from housing, composting treatment processes, liquefied fertilization treatment processes (including purification treatment) and land application by compost and liquid fertilizer, were derived from the report on the ammonia emissions inventory from the UK's agricultural sector in 2019, as shown in Table 5 [7]. Modified emission factors for housing were derived by averaging the number of animals in each subdivision and the ages of each animal type in Korea. The weighted mean EF for beef cattle was modified by the age group (i.e., 2 years or more and less than 2 years) and the subdivisional sector (i.e., fattening pigs and dry sows) for pigs and by two types (i.e., broilers and belt-cleaned layers in cages) for poultry. The ammonia emission factor from land application for farmyard manure (FYM) was reported as 68.3% for all cattle and pigs in DEFRA 2021 [7]. However, this reported emission factor is much higher compared to the report of Oenema et al. in 2007, which stated that the ammonia emission factors from land application for both FYM and liquid fertilizer were approximately 7 to 11% of the initial TAN excretion [41]. This difference is probably caused by the bias due to the evaporated water content from the mixture (dry matter base). In this study, the same emission factors (68.3%) were applied as for the land application of liquid fertilizer. In the previous study, which applied a similar approach, new emission factors were used, with 19% for composting, 20% for the liquefied fertilization of dairy cow manure, 19% for composting, 6.6% for the liquefied fertilization of pig manure, 41% for composting and 22% for the liquefied fertilization of poultry manure [42,43].

Table 5. Ammonia emission factors (EF, %) used in this study [7,44].

	Housing		Intermediate Treatment Processes		Land Application	
	Reported EF	**Modified**	**Composting**	**Liquefied Fertilization**	**Compost**	**Liquid Fertilizer**
Beef cattle	12.5	7.81	26.3	-	68.3	-
Dairy cows	27.7	14.23	26.3	10.6	68.3	32.4
Pigs	22.9	30.00	31.5	13.0	68.3	25.5
Poultry	10.5	8.90	11.0	-	52.3	-

3.4. Estimation of Ammonia Emissions from Four Major Animals

The ammonia emissions from beef cattle manure amounted to 42,384 tons per year, while the emissions from dairy manure were 24,985 tons per year (Table 6). Collectively, the emissions from cattle accounted for 19% of the total ammonia emissions from livestock manure. Pig manure showed the highest emissions, totaling 79,154 tons per year, representing 34% of the total ammonia emissions. Additionally, the emissions from poultry manure amounted to 83,577 tons per year, constituting 36% of the total ammonia emissions.

Table 6. Ammonia emissions (ton/yr) by five processes and animal types.

Stage	Process	Beef Cattle	Dairy Cows	Pigs	Poultry
1st stage	Housing	4221	4605	39,329	12,127
2nd stage	Composting	13,039	6739	10,552	13,690
	Liquefied fertilization	-	227	7576	-
3rd stage	Compost application	7571	12,899	15,672	21,811
	Liquid fertilization application	-	515	6026	-
	Total	42,384	24,985	79,154	83,577

Figure 3 illustrates the fractions of the ammonia emissions from each manure process. The ammonia emissions from beef cattle (dairy cows) and poultry manure were the highest from compost land application (59%, 52% and 69%, respectively), followed by composting treatment processes and housing (31%, 27% and 16%, respectively). Conversely, the highest emissions from pig manure occurred in housing (50%), followed by compost land application (20%), composting processes (13%), liquefied fertilization processes (9%) and its land application (8%). The lower emissions from composting and its land application for pig manure can be attributed to the liquid-type treatment methods, such as public and private purification, employed for pig manure treatment in Korea. In addition, the by-products from public purification processes were not applied to agricultural land in Korea, resulting in lower ammonia emissions from the land application of liquid fertilizer than expected.

Figure 4 compares the ammonia emissions from the five manure processes. The ammonia emissions from housing were the highest for pig manure (50%), followed by poultry manure (18%), dairy cow manure (15%) and beef cattle manure (10%). The ammonia emissions from the composting process exhibited similar values for beef cattle (31%) and dairy cow (27%) manure, while the emissions from pig (20%) and poultry manure (16%) were lower than those for beef cattle and dairy cows. The ammonia emissions for compost land application showed the highest values among the five processes, with poultry manure emitting the highest (48%), followed by beef cattle (23%), pig manure (14%) and dairy cows (12%). The majority of the ammonia emissions from liquefied fertilization and its land application processes originated from pig manure (17%). These results suggest that the control of the compost land application of poultry manure should be prioritized for the mitigation of ammonia emissions in Korea.

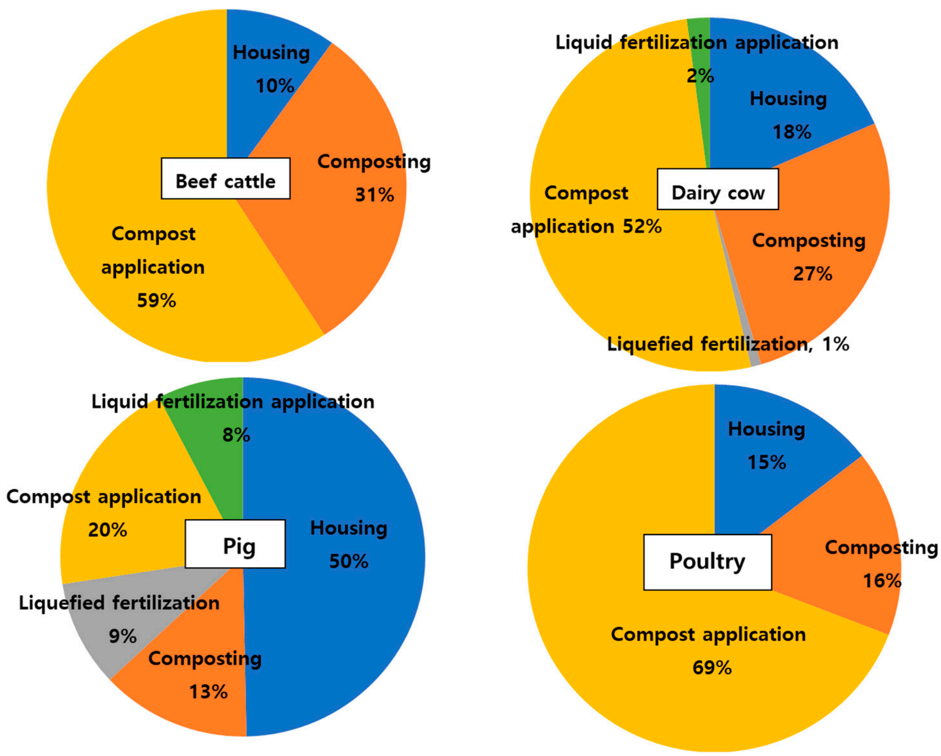

Figure 3. Fractions of ammonia emissions for each manure process.

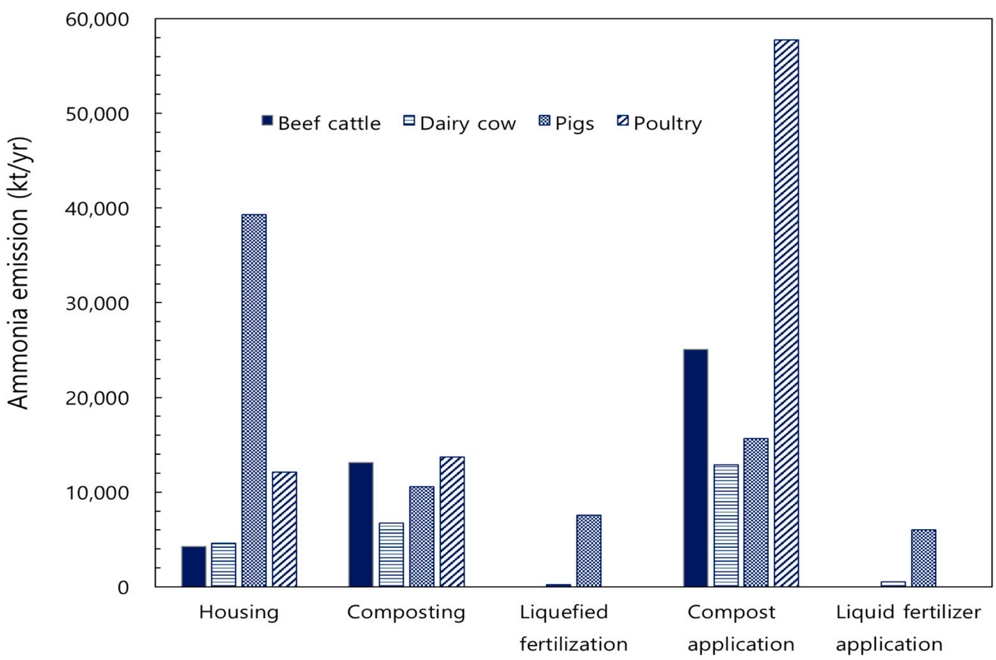

Figure 4. Comparison of ammonia emissions in five manure processes.

3.5. Comparison of Ammonia Emissions in This Study

Figure 5 compares the ammonia emissions between the CAPSS, the UK and this study. The ammonia emissions from beef cattle and pigs were similar in both the CAPSS and this study, while the emissions of dairy cows and poultry were much higher in this study compared to the CAPSS. In Korea, the emission factors for beef cattle and pigs were developed in 2008 [12]. These emission factors were applied in the CAPSS results; the CAPSS emissions showed similar values to those of this study. This means that the approach adopted in this study is comparatively affordable and that the emission inventory for beef cattle and pigs presents reliable values. However, the emission inventory for dairy cows and poultry still needs compensation, and emission factors for dairy cows and poultry must be developed in the near future. In the manure management sector of the agriculture industry in Korea, the ammonia emissions estimated in this study (230 kt/yr) were 33% higher than those reported by the CAPSS (170 kt/yr), primarily due to the increased emissions from poultry manure. The total ammonia emissions from the CAPSS and the UK showed similar values, while the emissions estimated in this study were 39% higher than those of the UK. Considering the number of animals (particularly poultry) presented in Table 2, the estimations of this study may be more reasonable than the CAPSS data. The ammonia emissions per capita (human population) in Korea are 1.7 times higher than those in the UK. On the other hand, the ammonia emissions in Europe and the U.S. are 16 and 10 times higher than the national ammonia emissions of Korea, respectively. The ammonia emissions per capita in Korea are similar to those of Europe and slightly lower than those of the U.S. Although the types of manure management, feed, diet, food culture, meat export ratio and so on vary by country, the national ammonia emissions of Korea, estimated in this study, can be recognized reasonable, and the approach adopted in this study will be helpful for the upgrading of the ammonia emission inventory of Korea in the future.

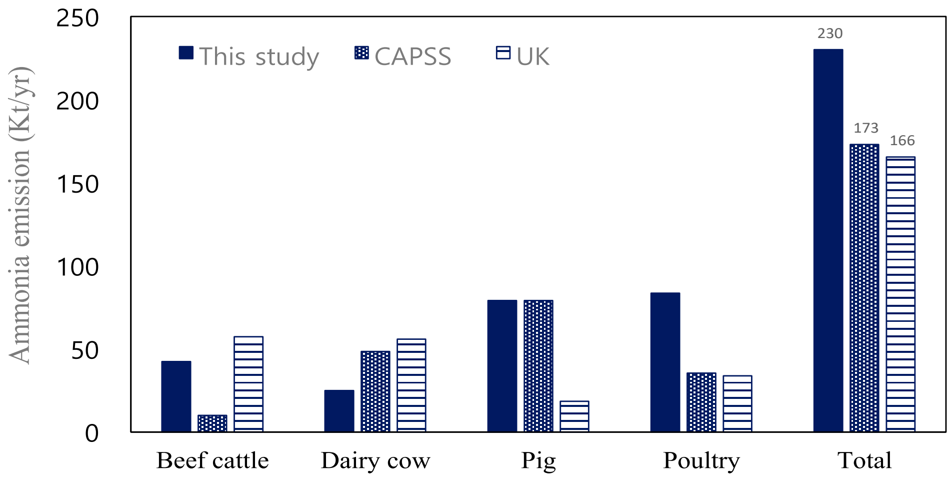

Figure 5. Comparison of ammonia emissions between the CAPSS, the UK and this study.

4. Conclusions

This study aimed to develop a methodology for the estimation of ammonia emissions in the agricultural manure sector of Korea. The methodology of the UK, which is based on nitrogen loss, was applied to manure production and the number of animals in Korea. The total ammonia emissions from the livestock industry (manure) in this study were found to be higher than those reported by the CAPSS. This increase in emissions was mainly attributable to the elevated levels of ammonia emitted from the composting and land application of poultry manure. The ammonia emissions from beef cattle and pig manure in both the CAPSS and this study showed similar levels because these emission factors were developed in 2008. The ammonia emissions from compost land application were the highest in the cattle and poultry industries, while the emissions from housing were the highest in the swine industry because the proportion of liquid-type treatment (liquefied fertilization and purification) is relatively high in the swine industry in Korea. The total ammonia emissions from poultry and pig manure were high in this study. In particular, compost land application in the poultry industry and housing in the swine industry showed the highest ammonia emissions in the manure flow. These results suggest that the ammonia emission mitigation strategy of Korea should be focused on these two processes (compost land application for poultry and housing for pigs). A comparison with the emissions from the UK revealed that the methodology used in this study for the estimation of ammonia emissions is more reasonable than the current methodology employed in Korea. Thus, the development of Korean-specific ammonia emission factors (based on N loss percentages (%) derived from TAN in manure) and the compilation of statistical data for the manure mass flow by the manure treatment type considering their life cycles should be considered in the future. For further study, spatiotemporal ammonia emission inventories using this new approach can be developed, including the yearly and regional variations, distribution and comparison of the ammonia emissions in Korea.

Author Contributions: Conceptualization, H.-M.L. and H.-S.J.; methodology, H.-M.L. and H.-S.J.; validation, H.-M.L., M.-W.K. and H.-S.J.; investigation, H.-M.L., J.-Y.L. and H.-S.J.; writing—original draft preparation, H.-M.L. and H.-S.J.; writing—review and editing, H.-M.L., K.-C.K. and H.-S.J. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the research project titled "Cooperative Research Program for Agriculture Science & Technology Development (Project No. PJ017075)", Rural Development Administration of Korea, and by the Particulate Matter Management Specialized Graduate Program through the Korea Environmental Industry & Technology Institute (KEITI), funded by the Ministry of Environment (MOE).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Paria, S.; Pishgar-Komleh, S.H.; Andr, J.A.A. Model Adaptation and Validation for Estimating Methane and Ammonia Emissions from Fattening Pig Houses: Effect of Manure Management System. *Animals* **2024**, *14*, 964. [CrossRef] [PubMed]
2. Le Dinh, P.; Van, D.; Peet-Schwering, C.M.C.; Ogink, N.W.M.; Aarnink, A.J.A. Effect of Diet Composition on Excreta compotion and Ammonia Emissions from Growing-Finishing Pigs. *Animals* **2022**, *14*, 964.
3. Anderson, N.; Strader, R.; Davidson, C. Airborne reduced nitrogen: Ammonia emissions from agriculture and other sources. *Environ. Int.* **2003**, *29*, 277–286. [CrossRef]
4. Ziru, L.; Weili, L.; Gang, Z. Sources, Variations, and Effects on Air Quality of Atmospheric Ammonia. *Curr. Pollut. Rep.* **2024**, *10*, 40–53.
5. William, B.; Viney, P.A.; Paul, A.R. Evaluation and improvement of ammonia emissions inventories. *Atmos. Environ.* **2003**, *37*, 3873–3883.
6. National Air Emission Inventory and Research Center (NAIR). National Air Pollutants Emission. 2020. Available online: https://www.air.go.kr (accessed on 20 October 2023).
7. Misselbrook, T.H.; Gilhespy, S.L. Inventory of Ammonia Emissions from UK Agriculture 2019; Inventory Submission Report: DEPRA Contract SCF0107; UK, 2021. Available online: https://uk-air.defra.gov.uk/assets/documents/reports/cat07/2103191000_UK_Agriculture_Ammonia_Emission_Report_1990-2019.pdf (accessed on 20 October 2023).
8. Meisinger, J.J.; Jokela, W.E. Ammonia Volatilization from Dairy and Poultry Manure. In *Managing Nutrients and Pathogens from Animal Agriculture (NARAES-130)*; Resource, Agriculture and Engineering Service: Ithaca, NY, USA, 2000.
9. Hung, C.H.; Hussain, N.; Barry, R.H.; Joann, K.W. Ammonia volatilization from manure mixed with biochar. *Can. J. Soil Sci.* **2021**, *102*, 177–186. [CrossRef]
10. Hill, R.A.; Richard, A. Emission, Dispersion and Local Deposition of Ammonia Volatilized from Farm Buildings and Following the Application of Cattle Slurry to Grassland. Ph.D. Thesis, University of Plymouth, Plymouth, UK, 2000.
11. Joo, H.S.; Ndegwa, P.M.; Wang, X.; Heber, A.J.; Ni, J.Q.; Cortus, E.L.; Ramirez-Dorronsoro, J.C.; Bogan, B.W.; Chai, L. Ammonia and hydrogen sulfide concentrations and emissions for naturally ventilated freestall dairy barns. *Trans. ASABE* **2015**, *58*, 1321–1331.
12. Jeon, E.C. *National Air Pollutant Emission Estimation Manual (II)*; National Institute of Environmental Research (NIER): Incheon, Republic of Korea, 2008.
13. Kim, J.S. *National Air Pollutant Emissions Calculation Method Manual (V)*; National Institute of Environmental Research (NIER): Incheon, Republic of Korea, 2023.
14. Jeon, E.C.; Sa, J.H.; Das, P.; Lee, S.R.; Roh, G.H. Flux and Emission factor of ammonia from pig Housing. *Environ. Soc. Jt. Conf.* **2007**, *6D7*, 283–286.
15. Sa, J.H.; Jeon, E.C. Estimation of Ammonia Flux and Emission Factor from the cattle Housing of Fall and winter. *J. Environ. Impact Assess.* **2010**, *19*, 1–13.

16. Lee, Y.B.; Lee, S.J.; Chang, H.H. Assessment of the Amount of Ammonia Emitted from Hanwoo Loose Barn and Winch-curtain Broiler House. *J. Agric. Life Sci.* **2013**, *47*, 193–201. [CrossRef]
17. Seo, S.Y.; Park, J.S.; Jang, Y.N.; Ha, T.H.; Kwon, K.S.; Jung, M.W. A Study on Ammonia Emission Characteristics in Naturally Ventilated Hanwoo-barn. *J. Korean Soc. Atmos. Environ.* **2021**, *37*, 919–930. [CrossRef]
18. CORINAIR. *EMEP/CORINAIR Atmospheric Emission Inventory Guidebook-Second Edition Group 10*; CORINAIR: Berlin, Germany, 1999.
19. Battye, R.; Battye, W.; Overcash, C.; Fudge, S. *Development and Selection of Ammonia Emission Factors*; EPA Contract Number 1994, 68-D3-0034; U.S. Environmental Protection Agency Office of Research and Development: Washington, DC, USA, 1994.
20. Frederick, K.T.; Mikko, H. A comparative assessment of four methods for estimating ammonia emissions at microclimatic locations in a dairy building. *Int. J. Biometeorol.* **2010**, *54*, 63–74. [CrossRef]
21. Faulkner, W.B.; Shaw, B.W. Review of ammonia emission factors for United States animal agriculture. *Atmos. Environ.* **2008**, *42*, 6567–6574. [CrossRef]
22. EPA. *2020 National Emissions Inventory Technical Support Document: Agriculture–Livestock Waste*; EPA: Washington, DC, USA, 2020.
23. Webb, J.; Menzi, H.; Pain, B.F.; Misselbrook, T.H.; Dammgen, U.; Hendriks, H.; Dohler, H. Managing ammonia emissions from livestock production in Europe. *Environ. Pollut.* **2005**, *135*, 399–406. [CrossRef] [PubMed]
24. Zhuang, S.; Eva, B.; Bart, S.; Peter, D. Validation of Five Gas Analysers for Application in Ammonia Emission Measurements at Livestock Houses According to the VERA Test Protocol. *Appl. Sci.* **2020**, *10*, 5034. [CrossRef]
25. *Vera Test Protocol for Livestock Housing and Management Systems*; International VERA Secretariat: Delft, The Netherlands, 2018.
26. Misselbrook, T.H.; Gilhespy, S.L.; Carswell, A.M.; Cardens, L.M. *Report: Inventory of Ammonia Emissions from UK Agriculture 2021. Inventory Submission Report*; DEPRA: Ballston, VA, USA, 21 March 2023; Contract SCF0107.
27. Demmers TG, M.; Phillips, V.R.; Short, L.S.; Burgess, L.R.; Hoxey, R.P.; Wathes, C.M. Validation of Ventilation Rate Measurement Methods and the Ammonia Emission from Naturally Ventilated Dairy and Beef Buildings in the United Kingdom. *J. Agric. Eng. Res.* **2001**, *79*, 107–116.
28. Koerkamp, P.; Metz, J.H.M.; Uenk, G.H.; Phillips, V.R.; Holden, M.R.; Sneath, R.W.; Short, J.L.; White, R.P.; Hartung, J.; Seedorf, J.; et al. Concentrations and emissions of ammonia in livestock buildings in Northern Europe. *J. Agric. Eng.* **1998**, *70*, 79–95. [CrossRef]
29. Palakodeti, A.; Azman, S.; Rossi, B.; Dewil, R.; Appels, L.A. Critical Review of Ammonia Recovery from Anaerobic Digestate of Organic Wastes via Stripping. *Sustain. Energy Rev.* **2021**, *143*, 110903. [CrossRef]
30. Ester, S.d.P.; Raffaele, G.; Stefano, P.; Giovanni, E.; Elena, C.; Marco, B.; Stefania, P. Ammonia Air Stripping from Different Livestock Effluents Prior to and after Anaerobic Digestion. *Sustainability* **2023**, *15*, 9402. [CrossRef]
31. Ministry of Agriculture, Food and Rural Affairs (MAFRA). *Production and Treatment Types for Livestock Manure*; Livestock Environmental Management Institute: Sejong-si, Republic of Korea, 2022. Available online: https://thecce.kr/5008 (accessed on 20 October 2023).
32. Misselbrook, T.H.; Sutton, M.A.; Scholefield, D.A. Simple process-based model for estimating ammonia emissions from agricultural land after fertilizer applications. *Soil Use Manag.* **2004**, *20*, 365–372.
33. *Farming Statistics Final Crop Areas, Yields, Livestock Populations and Agricultural Workforce*; Department for Environment Food & Rural Affairs: Defra, UK, 2019.
34. Ministry of Environment (ME). *Clean Air Policy Support System (CAPSS)*; Ministry of Environment (ME): Sejong, Republic of Korea, 2020.
35. Korean Statistical Information Service (KOSIS). *Number of Farmers by Livestock Manures*; Korean Statistical Information Service (KOSIS): Daejeon, Republic of Korea, 2019.
36. Gabriel, A.M.; Aliyu, S.M.; Stephen, A.B. *Sustainable Animal Manure Management Strategies and Practices*; Intechopen: London, UK, 2018. [CrossRef]
37. FAO (Food and Agriculture Organization of the United Nations). *Livestock and Environment Statistics: Manure and Greenhouse Gas Emissions. Global, Regional and Country Trends 1990–2018*; FAO: Rome, Italy, 2020.
38. Gerard, L.V.; Yong, H.; Oene, O. *Society of Chemical Industry, Nitrogen Excretion Factors of Livestock in the European Union: A Review*; Intechopen: London, UK, 2015.
39. Smith, K.A.; Williams, A.G. Production and management of cattle manure in the UK and implications for land application practice. *Soil Use Manag.* **2016**, *32* (Suppl. S1), 73–82. [CrossRef]
40. Misselbrook, T.H.; Nicholson, F.A.; Chambers, B.J. Predicting ammonia losses following the application of livestock manure to land. *Bioresour. Technol.* **2005**, *96*, 159–168. [CrossRef] [PubMed]
41. Oene, O.; Diti, O.; Gerard, L.V. Nutrient losses from manure management in the European Union. *Livestock Sci.* **2007**, *112*, 261–272.
42. Sven, G.S.; Webb, J.; Nicholas, D.H. New emission factors for calculation of ammonia volatilization from european livestock manure management Systems. *Front. Sustain. Food Syst.* **2019**, *3*, 101.
43. Owusu-Twum, M.Y.; Kelleghan, D.; Gleasure, G.; Forrestal, P.; Lanigan, G.J.; Richards, K.G.; Krol, D.J. Ammonia emission factors from cattle production systems in Ireland: A review. *Ir. J. Agric. Food Res.* **2023**, *62*, 75–95. [CrossRef]
44. *Emission Factors by the Number of Herds: Farming Statistics Final Crop Areas, Yields*; DEPRA: Ballston, VA, USA, June 2019.