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Characterizing Spatial and Temporal Variations in N_2O Emissions from Dairy Manure Management in China Based on IPCC Methodology

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Abstract: The emission factor method (Tier 1) recommended by the Intergovernmental Panel on Climate Change (IPCC) is commonly used to estimate greenhouse gas (GHG) emissions from livestock and poultry farms. However, the estimation accuracy may vary due to practical differences in manure management across China. The objectives of this study were to estimate the direct and indirect nitrous oxide (N_2O) emissions from dairy manure management between 1990 and 2021 in China and characterize its spatial and temporal variations following IPCC guideline Tier 2. The N_2O emission factor (EF) of dairy cow manure management systems was determined at the national level and regional level as well. The results showed that the national cumulative N_2O emission of manure management from 1990 to 2021 was 113.1million tons of CO_2 equivalent, ranging from 90.3 to 135.9 million tons with an uncertainty of ±20.2%. The annual EF was 0.021 kg N_2O-N (kg N)$^{-1}$ for total emissions, while it was 0.014 kg N_2O-N (kg N)$^{-1}$ for direct emissions. The proportions of N_2O emissions in North China, Northeast China, East China, Central and Southern China, Southwest China and Northwest China were 32.3%, 18.6%, 11.4%, 5.8%, 6.1% and 25.8%, respectively. In addition, N_2O emissions varied among farms in different scales. The respective proportions of total N_2O emissions from small-scale and large-scale farms were 64.8% and 35.2% in the past three decades. With the improvement in farm management and milk production efficiency, the N_2O emissions per unit mass of milk decreased from 0.77×10^{-3} kg to 0.48×10^{-3} kg in 1990–2021. This study may provide important insights into compiling a GHG emission inventory and developing GHG emission reduction strategies for the dairy farming system in China.

Keywords: manure management; nitrous oxide; emission estimation; emission factor; uncertainty

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1. Introduction

Global warming caused by excessive emissions of greenhouse gases (GHG) such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) has induced severe damage to the ecological environment. The global warming potential of N_2O is 273 times that of CO_2 [1]. It was reported that 65% of the global N_2O emissions come from manure storage and management facilities on livestock farms [2]. Dairy farming is an important sector of the animal industry in China. In 2021, the GHG emissions from dairy farming in China accounted for nearly 9% of the GHG from the livestock and poultry industry [3]. Estimating N_2O emissions accurately in the process of manure management is critical to compiling the GHG inventory of China's dairy cow industry and formulating emission reduction strategies.

Based on relevant research, the Intergovernmental Panel on Climate Change (IPCC) developed three methods for estimating GHG emissions from livestock and poultry farms in different regions based on the climates [4–6]. Method 1 (Tier 1) directly uses the livestock and poultry inventory multiplied by the given emission factor (EF). Method 2 (Tier 2) uses national or regional data (including manure management systems) and the corresponding EFs. Method 3 (Tier 3) fully utilizes local emission source data and EFs. Generally, the complexity and accuracy of the three methods consistently increase from method 1 to 3. Countries such as the United States and Canada have used method 3 and EFs recommended by IPCC Guidelines to estimate N_2O emissions during the management of livestock and poultry manure based on localized conditions [7–9].

According to the estimation method recommended by the IPCC guidelines, China has submitted three national climate change communications and two national climate biennial update reports to the United Nations Framework Convention on Climate Change (UNFCCC) [10–12]. Provincial livestock and poultry GHG emissions have been estimated as well based on IPCC Tier 1. However, the research on GHG emissions in China started relatively late and still lacked the localized EFs. The spatial and temporal variations in GHG emissions at the regional level has not been fully understood.

GHG emissions from livestock farms are affected by various factors, such as geographical and climatic conditions, animal feeding practices, digestive and excretory capacities and manure management [13]. Therefore, IPCC encourages the countries and regions to use localized data to ensure the accuracy of estimating GHG emissions.

Manure management is the major source of GHG emissions in dairy farms, with N_2O emitted in both direct and indirect forms (Figure 1). The direct N_2O emission results from the nitrification and denitrification of nitrogen in manure, while the indirect N_2O emission refers to the volatilization of nitrogen as NH_3 and NO_x, and nitrogen losses due to the leaching and runoff from manure management systems [13].

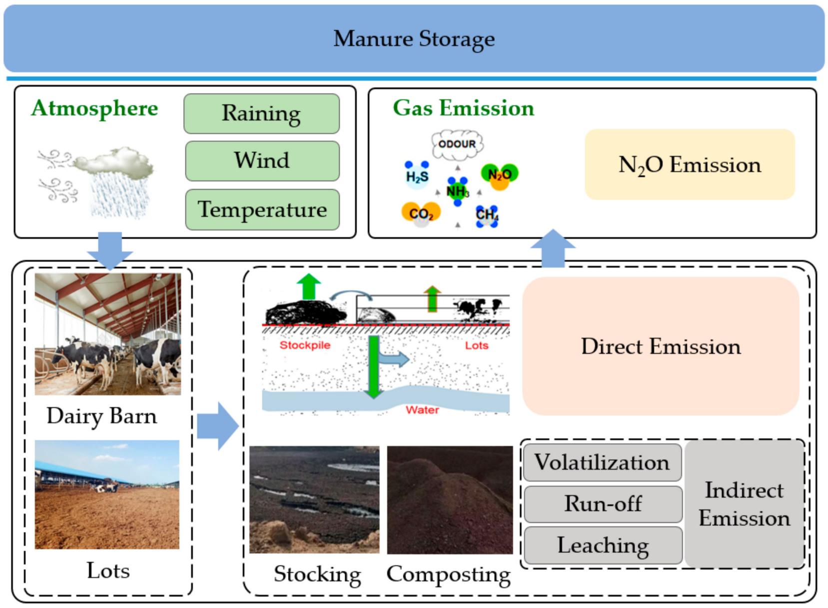


Figure 1. Gas emission processes from dairy farm. The image consists of elements drawn by the author and parts taken from a website, https://image.baidu.com/search/detail (accessed on 20 April 2024).

The objectives of this paper were to estimate the total emissions of N_2O (both direct and indirect) from manure management on dairy farms in different regions in China during 1990–2021. Localized data and the IPCC 2019 refinement of IPCC 2016 guideline methodology (Tier 2) were used for analysis. The study aims to provide data support for the GHG emission inventory accounting and emission reduction strategies in the dairy industry.

2. Materials and Methods

2.1. Estimating Methodology

The GHG estimation methods outlined in the IPCC Guidelines [13] have been widely used in previous studies. Considering the differences in farm management between China and foreign countries, IPCC Tier 1 may result in considerable uncertainty. The manure management systems on dairy farms in China are significantly different across provinces. However, the localized EFs has not been determined, which limits the application of IPCC Tier 3 [10]. To ensure the feasibility and accuracy of estimation, IPCC Tier 2 was used for estimating the N_2O emissions in this study.

The country was divided into six regions based on climate, including North China (NC), Northeast China (NE), East China (EC), Central and South China (CS), Southwest China (SW), and Northwest China (NW) [13]. The direct emissions of N_2O from dairy manure management systems in each region were estimated using Equation (1). Equations (2) and (3) were used to estimate indirect N_2O emissions from manure management. The three decades were divided into three periods (1990–1999, 2000–2009 and 2010–2021) according to the substantial variations in manure management systems and nitrogen excretion, which allows for a more accurate estimation of emissions.

$$E_{d(N_2O)} = \sum_R \left[\sum_S \left[\left[\sum_T (N_{RT} \cdot Nex_{RT}) \cdot M_{RST} \right] + N_{CD} \right] \cdot EF_d \right] \cdot \frac{44}{28} \tag{1}$$

$$E_{v(N_2O)} = \sum_R \left[\sum_S \left[\left[\sum_T (N_{RT} \cdot Nex_{RT}) \cdot M_{RST} \right] + N_{CD} \right] \cdot Frac_v \cdot EF_v \right] \cdot \frac{44}{28} \tag{2}$$

$$E_{l(N_2O)} = \sum_R \left[\sum_S \left[\left[\sum_T (N_{RT} \cdot Nex_{RT}) \cdot M_{RST} \right] + N_{CD} \right] \cdot Frac_l \cdot EF_l \right] \cdot \frac{44}{28} \tag{3}$$

$$E_{t(N_2O)} = E_{d(N_2O)} + E_{v(N_2O)} + E_{l(N_2O)} \tag{4}$$

where $E_{d(N_2O)}$ is the direct N_2O emission in the whole country, kg N_2O yr^{-1}.$E_{v(N_2O)}$ is indirect N_2O emissions of nitrogen volatilization from manure management, kg N_2O yr^{-1}. $E_{l(N_2O)}$ is indirect N_2O emissions of nitrogen leaching and runoff from manure management, kg N_2O yr^{-1}. $E_{t(N_2O)}$ is total N_2O emissions in China, kg N_2O yr^{-1}. N_{RT} is the population of dairy cows at different feeding stages in different regions of China, head. Nex_{RT} is the annual nitrogen excretion of dairy at different stages in different regions, kg N $head^{-1}$ yr^{-1}. M_{RST} is the percentage of different manure management systems at different stages in different regions, %. $Frac_v$ is the percentage of nitrogen that volatilizes as NH_3 and NO_x from different manure management systems at different stages in different regions, %. N_{CD} is the nitrogen input via co-digestate in anaerobic digestion system in China, kg N yr^{-1}. The value was set to zero in this study according to the condition of China.$Frac_l$ is percentage of nitrogen that leached and run off from different manure management systems at different stages in different regions, %. EF_d is direct N_2O EF of different manure management systems, kg N_2O-N (kg N)$^{-1}$. EF_v is N_2O EF caused by nitrogen volatilization and default value is 0.01 kg N_2O-N (kg NH_3-N+NO_x-N volatilized)$^{-1}$ [13]. EF_l is EF for N_2O from nitrogen leaching and runoff and its default value is 0.011 kg N_2O-N (kg N leaching and runoff)$^{-1}$ [13]. T is the different stage of the dairy cows, S is the manure management systems and R is the different regions in China. The 44/28 is the coefficient of conversion of N_2O-N to N_2O.

2.2. Input Parameters

According to the equations, multiple input parameters were localized based on the official dataset and previous studies, including the herd structure, excretion of cows at different feeding stages, manure management systems at different farm scales and regions, proportions of nitrogen loss, and the EFs.

2.2.1. Different Feeding Stages of Dairy Cow

Body weight and nitrogen excretion of dairy cattle at different feeding stages are significantly different. Therefore, the N_2O emissions from calves, heifers, and lactating cows were calculated separately [14].

2.2.2. Herd Structure of Dairy Cow

The dairy cow population at the provincial level from 1990 to 2021 was obtained from official documents and statistics, such as the National Bureau of Statistics and the literature. According to the statistics from the Ministry of Agriculture and Rural Development of China and the standards developed by the China Dairy Association, dairy farms were classified into two categories: small-scale farms (1–99 cows) and large-scale farms (≥100 cows) [15]. By analyzing the data on the proportion of dairy cows raised in different scales in China, the distribution of cows across the scales was determined [16]. The proportion of calves, heifers and lactating cows was 27:14:59 for small-scale farms and 16:29:55 for large-scale farms [17].

2.2.3. Manure Nitrogen Excretion

The nitrogen excretion data of cows during different feeding stages of the three time periods were obtained based on the manuals of production and discharge coefficients from the National Pollution Censuses in 2007 and 2017 and the relevant literature sources in China [14,18,19]. The compiled data are shown in Table 1.

Table 1. Nitrogen excretion of cows at different feeding stages of three time periods, kg head^{-1} yr^{-1}.

Period	Production Stage		
	Calf	Heifer	Lactating Cow
1990–1999 [19]	10.9	38.0	77.6
2000–2009 [18]	12.6	42.3	91.3
2010–2021 [14]	14.4	58.8	96.9

2.2.4. Manure Management System

As shown in Table 2, the proportions of four manure management systems in each time period were identified based on published documents and statistics [20–24]. In 1990–1999, manure treatment on dairy farms was rarely regulated in China. Manure was mainly accumulated within farms before applying it to fields. After the Regulations on Prevention and Control of Animal Husbandry Pollution was issued in 2013, the utilization rate of dairy manure significantly increased. Due to the lack of data, average proportion of manure management systems in Zhejiang, Xinjiang, Beijing and Heilongjiang from 1990 to 2009 was referenced (Table 2) [20–24]. In 2010–2021, more detailed proportions of manure management systems were determined at the regional level (Table 3) [25–27].

Table 2. Proportions of manure management system at different scaled farms from 1990 to 2009 [20–24].

Period	Mode	Proportions of Different Manure Management Systems, %			
		Solid Storage	Composting mode	Anaerobic Fermentation	Others
1990–1999	Small and Large	87.99	0.20	10.73	1.08
2000–2009	Small	87.99	0.20	10.73	1.08
	Large	74.97	15.31	4.64	5.08

Table 3. Proportions of manure management system at different scaled farms from 2010 to 2021 [25–27].

Scale	Region	Proportions of Different Manure Management Systems, %			
		Solid Storage	Composting Mode	Anaerobic Fermentation	Others
Small	NC	39.57	39.57	18.43	2.43
	NE	25.37	63.15	11.48	0.00
	EC	35.13	38.39	14.49	12.00
	CS	41.41	21.45	35.90	1.24
	SW	22.52	37.71	37.73	2.04
	NW	42.19	32.03	25.00	0.78
Large	NC	69.57	29.21	1.22	0.00
	NE	76.12	23.45	0.43	0.00
	EC	58.41	40.47	1.15	0.00
	CS	63.02	34.97	2.01	0.00
	SW	70.44	29.56	0.00	0.00
	NW	77.33	19.21	3.46	0.00

Notes: NC (North China), NE (Northeast China), EC (East China), CS (Central and South China), SW (Southwest China), NW (Northwest China).

2.2.5. Proportion of Nitrogen Loss

Both volatilization and leaching/runoff can cause significant nitrogen losses [13]. The proportions of nitrogen loss in different manure management systems are shown in Table 4. All data were obtained from IPCC 2006 guidelines [28] and domestic research [29].

Table 4. The proportion of nitrogen loss caused by volatilization and leaching or runoff in different manure management systems [28,29].

Nitrogen Loss Pathways	Solid Storage	Composting Mode	Anaerobic Fermentation	Others
volatilization	30%	20%	0%	27.5%
Leaching and runoff	20%	20%	0%	20%

2.2.6. Direct EF

Due to the lack of comprehensive emission data corresponding to livestock manure management systems in China, the N_2O EFs of solid storage (0.01 kg N_2O-N (kg N)$^{-1}$), composting (0.01 kg N_2O-N (kg N)$^{-1}$), anaerobic fermentation (0.0006 kg N_2O-N (kg N)$^{-1}$) and other manure management systems (0.001 kg N_2O-N (kg N)$^{-1}$) given by the IPCC 2019 refinement of IPCC 2006 Guidelines [13] were used in this study. The N_2O EF of dairy manure management in China was then calculated based on the total N_2O emissions and the nitrogen excretion of the nation.

2.3. Uncertainty Analysis

Uncertainty is critical in GHG inventories as it can evaluate the reliability and quality of the data used, thereby enhancing transparency and credibility of the estimation. In this study, estimation uncertainty was determined using the error propagation formula (EPF) Equations (5) and (6) [30]. The EPF combines uncertainties from multiple components to estimate the overall uncertainty of the inventory using the additive error propagation (Equation (5)), while the multiplicative error propagation equation (Equation (6)) is used for the estimates that are the product of several values.

$$U_c = \frac{\sqrt{(U_1 \cdot \mu_1)^2 + (U_2 \cdot \mu_2)^2 + \cdots + (U_n \cdot \mu_n)^2}}{|\mu_1 + \mu_2 + \cdots + \mu_n|} \tag{5}$$

$$U_c = \sqrt{U_1^2 + U_2^2 + \cdots + U_n^2} \tag{6}$$

where U_c is the uncertainty (%) of the sum or product of several values; μ_n is the n-th estimate and U_n is the uncertainty (%) of the n-th estimate.

3. Results and Discussion

3.1. N_2O Emissions from Manure Management on Dairy Farms

3.1.1. National N_2O Emission

This is the first attempt at using the IPPC Tier 2 to systematically estimate N_2O emissions from dairy manure management across provinces in the past three decades. By including the extensive collection of localized data, more accurate and representative results are expected. From 1990 to 2021, the accumulated total N_2O emissions from dairy manure management was 414.4 thousand tons, equivalent to 113.1 million tons of CO_2-eq (Figure 2). The direct N_2O emissions were 276.0 thousand tons (75.3 million tons of CO_2-eq), accounting for 66.6% of the total N_2O emission, while the indirect N_2O emission was 138.4 thousand tons (37.8 million tons of CO_2-eq). The average annual N_2O emissions during the periods of 1990–1999, 2000–2009 and 2010–2021 were 4332 tons, 14,697 tons and 18,671 tons, respectively. The direct N_2O emissions were 2847 tons, 9655 tons, and 12,581 tons for the three periods, and the respective percentages of the total emissions were 65.7%, 65.6% and 67,4%.

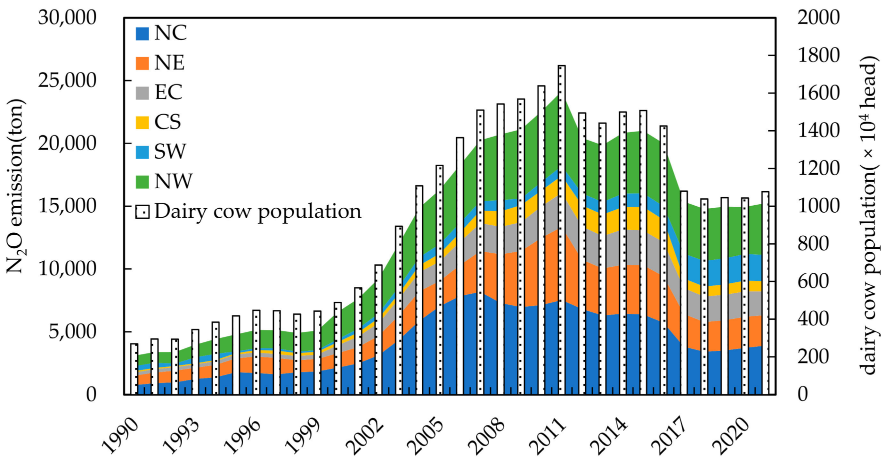


Figure 2. N_2O emissions of manure in different regions in China. Notes: NC (North China), NE (Northeast China), EC (East China), CS (Central and South China), SW (Southwest China), NW (Northwest China).

In general, N_2O emissions increased from 1990 to 2012, then gradually decreased afterwards. The total N_2O emissions was highly correlated with the dairy cow population (Figure 2). Before 2000, China's dairy cow population increased slowly, as did the N_2O emissions. From 2000 to 2009, the N_2O emissions significantly increased, with an average annual growth rate of 13.8%. It is mainly caused by the wide application of solid manure storage and composting. The growth of dairy cow populations could be another reason. The number of cows and N_2O emissions started to decrease after 2017. Compared with 2010, the total N_2O emissions and indirect N_2O emissions decreased by 32.4% and 31.5%, respectively, by 2021. Promotion of the sustainable farm system and development of environmental policies in China after 2017 could be the major reason. For example, many small-scale dairy farms were closed due to regulatory measures targeting improper manure management, therefore significantly reducing N_2O emissions [15].

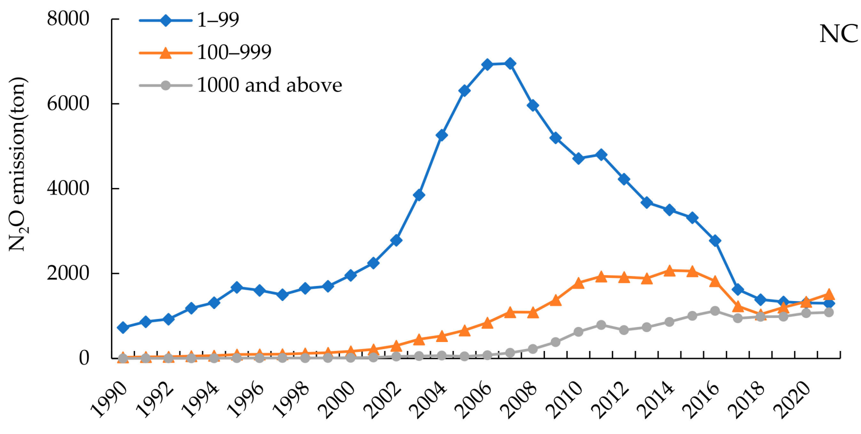
3.1.2. Spatial and Temporal Variations in N_2O Emissions

From 1990 to 2021, the NC had the highest total N_2O emissions from dairy manure management (133.9 thousand tons, 32.3%), followed by the NE (77.1 thousand tons, 18.6%), EC (47.1 thousand tons, 11.4%), CS (23.9 thousand tons, 5.8%), SW (25.5 thousand tons, 6.1%), and NW (106.8 thousand tons, 25.8%). The results indicated that the NC, NE and NW were the hotspots of dairy farming in China due to their abundant resources in pasture and cropland, as well as suitable climates. The NE and NW showed a similar growth trend in cumulated N_2O emissions from dairy manure management. The CS and SW had lower N_2O emissions than other regions because of a slower growth of the dairy population. In 2017–2021, the number of dairy farms in the SW increased, leading to an increase in N_2O emissions in this region.

Different manure management among regions could be the major reason of spatial variations in N_2O emissions. From 1990 to 2021, the average proportions of N_2O emissions (in both direct and indirect forms) from solid manure storage in the NC, NE, EC, CS, SW and NW were 79.8%, 73.6%, 71.0%, 77.0%, 73.3% and 83.7%. Meanwhile, the corresponding proportions for manure composting were 19.5%, 26.0%, 27.0%, 22.5%, 26.2% and 15.8%. The remaining manure management systems, such as anaerobic fermentation, contributed less than 1% of the total N_2O emissions. Over the surveyed periods, N_2O emissions from solid manure storage in NE decreased from 99.0% in 1990 to 65.2% in 2021. Meanwhile, the proportion of N_2O emissions from manure composting increased from 0.2% in 1990 to 34.7% in 2021, becoming one of the main manure management systems contributing to N_2O emissions. Similar results were observed in other regions.

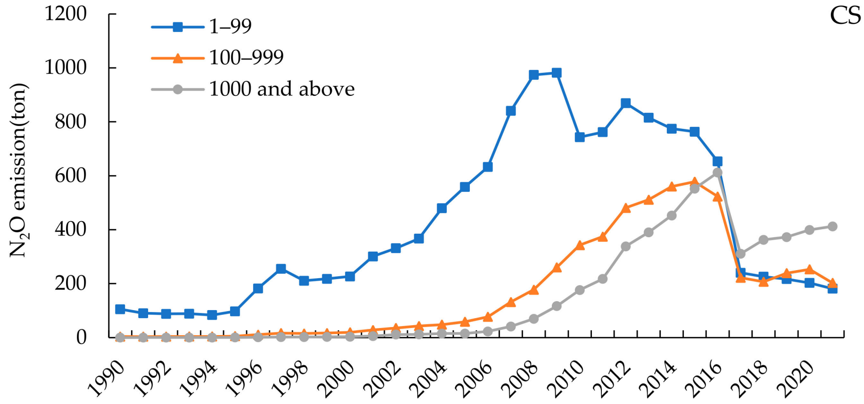
3.1.3. N_2O Emissions from Dairy Farms at Different Scales

From 1990 to 2021, total N_2O emissions from dairy farms with different scales were 268,578 tons (1–99 cows, 64.8%), 83,253 tons (100–999 cows, 20.1%) and 62,519 tons (1000 cows and above, 15.1%), respectively. Among that, the direct N_2O emissions accounted for 37.24%, 12.09%, and 9.24% of the total. The annual N_2O emissions per cow in different scaled dairy farms were 1.25 kg (1–99 cows), 1.44 kg (100–999 cows) and 1.23 kg (1000 cows and above). The total number of dairy farms continuously decreased from 1.36 million in 2002 to 0.46 million in 2021. Specifically, the number of small-scale farms decreased by 0.90 million, while the number of large-scale farms increased by 4000 [31]. Between 1990 and 2021, the population of cows on small-scale farms far exceeded that on large-scale farms, significantly increasing manure production and N_2O emissions. With the advancement in breeding technologies, animal management practices, and market demand and improved public awareness of environmental issues, dairy farms gradually transformed from a small scale to large scale. Correspondingly, proportions of N_2O emissions from large-scale farms remarkably increased. For example, N_2O emissions from small-scale farms with 1–99 cows in NC and CS consistently decreased after 2012. Conversely, N_2O emissions from large-scale farms (>99 cows) in SW exceeded those of small-scale (1–99 cows) farms in 2013 (Figure 3). By 2021, the proportions of N_2O emissions from different scales were 26.2% (1–99 cows), 31.6% (100–999 cows), and 42.2% (1000 cows and above), indicating that large-scale farms have become a major source of N_2O emissions.



(**a**)

Figure 3. *Cont.*



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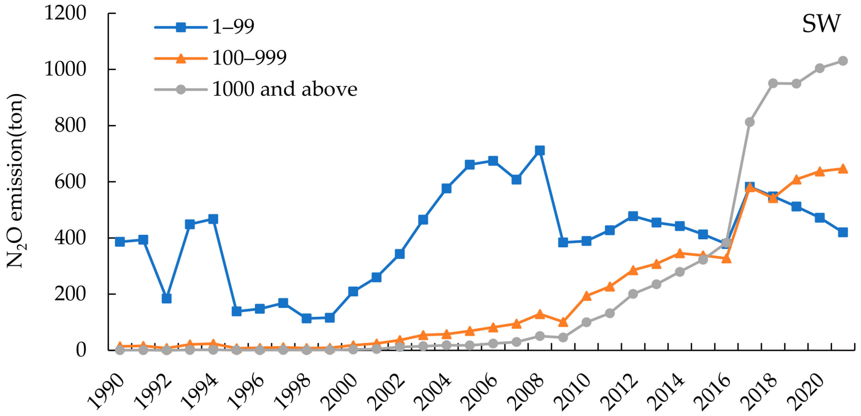

(**c**)

Figure 3. Manure N_2O emissions of farms at different scales in (**a**) North China (NC), (**b**) Central and South China (CS) and (**c**) Southwest China (SW).

3.1.4. N_2O Emission Intensity

As indicated in Figure 4, the average N_2O emissions per unit mass of milk over the past three decades were approximately 0.62×10^{-3} kg. The N_2O emission intensity reported in previous studies ranged from 0.26×10^{-3} kg to 0.39×10^{-3} kg based on the dataset of Beijing, Tianjin and Shanxi province in 2012 [29,32]. The annual N_2O emissions per unit mass of milk under intensive dairy farming highly depend on the milk yield, feed regimes, manure management, and regional climates. In Australia, Ireland and Canada, the N_2O emissions per unit mass of milk ranged from 0.25×10 kg to 0.38×10^{-3} kg [33–36]. The discrepancy could be attributed to variations in the duration of nutrition and manure management.

Annual milk yield in 2000–2009 significantly increased due to the fast growth of the dairy cow population, leading to an increase in total N_2O emissions. However, the N_2O emissions per unit yield of milk decreased because of the improvement in cow productivity and the advancement of manure and feed management. During the periods of 1990–1999, 2000–2009 and 2010–2021, the average N_2O emissions per unit mass of milk were 0.77×10^{-3} kg, 0.63×10^{-3} kg and 0.48×10^{-3} kg. As breeding techniques and milk yield improved, the emission intensity per unit mass of milk generally decreased, with notable reductions being observed in 2020 (0.43×10^{-3} kg) and 2021 (0.41×10^{-3} kg). The number of dairy cows is one of the major factors of total milk yield. Although the yield per cow increased, the population of dairy cows decreased after 2011, leading to a decrease in overall milk production. For N_2O emissions, the number of dairy cows and manure management practices are the key determinants. The expansion of the cow population in 2011 led to a rise in both manure and milk production, which in turn increased the N_2O emissions.

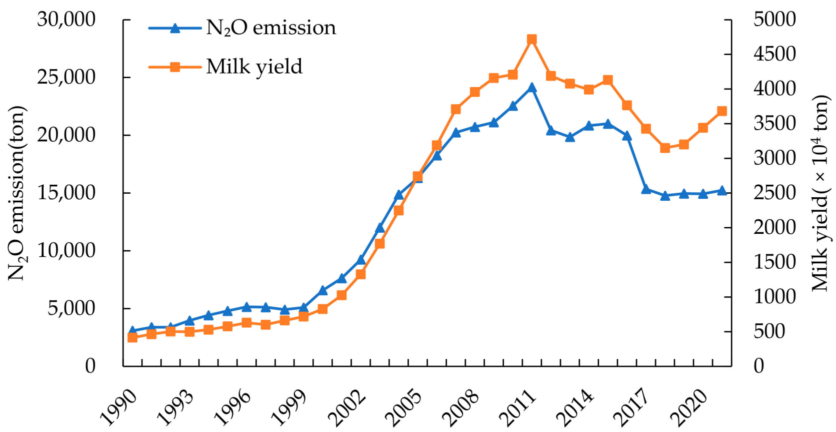

Figure 4. Annual milk yield and annual N_2O emissions in China.

3.2. N_2O Emission Factor (EF)

3.2.1. National and Regional N_2O EFs

At the national level, the average EF of total N_2O from dairy manure management during 1990–2021 was approximately 0.021 kg N_2O-N (kg N)$^{-1}$ and the EF of direct N_2O emissions was 0.014 kg N_2O-N (kg N)$^{-1}$. At the regional level, the average N_2O EF of NE was 0.022 kg N_2O-N (kg N)$^{-1}$ in 2010–2021, higher than that of NC and EC. The N_2O EF of CS was comparatively lower, and was highly correlated with the farm scales and manure management. The provincial GHG inventory guideline of China reports that the N_2O EF of dairy manure management across regions ranges from 0.011 to 0.021 kg N_2O-N (kg N)$^{-1}$, involving both direct and indirect N_2O emissions. The results of this study aligned well with the recommended range of EFs in the guidelines [24].

3.2.2. Analysis of N_2O EF

EF is one of the most critical parameters of calculating N_2O emissions and its intensity from dairy manure management. Many studies have been conducted in European and American countries to obtain the localized N_2O EF, such as Germany, the Netherlands, the United Kingdom and Denmark. Their N_2O EFs ranged from 0.011 to 0.025 kg N_2O-N (kg N)$^{-1}$ [8,37–41]. Factors on N_2O emissions during manure management are multifaceted and region-specific, including feeding, the design and operation of manure management systems, and the prevailing climatic conditions [28]. Although there are many driving factors, the N_2O EFs of different countries and regions were generally maintained at a stable level.

Hebei, as one of the dominant provinces of dairy farming in China, is representative in terms of feeding and manure management. According to a study conducted in 2017, the estimated N_2O EF for dairy manure in Hebei province was 0.013 kg N_2O-N (kg N)$^{-1}$ based on local research and literature data. Additionally, the direct EF of manure management was 0.009 kg N_2O-N (kg N)$^{-1}$ [18]. The discrepancies with the results presented in the current study could possibly be because different methodologies (Tier 1 and Tier 2) were used for N_2O emission estimation. The Guidelines for the Preparation of Provincial Greenhouse Gas Inventories (Trial), introduced in 2011, set the EF for the manure management process of dairy cows to 0.017 kg N_2O-N (kg N)$^{-1}$ [26]. Guidelines for accounting GHG emissions from livestock products and breeding enterprises set the N_2O EF during dairy manure management to 0.020 kg N_2O-N (kg N)$^{-1}$ [42,43], which was similar to the value estimated in this paper (0.021 kg N_2O-N (kg N)$^{-1}$).

Spatial variation was observed by considering the farm scales, feeding stages and manure management systems. Extensive local data were used to enhance the scientific validity and accuracy of the N_2O emission estimation, which is expected to be more precise than those in the literature. The differences in N_2O EF observed in this study compared to European and American countries could be caused by different manure management. For example, crop–livestock integration is commonly used in Europe and the United States, while it is not as prevalent in China. In the past, cow manure on small-scale farms in China was typically used as organic fertilizer without proper management. However, with the development of dairy farming, manure management in China has become more standardized, environmentally friendly and diversified, such as solid storage, composting and biogas fermentation. N_2O emissions from the above-mentioned manure management systems are significantly different. It was indicated that solid storage and composting can significantly increase N_2O emissions, while biogas fermentation can reduce N_2O emissions [44,45].

3.3. Uncertainty Analysis

In this paper, a range of uncertainties were considered to determine the overall uncertainty of N_2O emission estimation. The uncertainty of the dairy cow population was assumed to be 5%, and the uncertainty of nitrogen excretion and manure management systems was set to 10% according to previous studies [45]. Moreover, the uncertainty of EF for different manure management systems in China was taken as 100% [17]. The uncertainties of nitrogen loss and N_2O EF caused by volatilization were 10% and 5%, respectively, and the uncertainties of nitrogen loss and N_2O EF caused by leaching and runoff were 10% and 2.5%, respectively [13,46]. In addition, other factors affecting the uncertainty of the results, such as the number of grazing cows and seasonal differences, were not considered due to the lack of data.

The uncertainty of N_2O emissions from dairy cow manure management in China calculated by the EPF was ±20.2%. A similar uncertainty (±23.5%) was reported for GHG emission from dairy farms in Hebei province [14]. The uncertainty of GHG emissions calculated by EPF in the IPCC guidelines was ±20.0% [13]. The uncertainty of this paper is consistent with the above-mentioned studies. Canada used the Monte Carlo method to estimate N_2O emissions from dairy manure management in 2020 and found the uncertainty was ±43.0% [47]. The difference in results may be attributed to the utilization of different methods for uncertainty calculation.

Based on the uncertainties reported in this study, the upper and lower limits of N_2O emissions from dairy manure management in China in 1990–2021 were determined. Figure 5 displays the range of cumulative N_2O emissions, which fell between 330.6 to 498.1 thousand tons (equivalent to 90.3–135.9 million tons of CO_2-eq).

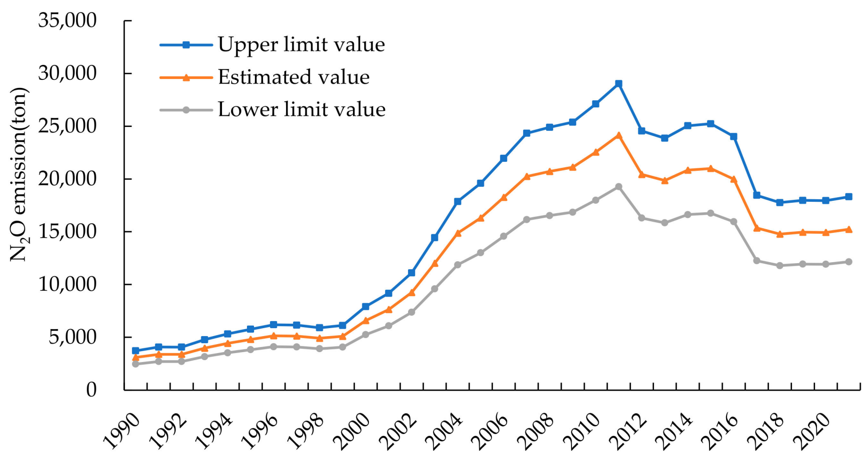

Figure 5. Estimated, upper and lower limit value of direct N_2O emission.

4. Conclusions

In this study, N_2O emissions from dairy manure management in China were estimated using the IPCC Tier 2. Localized data and recommended EFs were incorporated to improve the estimation accuracy. There is a positive correlation between the population of dairy cows and N_2O emissions from manure management. Assuming steady demand in the dairy market, an increase in milk yield per cow coupled with a reduction in the cow population would result in a corresponding decrease in N_2O emissions. In addition, the manure management system decides the intensity of the N_2O emissions. Strategies of reducing N_2O emissions during manure management process could be one of the key topics in the future. The main conclusions are as follows:

(1) During the period of 1990–2021, the cumulative N_2O emissions from dairy manure management in China were estimated to be 414.4 thousand tons (113.1 million tons of CO_2-eq), ranging from 330.6 to 498.1 thousand tons, with an uncertainty of ±20.2%. Additionally, the average annual total N_2O EF was 0.021 kg N_2O-N (kg N)$^{-1}$ and the direct N_2O EF was 0.014 kg N_2O-N (kg N)$^{-1}$.

(2) The NC, NE and NW were major sources of N_2O emissions during dairy manure management in China. These regions possess favorable conditions in terms of resources and climate, contributing to 32.3%, 18.6% and 25.8% of the total emissions, respectively. The spatial variations in N_2O emissions were mainly caused by the difference in farming technology and manure management systems across regions.

(3) Under different feeding modes, the respect proportions of total N_2O emission from manure management in small-scale and large-scale farms were 64.8% and 35.2%. Initially, small-scale farms were the major sources of N_2O emissions. However, with the development of large-scale farming, its N_2O emissions gradually increased and became the main source by 2014 (>50%).

(4) N_2O emissions per unit mass of milk was 0.77×10^{-3} kg, 0.63×10^{-3} kg and 0.48×10^{-3} kg in the periods of 1990–1999, 2000–2009 and 2010–2021. It generally decreased with the improvement in feed management and milk production efficiency.

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