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Estimation of Nitrous Oxide Emissions from Agricultural Sources and Characterization of Spatial and Temporal Changes in Anhui Province (China)

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Abstract: To evaluate the estimation and spatiotemporal variation characteristics of nitrous oxide emissions from agricultural sources in Anhui Province, the nitrous oxide emissions generated during crop cultivation and manure management were assessed based on the recommended methods in the "Guidelines for Provincial Greenhouse Gas Inventories" and official statistical data. The results showed that the overall emission of nitrous oxide from agricultural land showed a downward trend, reaching a valley value in 2019 with an emission of 2.83×10^4 tons. The annual average emissions of nitrous oxide from agricultural land and manure management account for 80.98% and 19.02% of the total annual average emissions of nitrous oxide from agricultural activities in Anhui Province, respectively. Both agricultural land emissions and livestock manure management show a trend of nitrous oxide emissions decreasing from the northern region of Anhui > central region of Anhui > southern region of Anhui. In this paper, we explored and discussed the intrinsic driving factors behind the spatiotemporal changes in nitrous oxide emissions, and analyzed the potential for future emission reductions. It is suggested that the emissions of nitrous oxide from agricultural sources can be reduced through measures such as reasonable nitrogen application, adjustment of aquaculture structures, and the improvement of manure treatment methods, providing a theoretical reference for the estimation of greenhouse gas emissions from agricultural sources.

Keywords: Anhui Province; agriculture; nitrous oxide emissions; greenhouse gases

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1. Introduction

Against the backdrop of an increasingly severe global climate, greenhouse gas emissions have become a focus of international attention [1]. Nitrous oxide (N_2O), as an important greenhouse gas, has an impact on global climate change that cannot be ignored [2], and its global warming potential (GWP) is 273 times higher than that of carbon dioxide (CO_2) on a 100-year scale [3]. Related studies have shown that agricultural activities are the main source of nitrous oxide in the atmosphere [4], with a contribution of more than 70%. According to the Intergovernmental Panel on Climate Change (IPCC) report, two-thirds of nitrous oxide emissions come from the use of agricultural nitrogen fertilizers and manure organic fertilizers [5], which account for 84% of anthropogenic N_2O emissions [6].

At present, the global annual application of nitrogen fertilizers to farmland is as high as 120 million tons [7], and is still showing an increasing trend year by year. However, from the perspective of nitrogen utilization efficiency, the comprehensive utilization efficiency is less than 50%. After nitrogen fertilizer is applied to the soil, a large amount of nitrogen is lost into the environment in the form of ammonia volatilization, nitrous oxide emissions, and leaching runoff [8]. Nitrous oxide enters the air to participate in photochemical reactions, destroying the ozone layer, and nitrogen deposition accelerates its emission rate, leading to soil acidification. Nitrous oxide enters the groundwater through surface runoff, etc., causing eutrophication of water bodies and imbalance in the ecosystem [9]. Therefore, controlling and reducing nitrous oxide emissions is important for controlling the balance of the ecosystem.

To reasonably and accurately estimate the greenhouse gas emissions from agricultural sources, relevant scholars have conducted research on nitrous oxide emissions. For example, Li et al. used the regional nitrogen cycling model IAP-N method to preliminarily estimate the nitrous oxide emissions from the ecosystem in Fujian Province, resulting in a value of 3.13×10^4 t [10]. Zhu et al. used the IPCC method to estimate the nitrous oxide emissions from agriculture in Jilin Province to be 4.27×10^4 t [11]. Ma et al. estimated the agricultural nitrous oxide emissions in Beijing and found that the agricultural nitrous oxide emissions in Beijing in 2019 were 2.61×10^6 t CO_2 [12]. Yang et al. found that the agricultural greenhouse gas emissions in Anhui Province remained at a level of 3×10^3 tons through their study on the characteristics of agricultural greenhouse gas emissions in Anhui Province [13]. Bai et al. studied the N_2O emissions from farmland soil in North China, and concluded that the fluxes of N_2O emissions from maize in summer were much higher than those from wheat in winter [14]. However, N_2O emissions naturally show large differences between different provinces and regions; due to great differences in soil and climate, there are naturally significant variations in nitrous oxide emissions. The National Development and Reform Commission (NDRC) issued the "Guidelines for the Preparation of Provincial Greenhouse Gas Inventories (for Trial Implementation)" [15] in 2011, which attracted much attention in the agricultural environment field and in society as a whole upon its promulgation.

In this work, we take the 2013 N_2O emissions from agricultural sources in Anhui Province as the base year, estimate the N_2O emissions from agricultural sources in Anhui Province in the past 10 years (2013–2022) by combining emission factors and N_2O emission models based on the standard parameters, coefficients, and factors stipulated in the "Guidelines for the Preparation of Provincial Greenhouse Gas Inventories (for Trial Implementation)", and draw a trend chart of the changes in N_2O emissions and analyze various factors affecting the N_2O emissions. Nitrous oxide emission is analyzed in the light of these changes, aiming to provide a basis for reducing nitrous oxide emissions from agricultural sources, and can also serve as a theoretical reference for estimating greenhouse gas emissions from agricultural sources.

2. Research Methodology and Rationale

2.1. Overview of the Study Area

Anhui Province is a typical agricultural and grain-producing province, located in the hinterland of East China, adjacent to the river near the sea. The total land area of the province is about 1.4×10^5 square kilometers, including more than 5.87×10^4 square kilometers [16]. The agricultural climate conditions are suitable, with an average annual temperature of 14–17 °C and an annual rainfall of 700–1700 mm. The planting area of perennial crops exceeds 8.7×10^4 square kilometers, of which the area of grain crops accounts for more than 75%, ranking fourth in the country. Anhui has distinct regional characteristics and is divided into three regions. There are six prefecture-level cities in the north, including Fuyang, Huainan, Huaibei, Bengbu, Bozhou, and Suzhou; in central Anhui, there are mainly four prefecture-level cities, including Hefei (including Chao hu), Anqing, Chuzhou, and Lu'an; and to the south of Anhui, there are six prefecture-level cities, including Wuhu, Ma'anshan, Tongling, Mount Huangshan, Chizhou, and Xuancheng. In addition, Anhui Province is a prominent hub for animal husbandry in China. In 2022, the province had a total of 1.067×10^6 cattle, 1.6558×10^7 pigs, 6.3575×10^6 sheep, and 3.22842×10^8 poultry. Figure 1 shows the changes in the numbers of several farmed animals from 2013 to 2022, with poultry having the highest number of farmed animals (the data were sourced from the annual statistical yearbooks of Anhui Province).

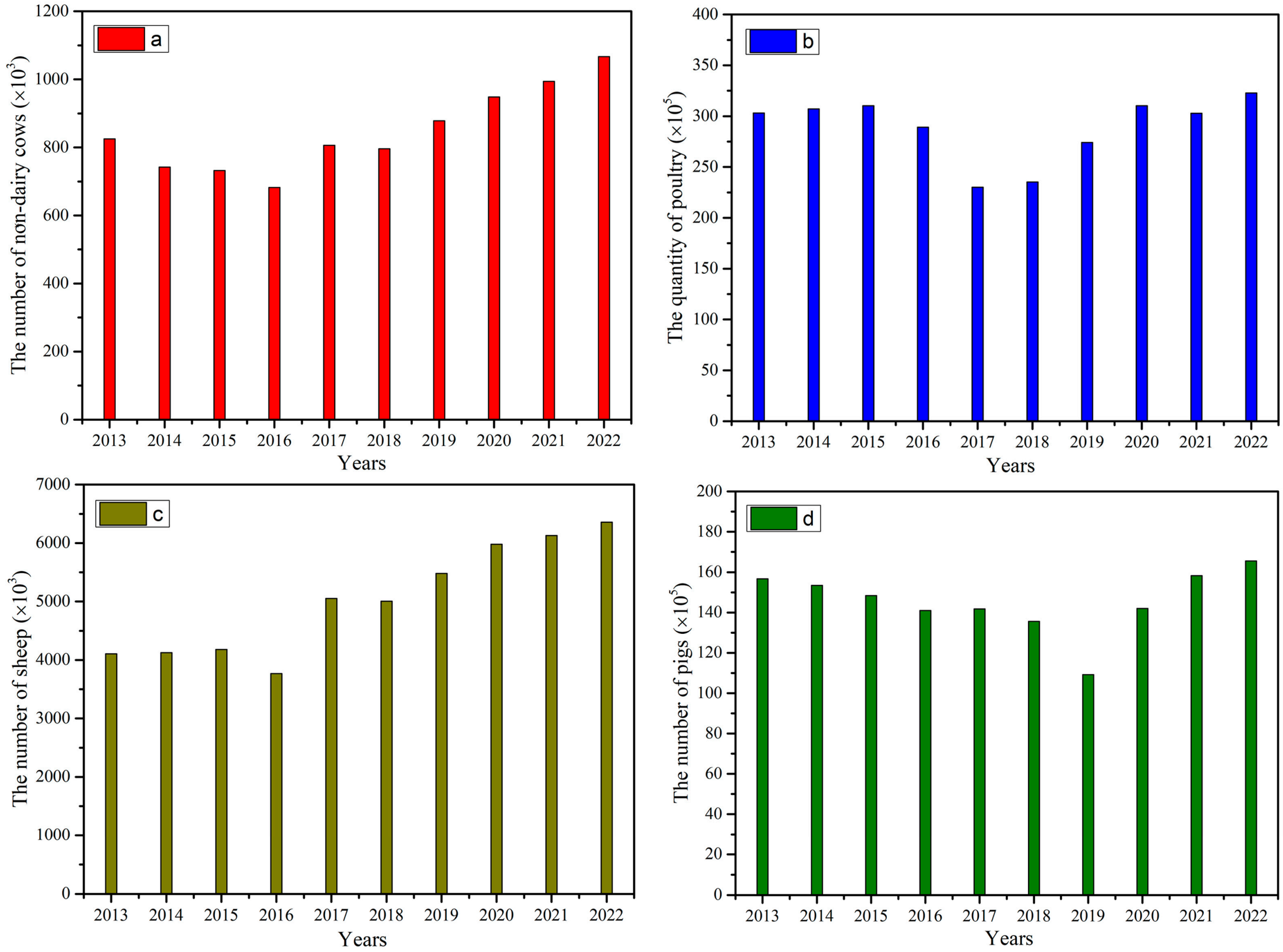

Figure 1. Changes in the number of farmed animals: (**a**) for non-dairy cows ($\times 10^3$), (**b**) for poultry ($\times 10^5$), (**c**) for sheep ($\times 10^3$), and (**d**) for pigs ($\times 10^5$).

2.2. Principles of Agricultural Nitrous Oxide Emissions

Ammonia oxidation, nitrifying bacteria denitrification, nitrite oxidation, heterotrophic denitrification, anaerobic ammonia oxidation, and nitrate reduction to ammonium (DNRA, or nitrate ammonification) are the main pathways for the production and consumption of nitrous oxide, each regulated by different microorganisms (Figure 2) [17]. The main sources of nitrous oxide emissions in soil are nitrification-related pathways (including ammonia oxidation and nitrifying bacterial denitrification) and heterotrophic denitrification [18].

Heterotrophic denitrification is considered the main respiratory process of microorganisms [19]. It is accomplished by multiple bacteria in multiple steps, reducing N (NO_3^- and NO_2^-) to the gaseous products NO, N_2O, and N_2 under limited oxygen conditions.

Nitrification is the aerobic oxidation of ammonium through nitrite ($NH_4^+ \rightarrow NH_2OH/HNO \rightarrow NO_2^- \rightarrow NO_3^-$) to nitrate, which is carried out by a specialized prokaryotic organism. The first step ($NH_4^+ \rightarrow NH_2OH/HNO \rightarrow NO_2^-$) is oxidation, catalyzed by the amoA gene of oxygenase (AMO). The second step ($NO_2^- \rightarrow NO_3^-$) is regulated by the nxrB gene of nitrite oxidoreductase in nitrite-oxidizing bacteria (NOB). The oxidation of NH_4^+ is considered the rate-limiting step in the entire nitrification process and plays an important role in the rate of nitrification reaction [20]. It is estimated that this process can account for over 80% of nitrous oxide emissions. The specific values are influenced by the type of soil ecosystem, temperature regulation, and water content balance.

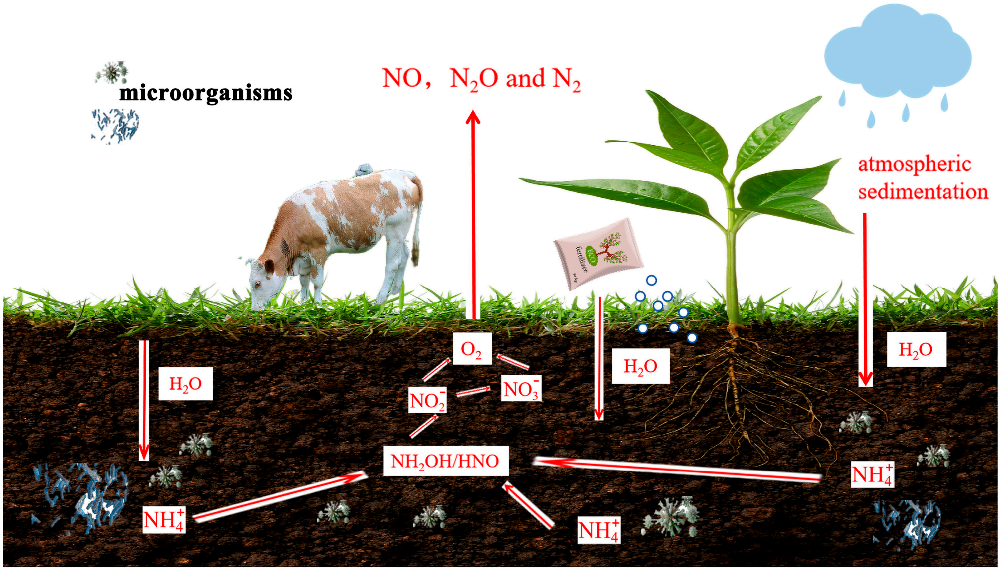

Figure 2. Mechanism diagram of nitrous oxide-emissions from agricultural sources [21].

2.3. Methodology and Data Sources

2.3.1. Nitrous Oxide Emissions from Agricultural Land

Direct Emissions

According to the "Guidelines for Compilation of Provincial Greenhouse Gas Inventories (Trial)" [15] (the same below), the main sources of direct nitrogen emissions are as follows: fertilizer nitrogen (denoted by "$N_{fertilizer}$"), manure nitrogen (denoted by "N_{manure}"), and straw returning nitrogen (denoted by "N_{straw}"), while EF_{direct} is the nitrous oxide emission factor from agricultural land. According to Equations (1)–(4), the direct emissions of nitrous oxide from agricultural land can be calculated. The caliber of the calculation of the rural population was finalized after consulting the Anhui Provincial Bureau of Statistics and other relevant departments.

$$N_2O_{direct} = (N_{manure} + N_{fertilizer} + N_{straw}) \times EF_{direct} \tag{1}$$

$$\begin{aligned} N_{manure} = {} & (\text{total N excretion of livestock and poultry} + \text{total excretion of rural population}) \times \\ & [1 - \text{leaching runoff loss rate}(15\%) - \text{volatilization loss rate}(20\%)] \\ & - N_2O \text{ livestock and poultry manure emissions} \end{aligned} \tag{2}$$

$$\begin{aligned} N_{straw} = {} & (\text{grain yield}/\text{economic coefficient} - \text{grain yield}) \times \text{dry weight ratio} \times \text{Straw returning rate} \times \\ & \text{straw nitrogen content} + \text{grain yield}/\text{economic coefficient} \times \text{root shoot ratio} \times \text{dry weight ratio} \times \text{straw nitrogen content} \end{aligned} \tag{3}$$

$$\text{Rural population} = \text{Permanent population} \times (1 - \text{Urbanization rate}) \tag{4}$$

Indirect Emissions

Indirect emissions of nitrous oxide result from atmospheric nitrogen deposition. They are mainly derived from the volatilization of NH_3 and NO_X from the agricultural excretion of nitrogen (including the excretion of nitrogen from livestock and poultry manure and the excretion of nitrogen from the rural population (denoted by "$N_{agricultural\ excretion}$") and nitrogen inputs from agricultural land (denoted by "N_{input}"). The emission factor of 0.01 was used, and the formula was calculated as follows [15]:

$$N_2O_{deposition} = (N_{agricultural\ excretion} \times 20\% + N_{input} \times 10\%) \times 0.01 \tag{5}$$

Nitrous oxide emissions due to losses from nitrogen leaching from agricultural land and runoff were calculated using Equation (6) below (the amount of nitrogen lost from this action was determined by estimating 20% of the total nitrogen input to the agricultural land).

$$N_2O_{leaching\ runoff} = N_{input} \times 20\% \times 0.0075 \tag{6}$$

Total Emissions

Total nitrous oxide emissions are equal to the nitrogen input to each emission process multiplied by its corresponding nitrous oxide emission factor [15].

$$E_{N_2O} = \sum (N_{input} \times EF) \tag{7}$$

2.3.2. Nitrous Oxide Emissions from Animal Manure

The formula for calculating nitrous oxide emissions from specific animal manure management is shown in Equation (8) [15].

$$E_{N_2O,manure,i} = EF_{N_2O,manure,i} \times AP_i \times 10^{-7} \tag{8}$$

In the formula, $E_{N_2O,manure,i}$ represents the nitrous oxide emissions from animal manure management for the i-th species, unit: 1×10^4 tons of N_2O/year; $EF_{N_2O,manure,i}$ is the management of nitrous oxide emission factors for specific population feces, unit: kg/head/year; and AP_i is the number of animals of species i in head.

2.3.3. Activity Level Data Sources Identified

To determine the activity level of nitrous oxide emissions from agricultural land, the direct and indirect emissions of N_2O from agricultural land were obtained by certain calculations from the effects of fertilizer N, manure N, straw return N, and N leaching runoff from agricultural land. The original calculation data were derived from the Anhui Statistical Yearbooks of past years. Fertilizer nitrogen covers nitrogen fertilizers and compound fertilizers in the nitrogen component, after reviewing the relevant literature and historical empirical data [11,22,23]. By analyzing the actual use of compound fertilizers in farming in Anhui Province, the compound fertilizer nitrogen element is analyzed; for the conversion of pure calculation of nitrogen content, the value of the purity rate is 15%. Since the annual average nitrogen contribution of the rural population and the direct straw return rate are not fully reflected in the statistical yearbook of Anhui Province, this article refers to the value of such research in Fujian Province [10], and the annual average nitrogen contribution of the rural population is 5.4 kg/year/person and the direct straw return rate is 0.171.

Activity level data on nitrous oxide emissions from animal manure management: The values of nitrogen excretion by different animals are shown in Table 1.

Table 1. Nitrogen excretion by different animals (kg/head/year) [15].

Wildlife	Non-Dairy Cows	Milk Cows	Poultry	Goats	Hogs	Others
Nitrogen excretion	40	60	0.6	12	16	40

2.4. Determination of Emission Factors

The determination of emission factors was achieved through a series of scientific methods and models to quantify the greenhouse gas emissions generated by a certain activity or process. The emission factor refers to a representative value that links the quantity of pollutants emitted into the atmosphere to the activities that produce those pollutants.

The determination of nitrous oxide emission factors from agricultural land is shown in Formula (1). This paper followed the average values of emission factors recommended in the Guidelines for the Preparation of Provincial Greenhouse Gas Inventories (for Trial Implementation) as the core calculation scale to ensure the accuracy and uniformity of the data [15]. In Anhui Province, the direct N_2O emission factor is 0.0109, with a range of 0.0026~0.022, while the N_2O emission factor caused by atmospheric nitrogen deposition is 0.0100, and the N_2O emission factor caused by nitrogen leaching and runoff loss is 0.0075.

The emission factors in Formula (8) were selected based on the nitrous oxide emission factors from animal manure management, as shown in Table 2.

Table 2. Nitrous oxide emission factors for manure management (kg/head/year) [15].

Prefecture or County (Area Administered by a Prefecture-Level City or County-Level City)	Non-Dairy Cows	Ovine	Goats	Hogs	Poultry
Eastern China	0.846	0.113	0.113	0.175	0.007

3. Result Analysis and Discussion

3.1. Time-Varying Characteristics of Nitrous Oxide Emissions from Agricultural Sources in Anhui Province

3.1.1. Characteristics of Temporal Changes in Nitrous Oxide Emissions from Agricultural Sources

Figure 3 shows the changes in nitrous oxide emissions from agricultural sources in Anhui Province over the years from 2013 to 2022. From a general point of view, the total amount of nitrous oxide emissions from agricultural sources in Anhui Province shows a trend of first decreasing and then slowly increasing. From a quantitative point of view, the total amount of nitrous oxide emissions from agricultural sources in Anhui Province decreased from 3.36×10^4 t in 2013 to 2.83×10^4 t in 2019, with a decrease of 0.53×10^4 t, or 15.8%. From the following figure, it can be clearly seen that agricultural land is the key emission source of nitrous oxide from agricultural sources in Anhui Province, the average annual share of agricultural land emissions is 80.98%, and the average annual share of manure management emissions is 19.02%. The average annual emissions of nitrous oxide from agricultural land in Anhui Province from 2013 to 2022 are 2.49×10^4 t/a, and the emissions from agricultural land in 2022 are 2.27×10^4 t, decreased by 0.50×10^4 t compared with 2013; the average emissions of nitrous oxide from livestock and poultry manure management are 0.58×10^4 t/a, the emissions in 2013 are 0.60×10^4 t, and the emissions in 2022 are 0.68×10^4 t, with an increase of 12.5%.

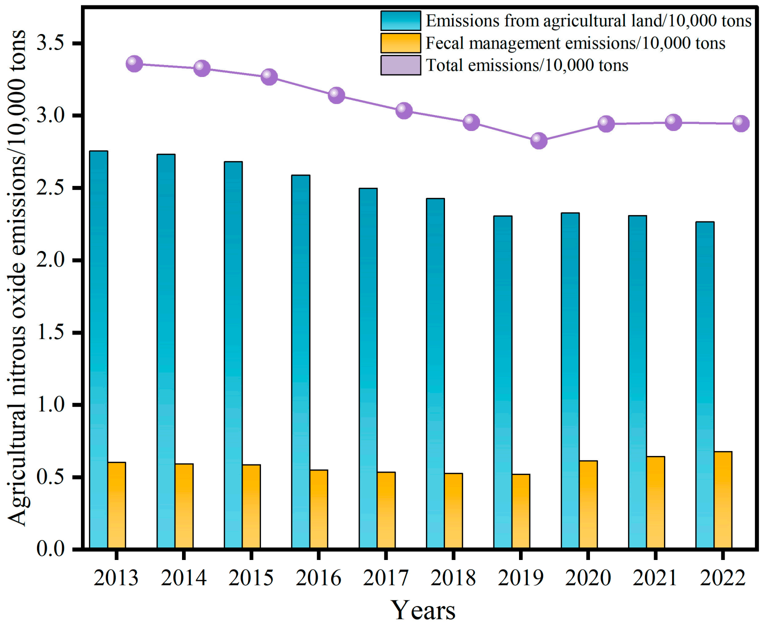

Figure 3. Historical changes in nitrous oxide emissions from agricultural activities in Anhui Province.

3.1.2. Characteristics of Temporal Changes in Nitrous Oxide Emissions from Agricultural Land

The dynamic trend of direct and indirect nitrous oxide emissions from agricultural land in Anhui Province is shown in Figure 4. It can be seen that the direct and indirect emissions of nitrous oxide from agricultural land show a decreasing trend year by year over time until 2019, when the emissions reached the lowest level of the calendar year, and then showed an increasing and then decreasing trend year by year, but the overall fluctuation is not large.

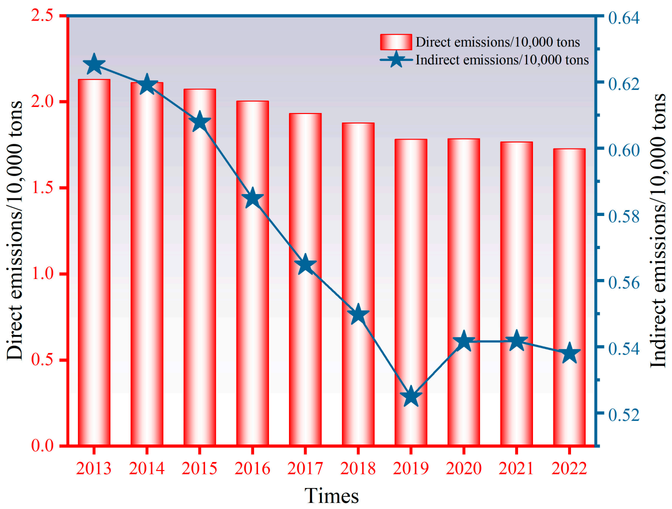

Figure 4. Annual emissions of nitrous oxide from agricultural land in Anhui Province.

The specific values of nitrous oxide emissions from agricultural land in Anhui Province are shown in Table 3 below. In 2013, the total amount of nitrous oxide emissions from agricultural land in Anhui Province was 2.76×104 t, of which the direct emissions were 2.13×10^4 t (accounting for 77.17% of the total emissions), and the indirect emissions were 0.63×10^4 t (accounting for 22.83%); in 2019, the total amount of nitrous oxide emissions from agricultural land in Anhui Province was 2.31×104 t, of which the direct emissions of nitrous oxide were 1.78×10^4 t (accounting for 77.06%) and the indirect emissions were 0.52×10^4 t (accounting for 22.51%). Due to the continuous reduction in agricultural fertilizer nitrogen application in Anhui Province from 2013 to 2019, agricultural nitrous oxide emissions decreased year by year [16]. The total amount of nitrous oxide emissions from agricultural land in Anhui Province in 2022 was 2.26×104 t, of which the direct emissions of nitrous oxide were 1.73×10^4 t (accounting for 76.55%) and the indirect emissions were 0.54×10^4 t (accounting for 23.89%).

Table 3. Nitrous oxide emissions from agricultural land in Anhui Province, 2013–2022.

Particular Year	Direct Emissions/10,000 t			Indirect Emissions/10,000 t		Emissions from Agricultural Land/10,000 t
	Fertilizer Nitrogen	Manure Nitrogen	Straw Nitrogen	Atmospheric Deposition	Runoff	
2013	1.50	0.48	0.16	0.33	0.29	2.76
2014	1.48	0.47	0.16	0.33	0.29	2.73
2015	1.44	0.46	0.17	0.32	0.29	2.68
2016	1.40	0.44	0.16	0.31	0.28	2.59
2017	1.35	0.42	0.16	0.30	0.27	2.50
2018	1.30	0.42	0.16	0.29	0.26	2.43
2019	1.22	0.41	0.16	0.28	0.25	2.31
2020	1.17	0.46	0.16	0.30	0.25	2.33
2021	1.13	0.48	0.16	0.30	0.24	2.31
2022	1.07	0.50	0.16	0.30	0.24	2.26

3.1.3. Characterization of Temporal Changes in Nitrous Oxide Emissions from Animal Manure Management

The nitrous oxide emissions from major animal manure management over the years are shown in Figure 5. From the year-to-year trend, the nitrous oxide emissions of major animals all showed a trend of decreasing and then increasing. Among them, the emission of nitrous oxide from the manure management of non-dairy cattle decreased from 0.07×10^4 t in 2013 to 0.06×10^4 t in 2016, with a decrease of 14.29%; the emission of nitrous oxide from the manure management of non-dairy cattle in 2022 was 0.09×10^4 t, with an increase of 28.6% compared with that of 2013; the emission of nitrous oxide from the manure management of sheep decreased from $0.05 \times 10\ 10^4$ t to 0.04×10^4 t in 2016, and by 2022, the nitrous oxide emissions from manure management of sheep were 0.07×10^4 t, an increase of 40% compared to 2013; the nitrous oxide emissions from the manure management of poultry reached its lowest level in 2017, with an emission of 0.16×10^4 t, which is not a significant performance in terms of the overall trend of change; and for the nitrous oxide emissions from swine manure management in 2013–2019, nitrous oxide emissions decreased from 0.27×10^4 t to 0.19×10^4 t, a decrease of 29.63%, and in 2022, nitrous oxide emissions from swine manure management increased to 0.29×10^4 t, an increase of 7.4% compared to 2013. In terms of animal species, the largest nitrous oxide emissions are from sheep and the smallest are from poultry.

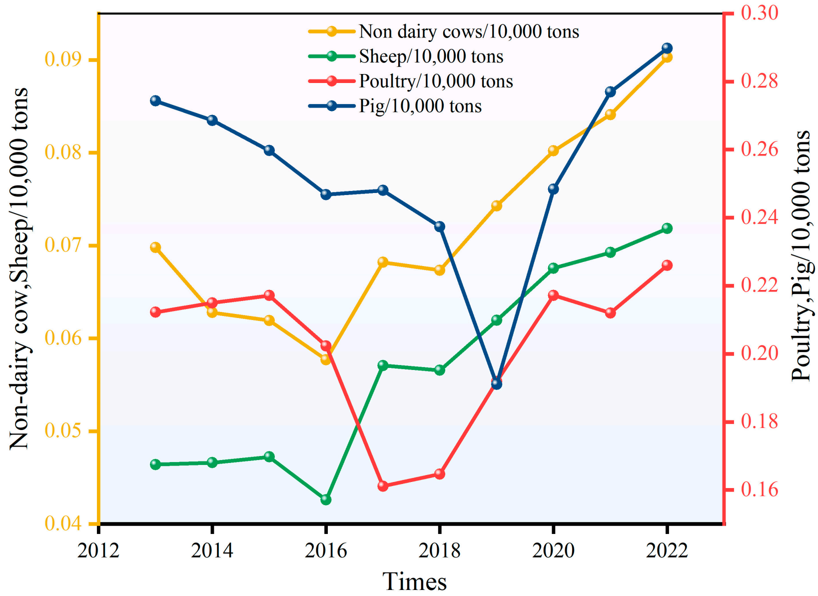

Figure 5. Annual emissions of nitrous oxide from animal fecal management.

3.2. Characteristics of Spatial Changes in Nitrous Oxide Emissions from Agricultural Sources in Some Areas of Anhui Province

The statistical results of the total nitrous oxide emissions from agricultural land and livestock manure management at some prefecture-level cities in Anhui Province from 2013 to 2022 are shown in Figure 6. Anhui Province is divided into north and south regions, with the Huaihe River as the boundary. In order to analyze and compare the differences in nitrous oxide emissions from agricultural sources between different regions, this article selected eight prefecture-level cities in central, southern, and northern Anhui as the research objects, in which Fuyang City and Suzhou City were selected as the representatives of northern Anhui; Wuhu City, Anqing City, and Mount Huangshan City as the representatives of southern Anhui (considering the balance of the distribution of the selected prefecture-level cities, Anqing City takes into account many characteristics of southern Anhui, and analyzes them as the representatives of southern Anhui); and Hefei City, Chuzhou City, and Lu'an City are the representatives of central Anhui. From the figure below, it can be seen that there are certain differences in nitrous oxide emissions from agricultural land in the north and south of Anhui Province due to factors such as geographical location, economy, and environment. The area with the largest amount of agricultural land emissions in 2014 was Lu'an City in central Anhui Province, with = agricultural land emissions of 0.35×10^4 tons; the emissions from livestock and poultry manure management were mainly concentrated in the northern Anhui region, such as Fuyang City and Suzhou City. In 2014, the emissions of nitrous oxide from livestock and poultry manure management reached 0.11×10^4 t and 0.12×10^4 t, respectively. In 2018 and 2020, emissions in various regions significantly decreased. According to the statistical yearbook data of Anhui Province over the years, the geographical environment in southern Anhui is superior, suitable for multiseason crop growth, and requires a large amount of fertilizer. Some cities in the central Anhui region, such as Chuzhou City, have a relatively large proportion of rice planting area, and the amount of irrigation water also has a certain impact on the emission of nitrous oxide. However, in the northern Anhui region (such as Fuyang City), there are a large number of animal farms, and the estimated emissions from the management of livestock and poultry manure are relatively high. Therefore, there is a significant difference in nitrous oxide emissions between the central, southern, and northern regions of Anhui.

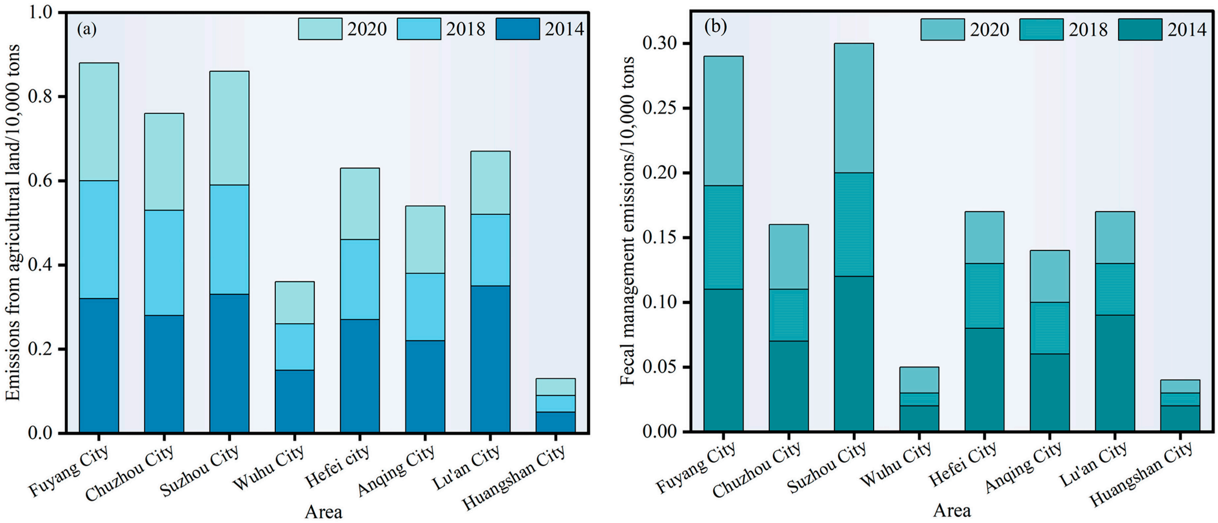

Figure 6. Statistical chart of nitrous oxide emissions from agricultural land at some prefecture-level cities in Anhui Province (**a**) and nitrous oxide emissions from livestock and poultry manure management (**b**).

In order to more intuitively analyze the characteristics of nitrous oxide emissions from agricultural activities, the article analyzes the nitrous oxide emissions from agricultural land and animal manure management in each region in 2014 and 2020, and the comparison is shown in Figure 7. For nitrous oxide emissions from animal manure management and nitrous oxide emissions from agricultural land, the contribution rate of nitrous oxide emissions was the largest in northern Anhui in the 2 years, followed by central Anhui, with southern Anhui being the smallest. Comparing 2014 and 2020, in terms of nitrous oxide emissions from animal manure management, the contribution rate of the northern Anhui region decreased from 40% to 33.3%, the contribution rate of the central Anhui region decreased from 26.7% to 13.3%, and the contribution rate of the southern Anhui region basically remained stable; in terms of nitrous oxide emissions from agricultural land, the contribution rate of the northern Anhui region decreased from 36.1% to 30.8%, the contribution rate of the central Anhui region decreased from 32.9% to 20.4%, and the contribution rate of the southern Anhui region decreased from 15.4% to 11%.

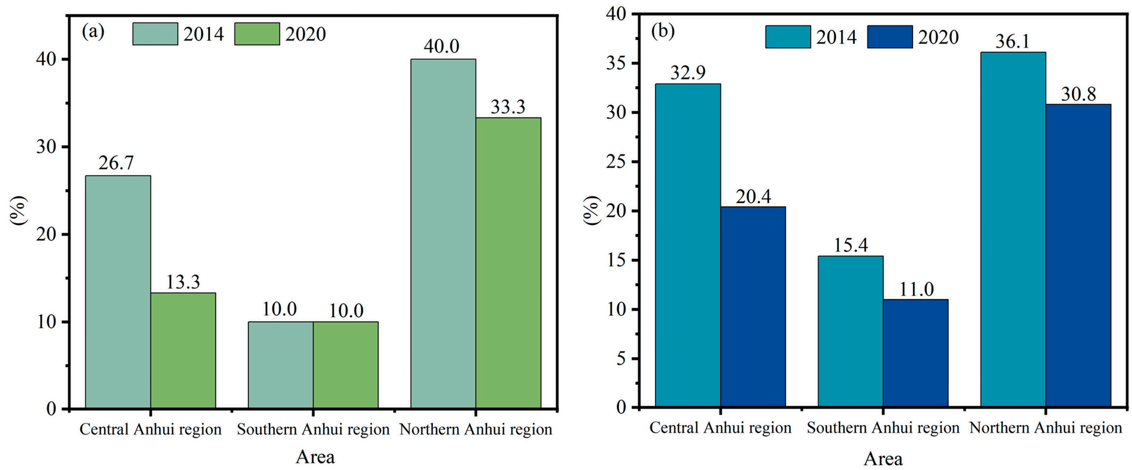

Figure 7. Contribution of animal manure management (**a**) and agricultural land (**b**) to nitrous oxide emissions in some prefecture-level cities of Anhui Province in 2014 and 2022.

3.3. Discussion

This study selected Anhui Province as its research object, and based on the relevant data released by the Anhui Provincial Department of Statistics, analyzed and estimated the nitrous oxide emissions from agricultural activities in Anhui Province. The results are as follows:

(1) Overall, from 2013 to 2022, the emissions of nitrous oxide from agricultural sources in Anhui Province showed a slow decrease followed by a slow increasing trend. In 2022, there was a decrease of 0.50 × 104 tons compared to 2013. Agricultural land is a key source of nitrous oxide emissions from agriculture in Anhui Province, with an average annual emission rate of 80.98%, while the average annual emission rate is 19.02% from manure management.

From the perspective of the mechanism of nitrous oxide production in agricultural land, the formation pathways of nitrous oxide in agricultural land include nitrification, denitrification (biological denitrification, chemical denitrification), and the transformation and reduction of nitrate nitrogen to ammonia. The most important ones are nitrification and denitrification, which can account for 70% to 90% of the total emissions. Therefore, controlling the emission of nitrous oxide from agricultural land mainly relies on inhibiting nitrification. The use of underground drip irrigation to improve microbial activity and the use of nitrification inhibitors to inhibit nitrifying bacteria are very effective control measures [24–27]. The amount of irrigation water also has a certain impact on the emission of nitrous oxide. In the production process, controlling the emission of nitrous oxide during irrigation and shallow water irrigation leads to lower emissions than long-term irrigation. This is because choosing controlled and shallow water irrigation can alternate nitrification and denitrification [28]. From the perspective of evaluation factors for nitrous oxide emissions from agricultural land, crops with large planting areas and high fertilizer application rates are positively correlated with nitrous oxide emissions from farmland [29]. Therefore, in order to reduce the emissions of nitrous oxide from agricultural land, emphasis should be placed on reducing fertilizer application, improving fertilizer utilization efficiency, and adjusting fertilizer structure. Researchers have pointed out that the use of the urea deep burial method produces nearly 30% less nitrous oxide emissions than the urea broadcasting method, and can increase net ecological benefits by nearly 48% [30]. In addition, using organic fertilizers and adding nitrogen fertilizer enhancers and biochar are also effective means to reduce soil nitrous oxide emissions [31,32].

(2) From a typological perspective, the emissions from agricultural land gradually decrease over time and then slowly increase again. The lowest emissions in 2019 were 2.31×10^4 t, with direct nitrous oxide emissions of 1.78×10^4 t (77.06%) and indirect emissions of 0.52 × 104 t (22.51%). The management of animal feces shows a trend of first

decreasing and then increasing nitrous oxide emissions. Compared to 2013, the nitrous oxide emissions from the animal manure management of pigs, poultry, non-dairy cows, and sheep increased by 7.4%, 9.5%, 28.6%, and 40%, respectively, in 2022.

The nitrous oxide emissions in livestock and poultry manure management mainly come from the nitrification and denitrification processes under the composting state of early storage and treatment. From the perspective of livestock and poultry species, the nitrogen content in the excrement of different types of livestock and poultry varies greatly, resulting in significant differences in emissions. The annual nitrogen excretions per head of cows, non-dairy cows, goats, and pigs are 60–100 kg, 40–70 kg, 12–20 kg, and 16–20 kg, respectively [33]. Therefore, adjusting the breeding structure appropriately and selecting livestock and poultry with low emission factors is obviously more conducive to reducing nitrous oxide emissions. Starting from the perspective of production mechanisms, changing the storage environment and processing methods is also an effective means to reduce nitrous oxide emissions. The research results of Zhou et al. [34] indicate that the emission of nitrous oxide from stored feces under anaerobic conditions is much lower than that under fixed storage and grazing conditions.

(3) From a spatial perspective, the area with the largest amount of agricultural land emissions is Lu'an City in central Anhui Province, with an emission of 0.35×10^4 tons; the emissions of livestock and poultry manure management are mainly concentrated in the northern Anhui region, with Fuyang City and Suzhou City achieving 0.11×10^4 t and 0.12×10^4 t, respectively, in 2014. In 2018 and 2020, emissions in various regions significantly decreased.

Therefore, selecting planting and breeding models that are suitable for local conditions and developing effective management measures are key to reducing emissions. The management and utilization of livestock and poultry manure should be strengthened, and the adoption of composting, biogas, and other treatment methods to reduce direct emissions. Exploring the integration of planting and breeding, and implementing the return of livestock and poultry manure to the field, are also important safeguarding measures for controlling greenhouse gas emissions [35,36].

4. Conclusions

This study sampled the methods recommended in the "Guidelines for Provincial Greenhouse Gas Inventories" and combined them with relevant data released by the statistical department of Anhui Province over the past 10 years to analyze and estimate the nitrous oxide emissions from agricultural activities in Anhui Province. Overall, from 2013 to 2022, the emissions of nitrous oxide from agricultural sources in Anhui Province showed a slow decrease followed by a slow increasing trend. In 2022, there was a decrease of 0.50×10^4 tons compared to 2013. Compared to 2013, the nitrous oxide emissions from the animal manure management of pigs, poultry, non-dairy cows, and sheep increased by 7.4%, 9.5%, 28.6%, and 40%, respectively, in 2022. The emissions from agricultural land significantly decreased in all regions in 2018 and 2020. From the perspective of crop management, rational nitrogen application is key, including inhibiting fertilizer nitrification and controlling fertilizer application time. Adjusting the livestock and poultry manure management structure appropriately is an effective low-carbon measure. A new agricultural model that combines planting and breeding to scientifically control nitrous oxide emissions should be explored.

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