

Article

# The Role of Soil N<sub>2</sub>O Emissions in Agricultural Green Total Factor Productivity: An Empirical Study from China around 2006 when Agricultural Tax Was Abolished

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**Abstract:** The decision in 2006 to abolish the agricultural tax, which had lasted for thousands of years, contributed to the prosperity of agriculture, and with it the growing importance of soil N<sub>2</sub>O emissions in China. However, most of the previous literature ignored soil N<sub>2</sub>O emissions due to their too small share in total agricultural greenhouse gas (GHG) emissions. This paper attempts to take soil N<sub>2</sub>O emissions as an important variable in the measurement of agricultural green total factor productivity (AGTFP), which incorporates environmental pollution into the analytical framework of agricultural production efficiency. Three impressive results were found. Firstly, soil N<sub>2</sub>O emissions play an increasingly important role in agricultural GHG emissions. The proportion of soil N<sub>2</sub>O emissions in agricultural GHG emissions increased from 4.52% in 1998 to 4.83% in 2006, and then to 5.36% in 2016. Secondly, the regional difference of soil N<sub>2</sub>O emissions in AGTFP is visible. In 2016, although soil N<sub>2</sub>O emissions accounted for a small proportion (about 5%) of the total agricultural GHG emissions in China, the AGTFP including soil N<sub>2</sub>O emissions was much lower than that excluding soil N<sub>2</sub>O emissions, especially in areas with high agricultural and population density. Finally, over time, soil N<sub>2</sub>O emissions have had an increasing effect on AGTFP. Compared with 1998–2006, the impact of excluding soil N<sub>2</sub>O emissions on AGTFP in 2007–2016 was more evident than that including soil N<sub>2</sub>O emissions.

**Keywords:** soil N<sub>2</sub>O emissions; greenhouse gas (GHG) emissions; agricultural green total factor productivity (AGTFP); traditional agricultural total factor productivity (TATFP)

## 1. Introduction

The prosperity and development of agriculture in China has entered a new stage since the abolition, in 2006, of the agricultural tax, which had lasted for two thousand years. [1]. According to the National Bureau of Statistics of China, the total real value of China's agriculture was 3.636 trillion yuan in 2005 and reached 5.856 trillion yuan in 2016, an increase of 61.06% [2]. In the process of China's transformation from a big agricultural country to a power agricultural country, pollution generated by the development of agriculture has, in addition to industrial pollution and its impact on health, become one of the social concerns [3–7]. As a result, a high number of studies on agricultural pollution have

appeared [8,9]. Developing low-carbon agriculture (which refers to agriculture with high efficiency, low energy consumption, and low emissions) is not only a necessary step for China to meet its commitment to reduce emissions in response to climate change but also a necessary means to ultimately achieve sustainable development of agriculture. Therefore, it is of considerable significance to analyze greenhouse gas (GHG) emissions from agricultural production and their impact on agricultural total factor productivity.

Total factor productivity (TFP), which is generally regarded as an essential indicator of scientific and technological progress, refers to the part where the output growth rate of factors exceeds the input growth rate. TFP is usually caused by technological development, organizational innovation, specialization and production innovation, and so on [10]. In recent years, there have been many types of research on agricultural TFP. These can be sorted into the following three types according to their calculation methods. The first type of accounting method was adopted in most of the earlier studies. Some researchers used the algebraic exponential method to discuss agricultural productivity [11,12], while other scholars took the Solow residual value [13,14]. In the second type, data envelopment analysis (DEA) was often applied to analyze changes in agricultural productivity of China. This can cope with multiple input–output factors, facilitating the dismantling of agricultural productivity, and revealing the internal motive force of agricultural productivity growth [15–17]. The third method is stochastic frontier analysis (SFA), which can be grouped with the parametric and non-parametric methods, based on a specific form of production function or can consist of the stochastic frontier method and deterministic frontier method [18,19]. However, the gross agricultural product was used as the output variable in the calculation of agricultural production efficiency, and the cultivated area, agricultural machinery, chemical fertilizer, and labor force in rural were used as input variables in the articles above, ignoring the non-point source pollution problems caused by agricultural production, such as the residues of chemical fertilizers and pesticides, and the emissions of livestock and poultry feces. In the actual production process, the production unit often inevitably produces some non-desired or “bad” output, such as pollution, in addition to the desired “good” output. How to deal with the non-expected output becomes the key to the scientific measurement of agricultural production efficiency. Agricultural green total factor productivity (AGTFP) brings environmental pollution into the analysis framework of agricultural production efficiency [20]. This paper adopts agricultural GHG emissions as the non-expected output to measure the AGTFP of China. Besides, better progress should be made in the selection of GHG emissions sources since it is difficult to make a breakthrough in the calculation method [21–24].

The measurement of agricultural GHG emissions sources is a critical link in the research on agricultural GHG emissions. First of all, in terms of the definition of agriculture, there is not only research on narrow agriculture [25,26], which only refers to the planting industry but also research which analyses broad agriculture, including animal husbandry [27,28]. Secondly, considering regional studies on agricultural GHG emissions, most of them take the whole country or a province as the research object [29], while studies on the heterogeneity between different regions was rare [30]. Then, for the selection of agricultural GHG emissions sources, there are not only mainstream studies that take four categories, namely, livestock breeding, rice planting, agricultural materials and straw burning, as GHG emissions sources [31,32], but also a few scholars start to include soil N<sub>2</sub>O in the GHG emissions measurement system [33,34].

Nitrous oxide (N<sub>2</sub>O), as one of the important GHG. It has a global warming potential 190–270 times that of CO<sub>2</sub> and continues to increase at a rate of 0.25% per year [35]. At the same time, N<sub>2</sub>O is a significant factor in destroying the ozone layer [36]. Therefore, N<sub>2</sub>O emissions have been widely concerned with the studies of global climate and ecological environment change. Agricultural activities are the most significant anthropogenic emission source of N<sub>2</sub>O, to which farmland soils contribute the most [37–39]. The annual N<sub>2</sub>O emissions from farmland soils account for about 42% of the total ( $6.7 \times 10^6$  t) global anthropogenic activities [40]. Taking China’s farmland soils as an example, N<sub>2</sub>O emissions in 2014 were about 1.21t, accounting for 31% of the global N<sub>2</sub>O emissions [41]. Agricultural

taxes, which had lasted for one thousand years, were abolished in 2006, and the subsidies and other incentives for agricultural arable land from the Chinese government have greatly promoted enthusiasm in agricultural production. One of the biggest effects is that soil N<sub>2</sub>O emissions, as one of the GHG emissions sources of agriculture, are becoming more and more important. In recent years, the study of soil GHG emissions has become a frontier issue. The focus of this paper is to include soil N<sub>2</sub>O emissions into the estimation of agricultural GHG and explore the role of soil N<sub>2</sub>O emissions in AGTFP.

The structure of the paper is as follows: the measurement of agricultural GHG emissions and AGTFP is discussed in detail in Section 2; the empirical results of the comparison of AGTFP, including whether soil N<sub>2</sub>O emissions can be seen or not, is discussed in Section 3; and the discussion and conclusion of empirical analysis is provided in Sections 4 and 5.

## 2. Materials and Methods

Corresponding to the previous literature review, the writing process of this paper was divided into two steps: (a) measurement of the scale and density of agricultural GHG emissions, including soil N<sub>2</sub>O emissions and (b) measurement of AGTFP including soil N<sub>2</sub>O emissions, if present.

### 2.1. Measurement of Agricultural GHG Emissions

The comprehensiveness of emission sources and the operability of measurement methods were the essential principles and the most difficult parts in the process of measuring agricultural GHG emissions. Therefore, the availability of data must be fully considered. This paper intended to make efforts in two aspects. Firstly, select livestock-breeding CH<sub>4</sub>, rice-planting CH<sub>4</sub>, straw-burning CO<sub>2</sub>, soil N<sub>2</sub>O, and agricultural materials' CO<sub>2</sub> as the sources of agricultural GHG emissions. Secondly, relevant agricultural GHG emissions calculation formulae were constructed, as shown in Formula (1).

$$E = \sum E_i = \sum Q_i * a_i \quad (1)$$

where,  $E$  represents the scale of agriculture GHG emissions (unit: 10,000 tons) and  $E_i$  represents the quantity of agriculture GHG emissions (unit: 10,000 tons) that came from different emissions sources. The amount of agriculture GHG emissions sources is represented by  $Q_i$  (unit: kg when  $i$  is agricultural materials or straw burning; unit: head when  $i$  is livestock breeding; unit: hm<sup>2</sup> when  $i$  is soil N<sub>2</sub>O; and unit: m<sup>2</sup> when  $i$  is rice planting) and  $a_i$  represents the coefficient of agriculture GHG emissions from different emissions sources. It should be noted that, due to the inconsistency of units, when GHG emissions are added up in Formula (1), CH<sub>4</sub> and N<sub>2</sub>O emissions must be converted into standard carbon emissions. According to the Intergovernmental Panel on Climate Change (IPCC) (IPCC fourth assessment report), the greenhouse effect caused by 1 t CH<sub>4</sub> and 1 t N<sub>2</sub>O is equivalent to that caused by 6.8182 t CO<sub>2</sub> and 181.2727 t CO<sub>2</sub>, respectively (1t = 1000 kg) [42]. Some scholars call this carbon emissions, but to avoid unnecessary misunderstanding, the name GHG emissions was still used in this paper.

The coefficients of different agriculture GHG emissions sources are an important part of Formula (1). The related reference data from some authoritative institutions or previous research are listed in Table 1.

**Table 1.** Different agriculture greenhouse gas (GHG) emission sources and their emission coefficients.

Source (1)	Emission Coefficients	Source (2)	Emission Coefficients	Source (3)	Emission Coefficient	Source (4)	Emission Coefficients	Source (5)	Emission Coefficients
<b>Agricultural Materials CO<sub>2</sub> (kgC/kg)</b>		<b>Straw Burning CO<sub>2</sub> (kgC/kg)</b>		<b>Livestock Breeding CH<sub>4</sub> (kg/each head)</b>		<b>Soil N<sub>2</sub>O (kg/hm<sup>2</sup>)</b>		<b>Rice Planting CH<sub>4</sub> (g/m<sup>2</sup>)</b>	
Fertilizer	0.89	Rice	0.18	Cow	84	Rice	0.24	Early rice	14.66
Pesticide	4.93	Wheat	0.16	Water buffalo	57	Winter wheat	2.05	Late rice	29.83
Mulching films	5.18	Corn	0.17	Scalpers	48.8	Spring wheat	0.4	Mid-season rice	33.25
Diesel	0.59	Rapeseed	0.22	Camel	47.92	Soybean	0.77		
Irrigation	266.48	Soybean	0.15	Horse	19.64	Corn	2.53		
		Cotton	0.13	Pig	4.5	Vegetables	4.21		

Sources: ORNL (American Oak Ridge National Laboratory, 2009), IPCC (Intergovernmental Panel on Climate Change) report. Note: This table only lists sources of relatively large amounts of pollution. hm<sup>2</sup> = hectare (ha.).

The relevant explanation of Table 1 is shown as follows.

(1) Agricultural materials: Carbon emissions from agricultural materials production fall into two main categories. First, CO<sub>2</sub> emissions produced by agricultural materials directly as inputs of fertilizers, agricultural film, or other inputs will inevitably cause carbon emissions. Carbon emissions are also caused by energy consumption, such as diesel, in agricultural activities.

(2) Straw burning: In the context of China's efforts to promote green development in recent years, the use of burning straw has been greatly reduced, but straw burning remains an important source of agricultural GHG emissions. Six major crops, including wheat, rape, or soybean, were measured as the GHG emissions sources of straw combustion [8].

(3) Livestock breeding: GHG emissions produced from livestock and poultry farming were mainly CH<sub>4</sub> and N<sub>2</sub>O. GHG production comes mainly from fecal processing and intestinal fermentation. Due to the different feeding cycles of livestock and poultry, it is necessary to properly regulate the feeding quantity in the calculation. For example, the average life cycle of pigs, rabbits, and poultry is 200 days, 105 days, and 55 days, respectively, and the feeding rate is greater than 1. According to existing research and data, the IPCC report selected the CH<sub>4</sub> and N<sub>2</sub>O emissions of the most important animals in the breeding industry to be included in the calculation system. Livestock and poultry breeding N<sub>2</sub>O emissions are not large and these are temporarily ignored in this paper.

(4) Soil N<sub>2</sub>O: N<sub>2</sub>O emissions are mainly in the soil, and tilling the soil while planting crops causes N<sub>2</sub>O from the soil to flow into the air. CO<sub>2</sub> also flows into the air when soil is turned over, but because of its small amount and the absorption of CO<sub>2</sub> for photosynthesis during the growth of crops, CO<sub>2</sub> is temporarily ignored in this paper.

(5) Rice planting: GHG emissions from rice cultivation play an important role in China's agricultural GHG emissions, mainly the production of CH<sub>4</sub>. CH<sub>4</sub> is produced in both rice cultivation and dryland crop production, but it can be ignored as dryland itself will absorb CH<sub>4</sub>, and dryland CH<sub>4</sub> emissions are low. In addition, because different rice varieties differ in CH<sub>4</sub>, the calculation of carbon emissions from rice planting needs to consider the factor of rice varieties.

## 2.2. Measurement of Agricultural Green Total Factor Productivity (AGTFP)

The measurement method of AGTFP was constructed as Formulae (2)–(7) (Table 2) by referring to [8] and [32], as illustrated in the following steps.

**Table 2.** List of measurement formulae of AGTFP.

Steps	Calculation Formulae	Numerical Order
The first step	$P(x) = \{(x, y, b) : x \text{ can produce } (y, b)\}$	Formula (2a)
	$P^G(x) = P^1(x^1) \cup P^2(x^2) \dots P^T(x^T)$	Formula (2b)
	$P^G(x) = \left\{ (x^t + y^t + b^t) : \sum_{t=1}^T \sum_{k=1}^K z_k y_{km}^t \geq y_m^t; \sum_{t=1}^T \sum_{k=1}^K z_k b_{ki}^t = b_i^t; \sum_{t=1}^T \sum_{k=1}^K z_k x_{kn}^t \leq x_n^t \right\}$	Formula (2)
The second step	$\overset{\rightarrow}{D}_0(x_k^t + y_k^t + b_k^t) = \min \frac{1 - [\frac{1}{N} \sum_{n=1}^N s_n^x / k_n^x]}{1 + [\frac{1}{M+I} (\sum_{m=1}^M s_m^y / y_m^t + \sum_{i=1}^I s_i^b / b_i^t)]}$	Formula (3)
	$x_{kn}^t = \sum_{t=1}^T \sum_{k=1}^K Z_k^t x_{kn}^t + s_n^x, n = 1, 2, \dots, N$	Formula (4)
	$y_{km}^t = \sum_{t=1}^T \sum_{k=1}^K Z_k^t y_{km}^t - s_m^y, m = 1, 2, \dots, M$	Formula (5)
	$b_{ki}^t = \sum_{t=1}^T \sum_{k=1}^K Z_k^t b_{ki}^t + s_i^b, i = 1, 2, \dots, I$	Formula (6)
The third step	$AGTFP = \frac{1 + \overset{\rightarrow}{D}_0(x^t, y^t, b^t; y^t, -b^t)}{1 + \overset{\rightarrow}{D}_0(x^{t+1}, y^{t+1}, b^{t+1}; y^{t+1}, -b^{t+1})}$ $= \frac{1 + \overset{\rightarrow}{D}_0(x^t, y^t, b^t; y^t, -b^t)}{1 + \overset{\rightarrow}{D}_0(x^{t+1}, y^{t+1}, b^{t+1}; y^{t+1}, -b^{t+1})}$ $* \frac{1 + \overset{\rightarrow}{D}_0(x^{t+1}, y^{t+1}, b^{t+1}; y^{t+1}, -b^{t+1})}{1 + \overset{\rightarrow}{D}_0(x^{t+1}, y^t, b^{t+1}; y^{t+1}, -b^{t+1})}$	Formula (7)

Firstly, the global production possibility set was designed as Formula (2), where all the provinces in China were taken as decision-making units. Here  $Z_k$  is the density variable, which represents the weight of each of  $k$  decision-making units in the construction of the environmental technical structure.  $G$  is the global benchmark, and  $T$  is the time, the input/output vector is  $(x_k^t + y_k^t + b_k^t)$ . The specific calculation process is referred to as the study of Xu et al [32]. Suppose each unit uses  $n$  kinds of input ( $x, x \in R^n_+$ ) in the production process, and obtains both  $m$  kinds of desired output ( $y, y \in R^m_+$ ) and undesired output—agricultural GHG emissions ( $b$ ), the possible production set ( $P$ ) is expressed as Formula (2a). Further, the union set of all production technology sets in the current period can be expressed as Formula (2b). Then the global production possibility set is expressed as Formula (2).

Secondly, the slacks-based measure (SBM) of directional distance function is applied to Formulae (3)–(6). The SBM directional distance function explores the effect of input and output slack variables on efficiency and can also avoid the bias of traditional radial DEA on efficiency evaluation. According to the non-radial and non-angle SBM efficiency model proposed by Tone [20], both input reduction and output increase should be considered in research. Based on Formula (3), the non-radial, non-angle SBM directional distance function, which contains an undesired output in time  $t$  of a decision-making unit,  $k'(x_k^t + y_k^t + b_k^t)$  is constructed. In Formulae (3)–(6),  $\overset{\rightarrow}{D}_0$  is the average distance between the production frontier and input/output, and represents the degree of input–output inefficiency.  $s_n^x, s_m^y$ , and  $s_i^b$  imply the relaxation variables of the input, expected output, and non-expected output, respectively, and they are all greater than or equal to 0.

Finally, the global Malmquist–Luenberger (GML) index was adopted to build the agricultural green total factor productivity index (AGTFP). It is generally acknowledged that the GML index is based on the common global frontier structure of each period, which is multiplicative and transitive. What is more, GML reflects the changes in total factor productivity, effectively eliminating the phenomenon of “technical regression” of GML index. The indexes mentioned above are reflected in Formula (7), where the variable in stage  $t+1$  is bigger than that in stage  $t$  when the index was above 1.

### 2.3. Data Source

Relevant data of 31 Chinese provinces (except Hong Kong, Macao, and Taiwan) from 1998 to 2016 were selected to calculate agricultural GHG emissions. Most of the data came from the China

Rural Statistical Yearbook, the China Agricultural Yearbook, China agricultural statistical data, and the China Animal Husbandry Yearbook. Treatment method for specific data and data sources have been mentioned above.

### 3. Results

By using the measurement method of agricultural GHG emissions, we first calculated the emissions scale and emissions intensity of each agricultural GHG emissions source in China for about ten years around 2006 and then calculated the AGTFP on this basis.

#### 3.1. Temporal Evolution of the Scale and Intensity of Agricultural GHG Emissions Including and Excluding Soil N<sub>2</sub>O Emissions

The scale and intensity of different agricultural GHG emissions sources in China from 1998 to 2016 are shown in Table 3.

**Table 3.** Scale and intensity of agricultural GHG emissions from 1998 to 2016.

Year	Agricultural Materials	Soil N <sub>2</sub> O	Rice Planting	Livestock Breeding	Straw Burning	Scale of GHG Emissions	Intensity of GHG Emissions	
							Included Soil N <sub>2</sub> O Emissions	Excluded Soil N <sub>2</sub> O Emissions
1998	7064.86	1448.61	6576.37	8878.34	8061.04	32029.22	1.23	1.17
1999	7217.29	1478.77	6256.81	9157.32	7880.17	31990.36	1.17	1.11
2000	7303.98	1486.77	6197.02	9074.69	7106.36	31168.82	1.11	1.05
2001	7515.69	1547.3	6168.34	9489.73	7187.62	31908.68	1.09	1.03
2002	7668.71	1584.2	6131.98	9660.69	7192.32	32237.9	1.04	0.99
2003	7802.36	1566.89	5836.83	10172.56	6789.99	32168.63	1	0.95
2004	8236.91	1577.7	6247.25	10727.21	7543.84	34332.91	1	0.95
2005	8496.07	1540.69	6355.9	10305.67	7785.91	34484.24	0.95	0.90
2006	8761.83	1655.55	6323.91	9518.38	8036.48	34296.15	0.89	0.84
2007	9082.56	1683.82	6294.53	7927.26	8209.13	33197.3	0.83	0.79
2008	9233.99	1712.86	6351.27	7597.17	8670.86	33566.15	0.8	0.76
2009	9501.43	1766.7	6398.97	8024.36	8749.41	34440.87	0.78	0.74
2010	9781.47	1811.73	6414.48	8227.74	8971.39	35206.81	0.77	0.73
2011	10042.18	1852.18	6427.34	8270.99	9372	35964.69	0.75	0.71
2012	10283.94	1901.7	6408.79	8379.11	9700.91	36674.45	0.73	0.69
2013	10443.84	1944.92	6417.81	8492.86	9909.37	37208.8	0.71	0.67
2014	10608.1	1978.82	6415.53	8647.39	9990.1	37639.94	0.69	0.65
2015	10680.17	2018.59	6432.36	8638.81	10227.9	37997.83	0.67	0.63
2016	10610.24	2006.77	6140.76	8529.24	10104.28	37391.29	0.65	0.61

Note: agricultural GHG intensity = total agricultural GHG emissions/agricultural output value. The total agricultural output value was adjusted according to the constant price in 1998. The unit of columns 2–7 is 10,000 tons (ten thousand tons), and the unit of columns 8–9 is tons/10,000 yuan.

First, in general, agricultural GHG emissions in China totaled 320.2922 million tons in 1998 but reached 373.9129 million tons in 2016, which was an increase of 16.74% over the past 19 years and an average annual increase of 0.88%. The intensity of agricultural GHG emissions was 1.23 tons/10,000 yuan in 1998 but dropped to 0.65 tons/10,000 yuan in 2016, a decrease of nearly 50%.

Second, although the scale of agricultural GHG emissions rose from 1998 to 2016, the intensity of agricultural GHG emissions declined year by year, especially in 2005 and 2006, which was a significant turning point. The intensity of agricultural GHG emissions was 1 or above (tons/10,000 yuan) in 1998–2004, and it began to fall below 1 (tons/10,000 yuan) in 2005. The following two factors may have played important roles in agricultural efficiency and carbon reduction: (a) advances in agricultural production technology and (b) the stimulus that may be expected and realized to abolish agricultural tax in China around 2006.

Third, from the perspective of GHG emissions sources, of all the five primary sources of GHG emissions, agricultural materials and straw burning contributed the most significant amount, exceeding

10 million tons. Among them, the GHG emissions of agricultural materials increased significantly from 70.6486 million tons in 1998 to 106.1024 million tons in 2016, with an increase of 50.18%.

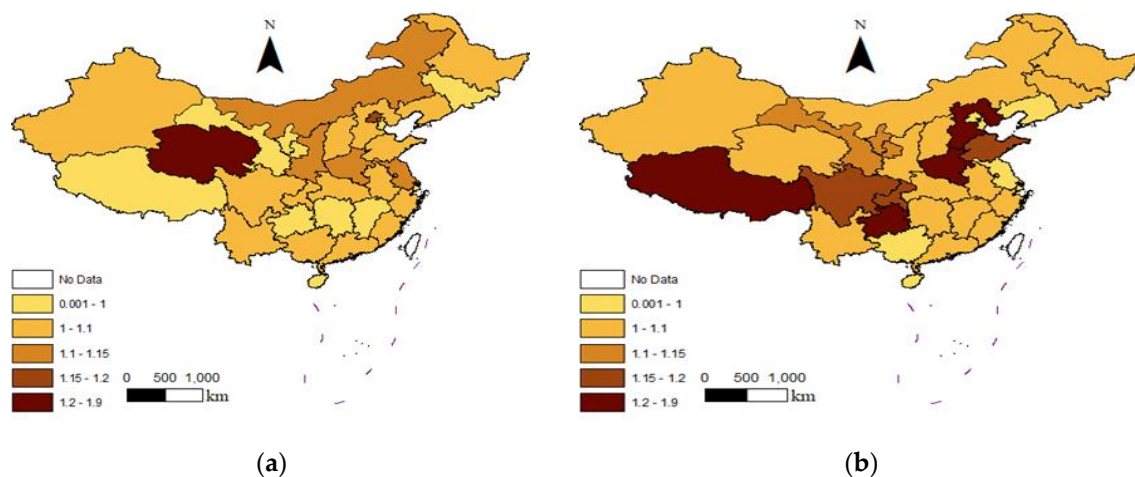
Finally, with respect to the role of soil N<sub>2</sub>O emissions: (a) Among all five types of GHG emission sources, the proportion of soil N<sub>2</sub>O emissions was the lowest. In 2016, for example, the scale of soil N<sub>2</sub>O emissions was 2006.77 million tons, only 18.91% of the GHG emissions of agricultural materials (106.1024 million tons), and 5.36% of the total GHG emissions of agriculture (373.9129 million tons). However, the proportion of soil N<sub>2</sub>O emissions increased year by year from 1998 to 2016 and the percentage of soil N<sub>2</sub>O in total agricultural GHG emissions increased from 4.52% in 1998 to 4.83% in 2006, and then to 5.36% in 2016. (b) The intensity of agriculture GHG emissions excluding soil N<sub>2</sub>O emissions was lower than that including soil N<sub>2</sub>O emissions. Despite this, it also shows that soil N<sub>2</sub>O emissions play an important role in agricultural GHG emissions.

### 3.2. Comparison of AGTFP Including and Excluding Soil N<sub>2</sub>O Emissions

Based on the calculation of the emissions scale and intensity of each agricultural GHG emissions source, this paper calculated AGTFP.

#### 3.2.1. Regional Comparison of AGTFP Including and Excluding Soil N<sub>2</sub>O Emissions in 2016

AGTFP including soil N<sub>2</sub>O emissions in 2016 is shown in Figure 1a, and AGTFP excluding soil N<sub>2</sub>O emissions in 2016 is demonstrated in Figure 1b.



**Figure 1.** Regional comparison of AGTFP in 2016. (a) AGTFP including soil N<sub>2</sub>O emissions and (b) AGTFP excluding soil N<sub>2</sub>O emissions.

As seen from Figure 1, although soil N<sub>2</sub>O emissions account for a small proportion (about 5%) of the total agricultural GHG emissions in China, their performance varies significantly among different provinces. Compared with Figure 1b, it can be observed from Figure 1a that the AGTFP including soil N<sub>2</sub>O emissions is much lower than that excluding soil N<sub>2</sub>O emissions, and the regional differences are particularly visible, especially in Hebei, Henan, Shandong, and Chongqing. These provinces all belong to areas with high population density (Hebei: population density = 355 people/km<sup>2</sup>, ranking 12/32 in China; Henan: population density = 553 people/km<sup>2</sup>, ranking 7/32 in China; Shandong: population density = 579 people/km<sup>2</sup>, ranking 6/32 in China; Chongqing: population density = 374 people/km<sup>2</sup>, ranking 11/32 in China) [43]. In these areas, the amount of labor per unit of soil is relatively high, so soil emissions play an important role. On the other hand, the AGTFP of Qinghai, Inner Mongolia, and other provinces increased when considering soil N<sub>2</sub>O emissions, which may have something to do with the fact that these areas are sparsely populated (Qinghai: population density = 7.2 people/km<sup>2</sup>, ranking 31/32 in China; Inner Mongolia: population density = 20 people/km<sup>2</sup>, ranking 29/32 in China) [43]. As a result, it can be predicted that the size of the population plays a significant role.

### 3.2.2. Regional Comparison of AGTFP Including and Excluding Soil N<sub>2</sub>O Emissions in Two Phases around 2006

Next, we took the agricultural tax abolition in China in 2006 as the time node to analyze the role of soil N<sub>2</sub>O emissions in AGTFP in two stages.

Some useful information can be found in Table 4. First, AGTFP excluding soil N<sub>2</sub>O emissions is higher than AGTFP including soil N<sub>2</sub>O emissions in any region, regardless of the time period (either 1998–2006 or 2007–2016). Therefore, it is obvious that soil N<sub>2</sub>O emissions play a certain role in AGTFP. Second, compared with 1998–2006, the change range of AGTFP excluding soil N<sub>2</sub>O emissions in 2007–2016 was larger than AGTFP including soil N<sub>2</sub>O emissions. This indicates that soil N<sub>2</sub>O emissions play a more and more important role in AGTFP.

**Table 4.** Agricultural green total factor productivity (AGTFP) in two periods in different provinces.

Regions	1998–2006		2007–2016	
	AGTFP Including Soil N <sub>2</sub> O Emissions	AGTFP Excluding Soil N <sub>2</sub> O Emissions	AGTFP Including Soil N <sub>2</sub> O Emissions	AGTFP Excluding Soil N <sub>2</sub> O Emissions
Beijing	1.036	1.088	1.061	1.221
Tianjin	1.021	1.072	1.124	1.292
Hebei	1.057	1.110	1.144	1.315
Liaoning	1.052	1.104	1.092	1.255
Shanghai	1.002	1.05	1.001	1.151
Jiangsu	1.074	1.128	1.044	1.200
Zhejiang	1.069	1.122	1.039	1.194
Fujian	1.041	1.092	1.058	1.216
Shandong	1.106	1.161	1.108	1.274
Guangdong	1.039	1.092	1.041	1.197
Guangxi	1.035	1.087	1.029	1.183
Hainan	0.962	1.011	1.033	1.187
Shanxi	1.027	1.078	1.041	1.197
Inner Mongolia	1.002	1.052	1.007	1.158
Jilin	1.026	1.077	1.025	1.178
Heilongjiang	1.033	1.084	1.037	1.192
Anhui	1.059	1.112	1.041	1.197
Jiangxi	1.018	1.069	1.053	1.211
Henan	1.055	1.108	1.084	1.246
Hubei	1.036	1.088	1.046	1.202
Hunan	1.035	1.086	1.034	1.189
Chongqing	1.036	1.088	1.107	1.273
Sichuan	1.045	1.097	1.123	1.291
Guizhou	1.004	1.054	1.103	1.268
Yunnan	1.030	1.081	1.034	1.189
Tibet	0.999	1.049	1.001	1.151
Shaanxi	1.082	1.136	1.091	1.254
Gansu	0.993	1.042	1.023	1.176
Qinghai	0.969	1.017	0.974	1.120
Ningxia	0.908	0.954	1.011	1.162
Xinjiang	1.027	1.078	1.026	1.179

### 3.3. Further Analysis of the Comparison between AGTFP and TATFP (Traditional Agricultural Total Factor Productivity)

Next, unlike most previous literature [8,10], this paper divided the whole country into three regions, that is, areas with high agricultural output ratio(HAOR-Areas), areas with low agricultural output ratio(LAOR-Areas)and areas with medium agricultural output ratio(MAOR-Areas), which may be more scientific than simple division by geographical location. As shown in Table 5, the analysis can be grouped to two stages, namely 1998–2006 and 2007–2016, taking the abolition of the agricultural tax in 2006 as the dividing line, and comparing them in the three central regions, namely HAOR-Areas, LAOR-Areas, and MAOR-Areas.



**Table 5.** Comparison between AGTFP (included soil N<sub>2</sub>O emissions or not) and traditional agricultural total factor productivity (TATFP).

Regions	Variables	1998–2006	2007–2016	1998–2016
The whole country	AGTFP (including soil N <sub>2</sub> O emissions)	1.022	1.056	1.035
	AGTFP (excluding soil N <sub>2</sub> O emissions)	1.037	1.102	1.066
	TATFP	1.106	1.153	1.130
Low agricultural output ratio areas (LAOR-Areas)	AGTFP (including soil N <sub>2</sub> O emissions)	1.027	1.064	1.042
	AGTFP (excluding soil N <sub>2</sub> O emissions)	1.029	1.086	1.054
	TATFP	1.101	1.162	1.137
Medium agricultural output ratio areas (MAOR-Areas)	AGTFP (including soil N <sub>2</sub> O emissions)	1.033	1.052	1.034
	AGTFP (excluding soil N <sub>2</sub> O emissions)	1.043	1.083	1.049
	TATFP	1.108	1.148	1.129
high agricultural output ratio areas (HAOR-Areas)	AGTFP (including soil N <sub>2</sub> O emissions)	1.059	1.078	1.025
	AGTFP (excluding soil N <sub>2</sub> O emissions)	1.076	1.109	1.107
	TATFP	1.003	1.144	1.118

Table 5 reveals some interesting information. Firstly, there is a difference in the influence of soil N<sub>2</sub>O emissions on AGTFP in different regions in the whole period from 1998 to 2016. Although there is an increasing trend in all the three regions, the role of soil in the LAOR-Areas is small but is most significant in HAOR-Areas.

Secondly, all three types of TFP in 2007–2016 were more extensive than those in 1998–2006 in all regions, which indicated that agricultural technology has made significant progress in recent years. At the same time, soil N<sub>2</sub>O emissions had a more substantial impact on the TFP in 2007–2016 than in 1998–2006. In HAOR-Areas, for example, the difference between AGTFP (excluding soil N<sub>2</sub>O emissions) and AGTFP (including soil N<sub>2</sub>O emissions) was 0.017 (1.076–1.059) in 1998–2006 and increased to 0.031 (1.109–1.078) in 2007–2016.

#### 4. Discussion

Research on soil N<sub>2</sub>O emissions has gained popularity worldwide due to the boom in low-carbon agriculture in recent years. However, most of them focused on the effects of factors such as soil properties and soil temperature on soil N<sub>2</sub>O emissions [44,45], and little literature discusses its role in Agricultural green production efficiency due to its too small share in total GHG emissions or treated it as just one of several GHG emissions sources from agriculture [8,24]. The decision in 2006 to abolish the agricultural tax, which had lasted for two thousand years, contributed to the prosperity of agriculture, and with it the growing importance of soil N<sub>2</sub>O emissions in China. Soil N<sub>2</sub>O emissions gradually become a more important emissions source of the agriculture GHG emissions that should not be ignored. Therefore, one innovation of this paper is to take soil N<sub>2</sub>O emissions as a separate variable in the measurement of AGTFP and to reveal its role around 2006 when Agricultural Tax was abolished. Besides, unlike many previous studies [8,10], which devised the whole country into east-region, middle-region, and west-region. This paper reclassified it to HAOR-Areas, LAOR-Areas, and MAOR-Areas, which is maybe more scientific than just geographical division. For example, it feels a bit unconvincing that the total factor productivity that they get with GHG emissions is higher than the total factor productivity that they get without. Some other interesting things about the role of soil N<sub>2</sub>O emissions in AGTFP were found.

Firstly, soil N<sub>2</sub>O emissions play an increasingly important role in agricultural GHG emissions sources. a) from the perspective of GHG emissions scale. Among all the five types of GHG emissions sources, the proportion of soil N<sub>2</sub>O emissions is the lowest. In 2016, for example, soil N<sub>2</sub>O emissions were 20.0677 million tons, only 18.91% of the agricultural materials GHG emissions (106.1024 million tons), and 5.36% of the total GHG emissions of agriculture (373.9129 million tons). However, the proportion of soil GHG emissions increased year by year from 1998 to 2016, and the ratio of total agricultural GHG emissions increased from 4.52% in 1998 to 4.83% in 2006, and then to 5.36% in 2016.

b) from the perspective of GHG emissions intensity. The intensity of GHG emissions excluded soil N<sub>2</sub>O emissions is lower than that included soil N<sub>2</sub>O emissions. It shows that soil N<sub>2</sub>O emissions also play an increasingly important role in agricultural GHG emissions, which may be caused by the advances in agricultural production techniques and the policy expectation or realization to abolish agricultural tax in China around 2006. This conclusion is basically consistent with [46] but has some differences from [47], which may reveal that the utilization efficiency of agricultural waste is not high, and further improvement is needed in China.

Secondly, the regional difference of soil N<sub>2</sub>O emissions in AGTFP is visible. For example, although soil N<sub>2</sub>O emissions in 2016 accounted for a small proportion (about 5%) of the total agricultural GHG emissions in China, the AGTFP included soil N<sub>2</sub>O emissions is much lower than that excluded soil N<sub>2</sub>O emissions, especially in areas with high density of agriculture and population, such as Hebei, Henan, Shandong, and Chongqing, but it is not evident in other areas such as northwest China or Tibet. This conclusion is like the study of [48] and may be due to the labor per unit of soil is relatively more, as a result, soil N<sub>2</sub>O emissions have a more significant impact in these areas.

Finally, soil N<sub>2</sub>O emissions have an increasing impact on AGTFP over time. (a) AGTFP excluded soil N<sub>2</sub>O emissions is higher than that included soil N<sub>2</sub>O emissions in any region, regardless of the period from 1998–2006 to 2007–2016. (b) Compared with 1998–2006, the impact of excluding soil N<sub>2</sub>O emissions on AGTFP in 2007–2016 is more evident than included soil N<sub>2</sub>O emissions. Taking HAOR-Areas as an example, the difference between AGTFP (excluded soil N<sub>2</sub>O emissions) and AGTFP (included soil N<sub>2</sub>O emissions) is 0.017 (1.076–1.059) in 1998–2006, while the difference expanded to 0.031 (1.109–1.078) in 2007–2016. In a word, it is indicated from these data that soil N<sub>2</sub>O emissions play an increasingly important role in AGTFP.

In conclusion, soil N<sub>2</sub>O emissions play an increasingly important role in GHG emissions and agricultural productivity in China, especially since the agricultural tax was abolished in 2006. From the discussion above, we can get the enlightenment that the government should take more policy measures to improve the utilization efficiency of agricultural waste. At the same time, there is some regional heterogeneity in its role. Different regions should adopt different agricultural produce stimulus policies and environmental regulation policies according to their environment and local conditions.

## 5. Conclusions

The decision of China to abolish the agriculture tax, which had lasted for two thousand years in 2006 led to the prosperity of agriculture and the increasingly important role of soil N<sub>2</sub>O emissions. Therefore, the purpose of this study is to evaluate the role of soil N<sub>2</sub>O emissions in AGTFP by taking 2006 as the dividing line and calculating the AGTFP, and. As a result, lots of interesting conclusions have been reached. For example, soil N<sub>2</sub>O emissions have an increasing effect on AGTFP with time. Compared with 1998–2006, the impact of excluding soil N<sub>2</sub>O emissions on AGTFP in 2007–2016 is more evident than that included soil N<sub>2</sub>O emissions. However, there are also some potential problems which need to be studied more in the future. For instance, the availability and accuracy of data for each province, such as Tibet, the rational and scientific division of different provinces, etc. Furthermore, it is generally believed that nitrification and denitrification processes are the main pathways for the generation of soil N<sub>2</sub>O. Meanwhile, environmental factors (soil type, humidity, type of crop, soil pH, temperature, etc.) and management measures (fertilization, irrigation, etc.) mainly affect these two processes to affect N<sub>2</sub>O emission. However, most scholars explored the impact of these environmental factors on N<sub>2</sub>O emissions based on the research scope of environmental science. In future research, it may be a very good and insightful novel topic to incorporate the above factors into our impact on agricultural output efficiency, which is also conducive to strengthening the theoretical basis for us to further propose reasonable N<sub>2</sub>O emission reduction measures.

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## Abbreviations

GHG	greenhouse gas
AGTFP	Agricultural Green Total Factor Productivity
TFP	Total factor productivity
TATFP	Traditional agricultural total factor productivity
HAOR-Areas	Areas with High agricultural output ratio
LAOR-Areas	Areas with Low agricultural output ratio
MAOR-Areas	Areas with Medium agricultural output ratio

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