sustainability

MDPI

Article

Inventory of Spatio-Temporal Methane Emissions from Livestock and Poultry Farming in Beijing

Yixuan Guo [1,2], Yidong Wang [1,2,*], Shufeng Chen [3,*], Shunan Zheng [4], Changcheng Guo [1], Dongmei Xue [1,2], Yakov Kuzyakov [1,5] and Zhong-Liang Wang [1,2]

1 Tianjin Key Laboratory of Water Resources and Environment, Tianjin Normal University, Tianjin 300387, China
2 Tianjin Key Laboratory of Environmental Change and Ecological Restoration, School of Geographic and Environmental Sciences, Tianjin Normal University, Tianjin 300387, China
3 Beijing Municipal Research Institute of Environmental Protection, Beijing 100037, China
4 Rural Energy and Environment Agency, Ministry of Agriculture and Rural Affairs, Beijing 100125, China
5 Department of Soil Science of Temperate Ecosystems, Department of Agricultural Soil Science, University of Göttingen, 37077 Göttingen, Germany
* Correspondence: wangyidong@tjnu.edu.cn (Y.W.); shufengchen@163.com (S.C.)

Received: 18 June 2019; Accepted: 11 July 2019; Published: 16 July 2019

check for updates

Abstract: Livestock and poultry farming sectors are among the largest anthropogenic methane (CH_4) emission sources, mainly from enteric fermentation and manure management. Previous inventories of CH_4 emission were generally based on constant emission factor (EF) per head, which had some weaknesses mainly due to the succession of breeding and feeding systems over decades. Here, more reliable long-term changes of CH_4 emissions from livestock and poultry farming in Beijing are estimated using the dynamic EFs based on the Intergovernmental Panel on Climate Change (IPCC) Tier 2 method, and high-resolution spatial patterns of CH_4 emissions are also estimated with intensive field survey. The results showed that the estimated CH_4 emissions derived by dynamic EFs were approximately 13–19% lower than those based on the constant EF before 2010. After 2011, however, the dynamic EFs-derived CH_4 emissions were a little higher (3%) than the constant EF method. Temporal CH_4 emissions in Beijing had experienced four developing stages (1978–1988: stable; 1989–1998: slow growth; 1999–2004: rapid growth and reached hot moments; 2005–2014: decline) during 1978–2014. Over the first two decades, the contributions of pigs (45%) and cattle (46%) to annual CH_4 emission were similar; subsequently, the cattle emitted more CH_4 compared to the pigs. At a spatial scale, Shunyi, Daxing, and Tongzhou districts with more cattle and pigs are the hotspots of CH_4 emission. In conclusion, the dynamic EFs method obviously improved the spatio-temporal estimates of CH_4 emissions compared to the constant EF approach, and the improvements depended on the period and aquaculture structure. Therefore, the dynamic EFs method should be recommended for estimating CH_4 emissions from livestock and poultry farming in the future.

Keywords: enteric emissions; greenhouse gases; livestock and poultry; CH_4 emission; China

1. Introduction

Methane (CH_4) has a 28-fold greater global warming potential than carbon dioxide (CO_2) on a centennial scale and is the second most important greenhouse gas, contributing approximately one-third of the total radiative forcing since 1750s [1]. Furthermore, CH_4 affects the chemical composition of the atmosphere [2]. Global atmospheric CH_4 concentration has nearly tripled since the Industrial Revolution [1], of which 50–65% of the total CH_4 emission was attributed to intensive anthropogenic sources in the past three decades [3,4]. Therefore, in the context of climate change and regional atmospheric environment, it is of importance to study CH_4 emissions from livestock and poultry farming in order to maintain the sustainability of the global and regional aquaculture development.

Livestock and poultry farming sector are among the largest anthropogenic CH_4 emission sources at both regional and global scales, mainly from enteric fermentation and manure management [5–10]. In general, the regional and global inventories of CH_4 emission from the livestock and poultry farming are using the framing population and annual emission factor (EF) per head of livestock and poultry. The previous studies generally used the temporally constant EFs according to the Intergovernmental Panel on Climate Change (IPCC) Guideline Tier 1 or National Greenhouse Gas Inventories derived from it [11,12]. In the real world, however, body weight and milk production of livestock are dynamic and in turn affect the EF because of the development in breeding technology and changes in animal diet and production systems [13,14]. For this reason, the new guideline of IPCC Tier 2 (using dynamic EFs of each livestock and poultry types during the past three decades) is more reliable and used more widely [9,10]. In China, CH_4 emission from livestock and poultry farming (12 Tg CH_4 yr^{-1}) is the second largest anthropogenic source after coal industry, accounting for 25% of the total anthropogenic CH_4 emissions [15]. The rapid growths in population and diet consumptions of meat, milk, and eggs should account for the substantial CH_4 emissions from livestock and poultry farming in China over the past decades [9,15]. Around the world, China is currently the largest meat producer and the third largest milk producer [16]. Thus, it is important to estimate CH_4 emissions from livestock and poultry farming in China as well as its regional spatio-temporal patterns of hotspots.

Beijing Municipality, the capital of China, has a population approximately 30 million and a gross domestic product (GDP) of US $4,403.9 billion currently. Based on the IPCC Guideline Tier 1, the annual CH_4 emissions from livestock and poultry farming in Beijing was estimated to be from 10 to 47 Gg yr^{-1} during 1970s–2000s [11,12]. However, these estimations of CH_4 emissions are of large uncertainties due to the constant EF values derived from the IPCC Guideline Tier 1 or domestic guidelines. Therefore, reliable and high-resolution spatio-temporal inventories of CH_4 emission from livestock and poultry farming in Beijing are urgently needed. Moreover, the spatio-temporal patterns of CH_4 emissions in recent years (after 2009) are also needed. In this way, more accurate spatio-temporal CH_4 emissions from livestock and poultry farming can be obtained, which should provide information that might be used in aquaculture sustainability as well as in dealing with climate change and regional atmospheric environment in the future.

The objectives of this study are to investigate: (i) The more reliable long-term variations of CH_4 emissions from livestock and poultry farming using dynamic EFs method (IPCC Tier 2) rather than the constant EF (IPCC Tier 1), and (ii) the high-resolution spatial patterns of CH_4 emissions from livestock and poultry farming in Beijing Municipality in North China.

2. Materials and Methods

2.1. Study Site

This study was conducted in Beijing Municipality (39.4–41.6° N, 115.7–117.4° E) in North China, with a total area of 16,410 km^2. The terrain is high in the northwest and low in the southeast. The mountainous and plain areas account for 62% and 38% of the total area, respectively. The region is characterized by a typical temperate semi-humid continental monsoon climate with four distinct seasons and simultaneous rain and heat. The mean annual precipitation is about 644 mm, and the average temperature is approximately 10–12 °C. The natural rivers in Beijing include Zhuma River, Yongding River, North Canal, Chaobai River, and Ju River from west to east. There are more than 80 tributaries and 88 reservoirs. Among them, Miyun reservoir and Guanting reservoir are the two major surface water sources in Beijing, with a total storage capacity of 8.5 billion m^3. The zonal vegetation types are warm temperate deciduous broad-leaved forests with temperate coniferous forests. With the increase of altitude, there are mainly cork oak forests, oak forests, pine forests, lateral Berlin, and birch forests.

By the end of 2018, Beijing had a resident population of 21.5 million and a population density of 1313 people km^{-2}. According to the Beijing Municipal Bureau of Land and Resources "Beijing Land and Resources Yearbook-2014" data, the agricultural and forestry area is the largest. Among them, cultivated land, garden land, and forest land account for 13.4%, 8.2%, and 44.9% of the total area, respectively. The construction lands account for 18.5% of the total land area, followed by water and water conservancy facilities (5.5%), and the other land area accounts for only 2.1%. Livestock and poultry farming in Beijing mainly include pigs, cattle, sheep, and poultry (chicken, duck, etc.,). To further produce meat and milk and provide employment opportunities, the number of breeding professional villages and aquaculture cooperative economic organizations in Beijing, especially in the suburbs, has increased rapidly [17]. At the same time, environmental problems such as insufficient livestock manure load tolerance and sewage pollution have also emerged. Therefore, China's "Laws and Animal Husbandry Plan during the 13th Five-Year Plan" also proposed corresponding countermeasures such as transformation and upgrading and green development including greenhouse gas emission reduction.

2.2. Data Collection

The spatio-temporal data of the livestock and poultry farming were collected using two approaches. First, the high-resolution spatial datasets during 2010–2014 were obtained by intensive field inventory survey of all aquaculture enterprises in the entire Beijing Municipality, including five types of livestock and poultry: meat cattle, dairy cattle, pigs, meat chickens, and laying hens. During the intensive field inventory survey, the data of annual breeding quantity (heads), breeding cycle, output amount, supporting agricultural utilization modes, and sewage treatment way were all collected. Second, the long-term (1978–2009) data of the livestock and poultry farming were collected based on the official statistical yearbook (Beijing Rural Statistical Yearbook 1978–2009, Beijing Statistics Yearbook 2005–2014, China Agricultural Statistical Yearbook, 1980–2010) and previous published articles [9,11,12].

2.3. Estimation of CH_4 Emission

The CH_4 emissions were estimated using the IPCC Tier 2 combined with the "Guidelines for the preparation of provincial greenhouse gas inventories" (No. [2011]1041) (hereinafter referred to as the "Guidelines") issued by the state in May 2011. The IPCC Tier 2 derived from IPCC has become a reliable and widely adopted method for estimating greenhouse gas emissions. The "Guidelines" can provide more reliable local EFs. Referring to the methane emission factors of intestinal fermentation and fecal management of different animals in Chinese Guidelines, the methane emission factors of different livestock and poultry from 1978 to 2014 were validated using the IPCC Tier 2. It was found that the methane emission factors given in the "Guidelines" were highly consistent with the results of 2010 after correction, which also explains the reference value of the "Guidelines" to some extent. Therefore, the combination of the above two methods is necessary for accurately estimating the spatio-temporal patterns of CH_4 emissions in the Beijing Municipality.

The annual CH_4 emissions from livestock and poultry are the sum of CH_4 effluxes from enteric fermentation and manure management [9]. Therefore, the annual total amount of CH_4 emissions is summed by the source emissions using Equation (1):

$$E_{\text{methane}} = \sum EF_{j,k} \times N_k / 10^6 \quad (1)$$

where E_{methane} is the annual total CH_4 emissions of livestock and poultry, Gg yr^{-1}; $EF_{j,k}$ is the annual CH_4 emission factor of each livestock and poultry head k with j source, kg $head^{-1}$ yr^{-1}; j indicates animal intestinal fermentation or animal manure management; k is the type of livestock and poultry (dairy cattle, meat cattle, pigs, meat chickens, and laying hens); N_k is the number of annual livestock, head.

The annual scale breeding quantity (heads) (N_k) were estimated using breeding cycles and slaughter data for different livestock and poultry farms according to Equation (2):

$$N_k = M/F \times 365 \quad (2)$$

where, N_k is the estimated annual feeding amount of a livestock and poultry, head; M is the surveyed actual stock of livestock and poultry, head; F is the surveyed actual breeding cycle of a specific type of livestock and poultry, day.

2.4. Data Analysis

The temporal patterns of CH_4 emissions from livestock and poultry farming calculated by the IPCC Tier 1 and the IPCC Tier 2 were compared. The spatial patterns of animal stock and CH_4 emissions of livestock and poultry farming were analyzed and shown using Global Positioning System (GPS) and Geographic Information System (GIS) 10.2 (ArcMap, ESRI, MA). Figures were prepared in ORIGIN 9.0 (OriginLab Corporation, Northampton, MA).

3. Results

3.1. Spatio-Temporal Distribution and Stock of Livestock and Poultry Farming

The livestock and poultry farming enterprises were distributed in the suburb areas of Beijing Municipality in the years 2010–2014 (Figure 1). The farming enterprises of pigs, meat cattle, most dairy cattle, and laying hens were distributed mainly in the plains of southeastern Beijing, especially for the Pinggu, Shunyi, Tongzhou, Daxing, and Fangshan districts (Figure 1). Meat chickens were distributed mainly in the mountain areas in Miyun, Huairou, Yanqing, and Mentougou districts. The number of entire farming enterprises in Beijing changed little during the past five years, with a coefficient of variation (CV) of 7% (Table 1). And the CV values of meat cattle, dairy cattle, pigs, meat chickens, and laying hens were 16%, 5%, 7%, 21%, and 8%, respectively (Table 1).

The livestock and poultry farming productions in Beijing did not change much during the past five years (Table 2), which was basically similar as the enterprise numbers. At a spatial scale (Figure 2), meat cattle are mainly distributed in the southeastern plain area of Beijing (especially in Huoxian and Weishanzhuang towns), while the dairy cattle are located around the central urban area of Beijing. The farming volume of meat cattle is smaller than that of the dairy cattle (Figure 2a,b). The swine farming has a relatively dispersed pattern in the entire suburb of Beijing Municipality (Figure 2c). The broiler and laying hens are mainly located in the north mountain areas of Beijing Municipality (Figure 2d,e), which have the highest breeding densities.

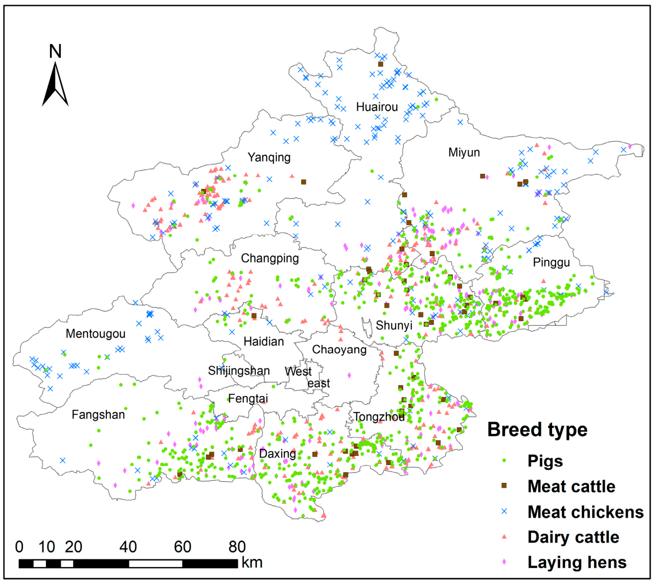

Figure 1. Distribution of livestock and poultry farming enterprises in Beijing Municipality during 2010–2014.

Table 1. Farming enterprises numbers of the five livestock and poultry types in Beijing area during 2010–2014.

Livestock and Poultry Type	2010	2011	2012	2013	2014	Coefficient of Variation
Meat cattle	30	23	26	26	36	0.16
Dairy cattle	257	221	235	228	227	0.05
Pigs	638	556	551	608	664	0.07
Meat chickens	187	155	118	116	107	0.22
Laying hens	171	135	142	152	151	0.08
Total	1283	1090	1072	1130	1185	0.16

Table 2. Farming volumes of the five livestock and poultry types in Beijing area during 2010–2014 (head).

Livestock and Poultry Type	2010	2011	2012	2013	2014
Meat cattle	6.8×10^4	5.8×10^4	6.2×10^4	4.9×10^4	4.1×10^4
Dairy cattle	1.2×10^5	8.4×10^4	9.9×10^4	1.0×10^5	1.1×10^5
Pigs	3.8×10^6	3.3×10^6	3.3×10^6	3.6×10^6	3.8×10^6
Meat chickens	3.1×10^8	2.3×10^8	2.2×10^8	1.9×10^8	1.7×10^8
Laying hens	8.8×10^6	8.3×10^6	8.6×10^6	1.2×10^7	1.4×10^7

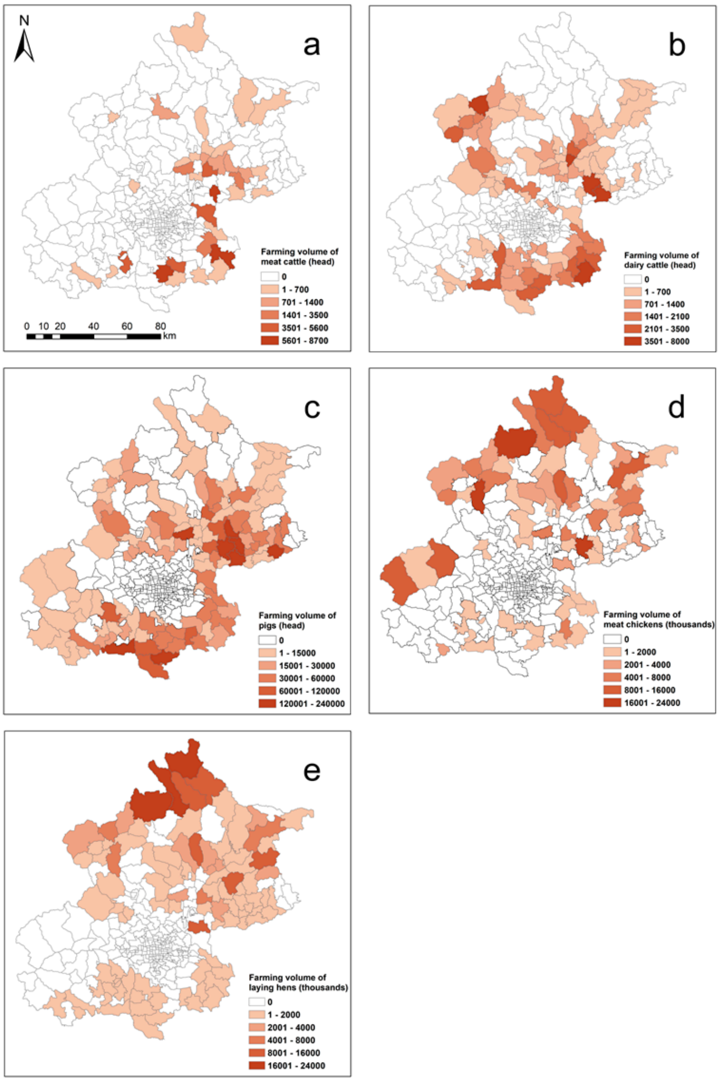

Figure 2. Spatial patterns of farming volumes of the five livestock and poultry: meat cattle (**a**), dairy cattle (**b**), pigs (**c**), meat chickens (**d**), and laying hens (**e**) in Beijing Municipality during 2010–2014.

3.2. Temporal Pattern of CH_4 Emission from Livestock and Poultry Farming

The estimated annual total CH_4 emissions based on both the constant and dynamic EFs had similar temporal patterns over the past four decades (Figure 3a). The annual CH_4 emission from livestock and poultry farming in Beijing had experienced four developing stages (1978–1988: stable; 1989–1998: slow growth; 1999–2004: rapid growth and reached hot moments; 2005–2014: decline) from 1978 to 2014. However, the dynamic EFs-derived annual total CH_4 emissions were approximately 13–19% (mean of) lower than the constant EF method before 2010 (Figure 3a). In contrast, the dynamic EFs-derived annual total CH_4 emissions were a little higher (3%) than the constant EF method after 2011 (Figure 3a). Approximately over the first two decades, the contributions of pig and cattle to annual CH_4 emission were similar (approximately 40–60%), however, the cattle sector emitted more CH_4 (45–67%) compared to the pig sector after 1999 (Figure 3b). The broiler and laying hens contributed less than 20% of the annual CH_4 emission from the whole livestock and poultry farming (Figure 3b). The CH_4 emission from the meat cattle, dairy cattle, pigs, and meat chickens all decreased during 2010–2014, while CH_4 emission from the laying hens increased (Table 3).

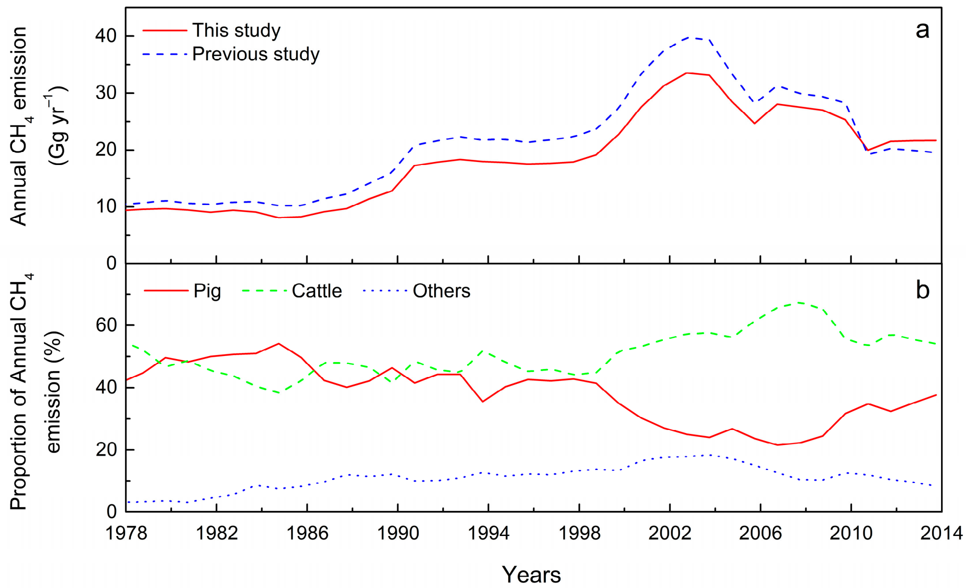

Figure 3. Temporal patterns of annual CH_4 emissions from livestock and poultry farming in Beijing area estimated using the IPCC Tier 1 (constant EF) and Tier 2 (dynamic EFs) during 1978–2014 (**a**), and the proportion of CH_4 emissions from different livestock and poultry to total CH_4 emissions (**b**).

Table 3. Estimated CH_4 emissions (tons) from the five livestock and poultry farming in Beijing area during 2010–2014.

Livestock and Poultry Type	2010	2011	2012	2013	2014
Meat cattle	3684	3117	3337	2662	2195
Dairy cattle	10435	7544	8953	9306	9519
Pigs	8034	6941	6955	7568	8151
Meat chickens	3103	2300	2159	1935	1652
Laying hens	88	69	86	121	140

3.3. Spatial Pattern of CH_4 Emission from Livestock and Poultry Farming

The annual CH_4 emission from livestock and poultry farming in Beijing had similar distribution during the past five years (Figure 4). The hotspots of annual CH_4 emission from livestock and poultry farming were Shunyi (4.73 t km^{-2}), Daxing (3.44 t km^{-2}), and Tongzhou (3.32 t km^{-2}), which is approximately triplex of the mean CH_4 emission in whole Beijing area (Table 4). In contrast, the areas with low CH_4 emissions were Yanqing, Fangshan, Mentougou, Haidian, Chaoyang, and Fengtai districts (Table 4); the Shijingshan, Dongcheng, and Xicheng districts have almost no CH_4 emissions. Overall, the dairy cattle and pigs have the largest CH_4 emissions, accounting for about 42% and 34% of the total CH_4 emissions, respectively.

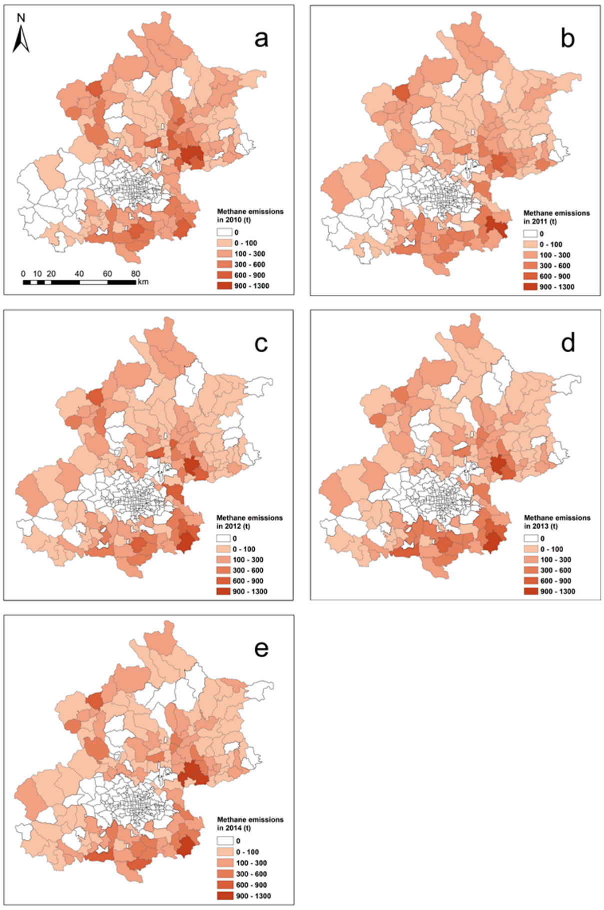

Figure 4. Spatial patterns of annual CH_4 emissions from livestock and poultry farming in Beijing area during 2010–2014: meat cattle (**a**), dairy cattle (**b**), pigs (**c**), meat chickens (**d**), and laying hens (**e**).

Table 4. Annual CH_4 emissions (tons) from the livestock and poultry farming in various districts in Beijing area during 2010–2014.

District	2010	2011	2012	2013	2014	CH_4 Emissions per Area During 2010–2014 (t km^{-2})
Shunyi	6564	4070	4294	4065	5104	4.73
Daxing	4145	2974	3618	3721	3290	3.44
Tongzhou	2514	2712	3691	3281	2850	3.32
Yanqing	2784	2462	2760	2269	2253	1.26
Fangshan	1612	1832	2096	2376	2063	1.00
Huairou	2245	1499	1513	1845	1786	0.84
Pinggu	1395	1584	1021	1365	1453	1.27
Miyun	2425	1079	963	974	1047	0.58
Changping	1126	904	842	962	1157	0.74
Mentougou	3	347	270	289	228	0.16
Haidian	242	200	166	232	265	0.51
Chaoyang	220	257	208	214	160	0.45
Fengtai	69	64	49	0	0	0.12
Total	25,344	19,984	21,491	21,593	21,656	1.34

4. Discussion

4.1. Temporal CH_4 Emission of Livestock and Poultry Farming

Nowadays, the development of low-carbon economy has become a global consensus, and the aquaculture sustainability is getting more and more attention especially in the context of climate change and regional atmospheric environment. As the capital of China and an international metropolis, Beijing is facing double pressures of rapid development and greenhouse gas emission reduction in livestock and poultry breeding [12]. Reduction of greenhouse gas emission is considered as an arduous and urgent task for the Chinese livestock industry [18]. Despite of different methods of IPCC Tier 1 (constant EFs) and Tier 2 (dynamic EFs) [19,20], the present study obtained similar temporal patterns of annual CH_4 emissions (10–36 Gg) (Figure 3a). However, the annual CH_4 emissions in this study derived from the lower dynamic EFs were approximately 13–19% lower than the previous results [12] based on the constant EF before 2010 (Figure 3). In contrast, after 2011, the dynamic EFs-derived annual total CH_4 emissions were a little higher (4–11%) than the constant EF method, which might due to the corresponding higher EFs of cattle. Although the proportion of meat cattle farming decreased gradually, the higher EFs still lead to the increases of CH_4 emissions, indicating that the considerable importance of EFs resulted from the cattle breeding, feeding, and production methods in this region. Furthermore, because of the high-resolution field survey in the present research, the estimating accuracy of CH_4 emissions from the livestock and poultry farming is much improved compared with previous studies which used the datasets of statistical yearbooks.

From the early 1960s to the mid-2000s, the global average carcass weight of meat cattle increased by 30%, and the milk yield per head cow also increased by 30% [21]. The growth in meat and milk demand may not slow down until 2050s [22–24]. In this global context of the growing demand for livestock products and breeding improvements [21], the estimates of CH_4 emissions derived by IPCC Tier 2 should be more reliable than that of the IPCC Tier 1. Over the past four decades, the dynamic EFs of CH_4 emission (intestinal fermentation and fecal management), driven by increasing body size and milk production per head increased for all types of livestock [9]. However, these dynamic EFs from the IPCC Tier 2 were lower than the constant EFs derived from the IPCC Tier 1. The corrected dynamic EFs were slowly increasing due to changes in farming techniques and dietary structure until it reached and exceeded the constant EFs around 2008, which partially explains the lower estimated CH_4 emissions in the present study (Figure 3a). In addition, the changes in the livestock and poultry farming composition/structure (especially the proportion of cattle and pig) might be the main reason for the lower estimated CH_4 emissions of the present study. The result of the correction of the total amount of methane emissions over the original calculation results before and after 2011 is due to the continuous increase of the cattle EFs. Although the proportion of meat cattle is gradually decreasing, the superposition of the above factors still leads to the total amount of methane emissions. The increase indicates that the proportion of cattle breeding, feeding, and production methods has a considerable impact on the total amount of methane emissions in the region. In summary, factors such as the decrease of cattle breeding scale with higher EFs, the increase of livestock and poultry breeding quantity with lower EFs all have a certain impact on the results of this study. Therefore, the reliable EFs derived by the IPCC Tier 2 should be recommended in other regions in order to get more actual estimates of CH_4 emissions.

The present study showed that the time series of CH_4 emission from livestock and poultry had four periods and reached its peak in 2003, which is generally consistent with the previous long-term results in China as well as its specific areas [9,16,18] and in East Asia [25]. However, there was a fluctuating upward trend in the 1990s and reached a hot moment in 2003, which was different from the result in Taiwan with an early peak in 1996 [16]. In contrast, the peak appearing period in Beijing in the present study is earlier than that in East Asia [25]. These different hot moments (peak appearing periods) may be explained by their corresponding temporal variations of economic and social development and environmental protection. Earlier hot moment might have resulted from earlier economic and social development and later environmental protection. In 2003 (hot moment in both Beijing and entire China), the amount of CH_4 emissions from livestock and poultry were comparable between China and India [18,26].

Compared with the existing studies in China and other countries in East Asia, our results on CH_4 emissions from livestock and poultry in Beijing, including types of livestock and poultry, main sources, emission coefficients, and overall trends are similar. The reliable estimated CH_4 emissions from the livestock and poultry farming provide information that might be used in aquaculture sustainability as well as in dealing with climate change and regional atmospheric environment in Beijing in the future. However, there are still uncertainties in the estimation process, such as the consideration of factors such as age and sex ratio in the composition of livestock. To reduce the uncertainties in inventory of CH_4 emissions, it may be necessary to build up more detailed datasets for livestock population and feeds for livestock [27].

4.2. Spatial CH_4 Emission of Livestock and Poultry Farming

There was a heterogeneous spatial pattern of CH_4 emission from livestock and poultry farming in Beijing, which may be due to its complex terrain. The present study showed that the livestock and poultry production is mainly distributed in the suburbs of Beijing. Among them, cattle and pigs are the important sources of CH_4 emission; so the southeastern plain area and the periphery of central urban area are the hotspots of CH_4 emission. This is basically consistent with previous studies on the Red River Delta [10] and Qinhuangdao City [28]. This result is because of the improvement in industrial technology level and efficient intensive management mode, due to which large-scale modern construction farms with a certain scale and level could be formed. The above shows that natural conditions have certain constraints on agricultural development, and the coupling relationship between different terrain and different types of livestock and poultry breeding ultimately results in uneven distribution of farming around the city. In addition, according to the results of the study in China [29], it was found that the high CH_4 emission concentrated areas were mainly in North China, Northeast Plain, and Southwest China, and cattle were the main sources of animal-derived methane emissions, which also explains to some extent that geographical location and climate advantages affect the distribution of livestock and poultry farming.

In addition, from the current distribution of livestock and poultry farming in Beijing, the distribution pattern should not change significantly in a short period of time. However in the long run, the total amount of livestock farming may decrease with the enhancement of ecological awareness and introduction of relevant management policies, and some industries with more serious pollution will transfer industries. For the characteristics and problems of CH_4 emission from livestock and poultry farming in Beijing, the author hopes that the series of studies in this paper can provide more accurate data on greenhouse gas emission reduction and trade cooperation between provinces, cities, and even countries in the future, and provide guidance for future regional trade. On the other hand, it will provide some guidance for the overall quality control of the atmospheric environment in Beijing, Tianjin, and Hebei in the future. It is hoped that relevant departments will pay attention to it in the future policy formulation and related planning.

5. Conclusions

Over the past 40 years, the dynamic EFs approach (IPCC Tier 2) obviously improved the spatio-temporal estimates of CH_4 emissions from livestock and poultry farming in Beijing Municipality of China compared with the constant EF method (IPCC Tier 1). The dynamic EFs-estimated CH_4 emissions were approximately 13–19% lower than that of the constant EF before 2010. In contrast, the dynamic EFs-derived CH_4 emissions were a little higher (3%) than the constant EF method after 2011. These temporal differences were attributed to the aquaculture development period (breeding and feeding improvements) and structure (proportion of cattle, pig and poultry). Therefore, the dynamic EFs method should be recommended for estimating CH_4 emissions in the future. At spatial scale, the hotspots of CH_4 emission were located in Shunyi, Daxing, and Tongzhou districts, which had more cattle and pigs. In summary, the reliable estimated CH_4 emissions from the livestock and poultry farming provide important information for aquaculture sustainability as well as dealing with climate change and atmospheric environment in Beijing in the future.

Author Contributions: Conceptualization, Y.W. and S.C.; data curation, Y.G., S.C., and C.G.; formal analysis, Y.G.; funding acquisition, Y.W., S.C., and Z.W.; investigation, Y.G., Y.W., S.C., S.Z., C.G., D.X., Y.K., and Z.W.; methodology, Y.G., Y.W., and C.G.; project administration, S.C.; resources, S.C. and S.Z.; supervision, Y.W.; visualization, Y.G.; writing—original draft, Y.G., Y.W., and S.C.; writing—review and editing, Y.W., S.Z., D.X., Y.K., and Z.W.

Funding: This research was supported by the National Key Research and Development Program of China (2016YFD0800601), the Ministry of Science and Technology of the People's Republic of China (2018YFD0800400), and the Innovation Team in Key Areas of the Tianjin Municipal Science and Technology Commission (TD12-5037).

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

References

1. IPCC. *Climate Change 2013, the Physical Science Basis*; Cambridge University Press: Cambridge, UK, 2014.
2. Cicerone, R.J.; Oremland, R.S. Biogeochemical aspects of atmospheric methane. *Glob. Biogeochem. Cycles* **1988**, *2*, 299–327. [CrossRef]
3. Kirschke, S.; Bousquet, P.; Ciais, P.; Saunois, M.; Zeng, G. Three decades of global methane sources and sinks. *Nat. Geosci.* **2013**, *6*, 813–823. [CrossRef]
4. Ghosh, A.; Patra, P.K.; Ishijima, K.; Umezawa, T.; Ito, A.; Etheridge, D.M.; Sugawara, S.; Kawamura, K.; Miller, J.B.; Dlugokencky, E.J.; et al. Variations in global methane sources and sinks during 1910–2010. *Atmos. Chem. Phys.* **2015**, *15*, 2595–2612. [CrossRef]
5. Weiss, F.; Leip, A. Greenhouse gas emissions from the EU livestock sector: A life cycle assessment carried out with the CAPRI model. *Agric. Ecosyst. Environ.* **2012**, *149*, 124–134. [CrossRef]
6. Caro, D.; Davis, S.J.; Bastianoni, S.; Caldeira, K. Global and regional trends in greenhouse gas emissions from livestock. *Clim. Chang.* **2014**, *126*, 203–216. [CrossRef]
7. Ripple, W.J.; Smith, P.; Haberl, H.; Montzka, S.A.; McAlpine, C.; Boucher, D.H. Ruminants, climate change and climate policy. *Nat. Clim. Chang.* **2014**, *4*, 2–5. [CrossRef]
8. Saunois, M.; Bousquet, P.; Poulter, B.; Peregon, A.; Ciais, P.; Canadell, J.G.; Dlugokencky, E.J.; Etiope, G.; Bastviken, D.; Houweling, S.; et al. The global methane budget 2000–2012. *Earth Syst. Sci. Data* **2016**, *8*, 697–751. [CrossRef]
9. Yu, J.; Peng, S.; Chang, J.; Ciais, P.; Dumas, P.; Lin, X.; Piao, S. Inventory of methane emissions from livestock in China from 1980 to 2013. *Atmos. Environ.* **2018**, *184*, 69–76. [CrossRef]
10. Truong, A.H.; Kim, M.T.; Nguyen, T.T.; Nguyen, N.T.; Nguyen, Q.T. Methane, nitrous oxide and ammonia emissions from livestock farming in the Red River Delta, Vietnam: An inventory and projection for 2000–2030. *Sustainability* **2018**, *10*, 3826. [CrossRef]
11. Liang, L.; Lal, R.; Du, Z.; Wu, W.; Meng, F. Estimation of nitrous oxide and methane emission from livestock of urban agriculture in Beijing. *Agric. Ecosyst. Environ.* **2013**, *170*, 28–35. [CrossRef]
12. Liu, Y.-X.; Liu, J.; Wu, W.-L. Spatiotemporal dynamics of greenhouse gases emissions from livestock and poultry in Beijing area during 1978–2009. *Chin. J. Eco-Agric.* **2013**, *21*, 891–897. [CrossRef]
13. Food and Agriculture Organization (FAO): Regional Conference. *Afr. Res. Bull. Econ. Financ. Tech.* **2010**, *47*, 18654. [CrossRef]
14. Dangal, S.R.S.; Tian, H.; Zhang, B.; Pan, S.; Lu, C.; Yang, J. Methane emission from global livestock sector during 1890–2014: Magnitude, trends and spatio-temporal patterns. *Glob. Chang. Biol.* **2017**, *23*, 4147–4161. [CrossRef] [PubMed]
15. Peng, S.S.; Piao, S.L.; Bousquet, P.; Ciais, P.; Li, B.G.; Lin, X.; Tao, S.; Wang, Z.P.; Zhang, Y.; Zhou, F. Inventory of anthropogenic methane emissions in Mainland China from 1980 to 2010. *Atmos. Chem. Phys.* **2016**, *16*, 14545–14562. [CrossRef]
16. Yang, H. Livestock development in China: Animal production, consumption and genetic resources. *J. Anim. Breed. Genet.* **2013**, *130*, 249–251. [CrossRef] [PubMed]

17. Shi, G.H. *The Impact of Intensive Livestock production on Eco-environment and Development Countermeasure in Beijing Suburban Area*; China Agricultural University: Beijing, China, 2004; (In Chinese with English abstract).
18. Zhou, J.B.; Jiang, M.M.; Chen, G.Q. Estimation of methane and nitrous oxide emission from livestock and poultry in china during 1949–2003. *Energy Policy* **2007**, *35*, 3759–3767. [CrossRef]
19. Dong, H.; Tao, X.; He, Q.; Xin, H. Comparison of enteric methane emissions in china for different IPCC estimation methods and production schemes. *Trans. ASAE* **2004**, *47*, 2051–2057. [CrossRef]
20. Nugrahaeningtyas, E.; Baek, C.-Y.; Jeon, J.-H.; Jo, H.-J.; Park, K.-H. Greenhouse Gas Emission Intensities for the Livestock Sector in Indonesia, Based on the National Specific Data. *Sustainability* **2018**, *10*, 1912. [CrossRef]
21. Gill, M.; Smith, P.; Wilkinson, J.M. Mitigating climate change: The role of domestic livestock. *Animal* **2010**, *4*, 323–333. [CrossRef]
22. Garnett, T. Livestock-related greenhouse gas emissions: Impacts and options for policy makers. *Environ. Sci. Policy* **2009**, *12*, 491–503. [CrossRef]
23. McIntyre, B.D.; Herren, H.R.; Wakhungu, J.; Watson, R.T. *Agriculture at a Crossroads*; A Synthesis of the Global and Sub-Global International Assessment of Agricultural Knowledge; Science and Technology for Development (IAASTD) Reports: Washington, DC, USA, 2009.
24. Alexandratos, N.; Bruinsma, J. *World Agriculture towards 2030/2050: The 2012 Revision*; ESA Working Paper; FAO: Rome, Italy, 2012; pp. 1–4.
25. Wolf, J.; Asrar, G.R.; West, T.O. Revised methane emissions factors and spatially distributed annual carbon fluxes for global livestock. *Carbon Balance Manag.* **2017**, *12*, 16. [CrossRef] [PubMed]
26. Chhabra, A.; Manjunath, K.R.; Panigrahy, S.; Parihar, J.S. Greenhouse gas emissions from indian livestock. *Clim. Chang.* **2013**, *117*, 329–344. [CrossRef]
27. Herrero, M.; Havlik, P.; Valin, H.; Notenbaert, A.; Rufino, M.C.; Thornton, P.K.; Bluemmel, M.; Weiss, F.; Grace, D.; Obersteiner, M. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 20888–20893. [CrossRef] [PubMed]
28. Ying, W.; Xiao-Liang, L.I.; Shi-Gang, G. Spatiotemporal dynamic analysis of greenhouse gas emissions from livestock and poultry in qinhuangdao. *Heilongjiang Anim. Sci. Vet. Med.* **2015**, *6*, 12–14.
29. Yu, L.; Wen, Z.; Yao, H. Estimating spatiotemporal dynamics of methane emissions from livestock in china. *Environ. Sci.* **2011**, *32*, 2212.