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Real Drivers and Spatial Characteristics of CO₂ Emissions from Animal Husbandry: A Regional Empirical Study of China

Xiaowen Dai *, Xin Wu, Yi Chen, Yanqiu He, Fang Wang and Yuying Liu 

College of Management, Sichuan Agricultural University, Chengdu 611130, China; 201907601@stu.sicau.edu.cn (X.W.); 2020209050@stu.sicau.edu.cn (Y.C.); 14063@sicau.edu.cn (Y.H.); wangfangscnd@sicau.edu.cn (F.W.); yuying.liu@sicau.edu.cn (Y.L.)

* Correspondence: daixiaowen@sicau.edu.cn

Abstract: (1) Studying the driving factors and spatiotemporal characteristics of China's regional animal husbandry emissions is highly relevant to policy formulation. (2) Methods: We calculated the total CO₂ equivalent emissions of animal husbandry across the country and each province separately, and then used the Logarithmic Mean Divisia Index (LMDI) to analyze how the driving forces of animal husbandry emissions changed across the country and in different provinces from 2001 to 2019. (3) Results: ① During the period 2001–2019, national animal husbandry carbon emissions showed an overall downward trend. Economic growth and population contributed positively to the emissions (which means more CO₂), while technological advancement, structural change in agriculture, and change in the national industrial structure had negative effects (which means less CO₂). ② Using aspects of provincial animal husbandry, we categorized 31 provinces into four types: fluctuating rising, fast falling, slow falling, and steadily falling. Then, according to the magnitude of the different driving forces in different provinces, we classified 31 provinces into three types: economic structure adjustment-driven, technological progress-driven, and economic growth-driven. ③ The driving effects of agricultural structural change and population in some provinces are not consistent with the effects shown at the national level.

Keywords: animal husbandry; CO₂ emissions; greenhouse gas; driving effect; spatial characteristics; regional differences



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1. Introduction

As the pace of urbanization and industrialization accelerates, China's economy has shifted from high-speed growth to high-quality development [1]; consequently, responding to the challenge of climate change and reducing carbon emissions have become new pressures that China must face [2]. Up to now, 192 countries in the world have signed the *Paris Agreement*, which means they have set a clear goal to limit global temperature increase by the end of the 21st century to no more than 2 °C before industrialization. In the general debate of the United Nations General Assembly in 2020, China first proposed some long-term strategic goals, such as reaching a carbon peak by 2030 and achieving carbon-neutrality by 2060 [3]. Subsequently, China officially upgraded its carbon peak and carbon-neutral targets to national strategic goals.

Animal husbandry accounts for the highest share of agricultural carbon emissions [4]. According to estimates by the United Nations Food and Agriculture Organization (FAO) in 2019, the proportion of GHG emissions caused by animal husbandry has reached as high as 15%. Animal husbandry has become the biggest GHG emissions sector in the agricultural domain. To do a better job of reducing CO₂ emissions from agricultural activity, it is necessary to study CO₂ emissions from animal husbandry. At present, most of the research on carbon emissions from animal husbandry is focused on calculating total carbon emissions and then analyzing the driving factors. The research objects are mainly large

livestock and poultry, such as cattle, sheep, and pigs. In terms of aggregate calculation, some scholars have used the Tapio decoupling model to analyze the relationship between animal husbandry carbon emissions and economic development and have found that national animal husbandry carbon emissions are generally on a downward trend. The relationship between the driving factors and the total emission amount is weakly decoupled, and the comprehensive effect is in an inverted “U” shape [5–7]. Some scholars have compared the difference in total carbon emissions between the traditional pig-raising circular economy model and the biogas-based circular economy model through the analysis of the pig carbon footprint inventory. They found that through carbon trading, carbon emission reduction in a circular mode can produce economic benefits [8,9]. In terms of driving factor analysis, some researchers have reviewed various CH₄ estimation techniques and mitigation methods in the livestock sector, decomposed the possible links to reduce carbon emissions at the micro-level, and found that diet management, livestock management, and breeding management are feasible ways to reduce emissions. Economic incentive policies can help livestock farmers choose diet management, reproduction management, and livestock management mitigation methods that wisely reduce CH₄ emissions [10,11]. Another study used the Life Cycle Assessment (LCA) method to comprehensively measure the carbon emissions from animal husbandry in 31 provinces in China and concluded that the production benefit per unit of the agricultural population is the most important factor leading to the continuous growth of China’s animal husbandry carbon emissions [12]. Some other scholars believe that farming subsidies from the government and the import and export of foreign livestock products will also lead to an increase in carbon emissions in the livestock industry [13]. In addition, pigs have a special status in China’s economic development, pork being the most consumed meat in China. Therefore, the total amount of CO₂ emissions and drivers of carbon emissions from pigs are widely analyzed. However, the research ideas about emissions from pig farming are the same as those about macro-level animal husbandry [14]. Although the drivers of different regions have a spillover effect on their adjacent areas [15,16], this is not the focus of our research, so we will not discuss it.

In conclusion, most of the research on animal husbandry carbon emissions is based on the calculation of total GHG emissions, including CH₄, N₂O, and CO₂, either addressing the combined effects of multiple drivers of GHG emissions in general or discussing specific drivers individually and then building models to demonstrate their positive or negative relationship to GHG emissions. The method of research varies from study to study. However, the previous literature has neglected research on the differences in the trends of total CO₂ equivalent emissions in different provinces and the reasons for the differences in the trends in total carbon emissions from animal husbandry between different provinces. However, we all know that China’s economic growth and population distribution show obvious provincial differences which will inevitably affect total provincial carbon emissions. Therefore, in this study, we intended to analyze the differences in the contribution of different driving factors in different provinces of China. It is hoped that this research can achieve the goal of improving the efficiency of carbon reduction measures in animal husbandry.

2. Description of the Data Sources

The data sources for the empirical part of this study are all from the *China Statistical Yearbook* and *China Livestock Industry Statistical Yearbook* from 2001 to 2019. The data missing from each yearbook are supplemented by local statistical yearbooks. In 2001, China joined the World Trade Organization (WTO). Since then, China’s economic development entered a new stage; therefore, our research period starts from 2001. In 2012, the livestock industry was hit by severe flooding in the area along the Yangtze River, which affected the livestock industry significantly. Due to the abnormality of the data for 2012, the study used the arithmetic average of the data for the previous and subsequent years to replace the total CO₂ emissions and livestock output data for 2012. Finally, the total number of years involved in the accounting was 19 years.

Since the provincial list only introduces the accounting formula for CH₄ and N₂O gases and does not involve CO₂, unity and convenience were considered when decomposing the driving factors.

We set the CO₂ equivalent to 1t CH₄ with a GWP value of 25t CO_{2e} and 1t N₂O with a GWP value of 296t CO_{2e} according to the conversion coefficients provided in the 2006 IPCC *National Greenhouse Gas Inventory Guidelines*. The main carbon emissions in the process of livestock breeding are intestinal fermentation and manure management [17,18]. Therefore, considering the simplicity of operation and the availability of data, we choose dairy cows, non-dairy cows, sheep, goats, pigs, horses, and donkeys/mules as objects of calculation. Since we focus on carbon emissions in China and different provinces, we do not consider microscopic factors such as differences in farm size. Without prejudice to the findings of the study, we applied the arithmetic average of carbon emission factors for farms of different sizes. The representative animal carbon emission coefficients used in this study are shown in Table 1. The emission coefficients of methane and nitrous oxide produced in animal manure management vary from region to region, and they are presented in Tables 2 and 3.

Table 1. Methane emission factors from intestinal fermentation of animals (kg/head/year).

Species	Enteric Fermentation CH ₄ Emission Coefficient	Reference Source
Dairy cows	92.23	The Provincial Greenhouse Gas Inventory Preparation Guidelines (Trial)
Non-dairy cow	68.70	The Provincial Greenhouse Gas Inventory Preparation Guidelines (Trial)
Sheep	5.00	The 2006 IPCC National Greenhouse Gas Inventory Guidelines
Goats	5.00	The 2006 IPCC National Greenhouse Gas Inventory Guidelines
Hogs	1.00	The Provincial Greenhouse Gas Inventory Preparation Guidelines (Trial)
Horses	18.00	Institute of Agricultural Economics and Development, Chinese Academy of Agricultural Sciences [19]
Donkeys	10.00	Institute of Agricultural Economics and Development, Chinese Academy of Agricultural Sciences
Mules	10.00	Institute of Agricultural Economics and Development, Chinese Academy of Agricultural Sciences

Note: The reference emission factors in the table are from the 2006 *National Greenhouse Gas Inventory Guidelines* and *Provincial Greenhouse Gas Inventory Compilation Guidelines* (for Trial Implementation) because this study does not involve the classification and discussion of micro-level farming methods and farming scales. Therefore, the methane emission factor in the intestinal fermentation of dairy cows and non-dairy cows in this paper is the arithmetic average.

Table 2. Methane emission factors for manure management (kg/head/year).

Region	Dairy Cows	Non-Dairy Cow	Sheep	Goats	Pigs	Horses	Donkeys/Mules
North China	7.46	2.87	0.15	0.17	3.12	1.09	0.60
Northeast China	2.23	1.02	0.15	0.16	1.12	1.09	0.60
East China	8.33	3.31	0.26	0.28	5.08	1.64	0.90
South China	8.45	4.72	0.34	0.31	5.85	1.64	0.90
Southwest China	6.51	3.21	0.48	0.53	4.18	1.64	0.90
Northwest China	5.93	1.86	0.28	0.32	1.38	1.09	0.60

Note: The reference emission factors in the table are from the *Provincial Greenhouse Gas Inventory Compilation Guidelines* (Trial). There are no data for Taiwan Province in East China, the Special Administrative Region of Hong Kong or Macau in South China. Decimals are rounded to two decimal places.

Table 3. Manure-management nitrous oxide emission factors (kg/head/year).

Region	Dairy Cows	Non-Dairy Cow	Sheep	Goats	Pigs	Horses	Donkeys/Mules
North China	1.86	0.79	0.09	0.09	0.23		
Northeast China	1.10	0.91	0.06	0.06	0.27		
East China	2.07	0.85	0.11	0.11	0.18	0.33	0.19
South China	1.71	0.80	0.11	0.11	0.16		
Southwest China	1.88	0.69	0.06	0.06	0.16		
Northwest China	1.45	0.55	0.07	0.07	0.19		

Note: The data in the table come from the *Provincial Greenhouse Gas Inventory Compilation Guide (Trial)*. Decimals are rounded to two decimal places.

3. Model Designation

3.1. Carbon Emission Accounting of Animal Husbandry

To measure the CO₂ eq emissions from animal husbandry in 31 provinces in China, the CO₂ eq emissions from the livestock industry we calculated involve enteric fermentation and manure management. The calculation involves the gas conversion rate between N₂O, CH₄, and CO₂. The specific calculation principle is as follows:

$$E_{CH_4, enteric} = EF_{CH_4, enteric} \times AP \times 10^{-7}. \quad (1)$$

In Formula (1), $E_{CH_4, enteric}$ represents the number of methane emissions from animal enteric fermentation (10,000 t/year), $EF_{CH_4, enteric}$ represents the methane emission coefficient in the enteric fermentation (Kg/head/year), and AP is the pigs in stock at the end of the year.

$$E_{CH_4} = \sum E_{CH_4, enteric} \quad (2)$$

In Formula (2), E_{CH_4} is the total methane emissions from enteric fermentation of animal husbandry (10,000 t/year). With the same calculation method, the total GHG emissions of CH₄ and N₂O from manure management can be calculated.

3.2. Driving Factor Decomposition

The Kaya identity was first proposed by the Japanese scholar Kaya [20], and its original expression is as follows:

$$CO_2 = \frac{CO_2}{E} \times \frac{E}{GDP} \times \frac{GDP}{P} \times P = f \cdot e \cdot g \cdot P \quad (3)$$

In Equation (3), CO₂, E , GDP , and P , represent, respectively, carbon dioxide emissions, energy consumption, gross domestic product, and total population. Through factorization, we decompose CO₂ into CO₂ emission intensity (f), energy intensity (e), and per capita GDP (g), population (P). This decomposition method is widely used in the research on CO₂ emissions.

First of all, according to research, technological advancement can bring about efficiency improvement. The same is true in terms of CO₂ eq. emission reduction. Technological advancement in animal husbandry is very likely to bring about productivity maintenance or improvement while reducing carbon emissions. Therefore, the technological advancement factor is one of the factors that needs to be considered in the context of reducing CO₂ eq. emissions in animal husbandry. Secondly, due to the trend of specialization and large-scale production in animal husbandry over recent years, the entry barriers to the animal husbandry industry have become higher than ever before, and small scattered households have lost their advantages. The enhanced environmental regulations and lack of production efficiency have led to small-scale farmers giving up engaging in animal husbandry, which has led to a downward trend in the overall scale of animal husbandry. As a result, the

structure of the agricultural sector and the income per unit of agricultural labor has changed, and the CO₂ eq. emissions from animal husbandry have changed accordingly. Thirdly, because agricultural production efficiency is far lower than that of the secondary and tertiary industries, a large number of farmers have abandoned commercial agriculture and turned to secondary and tertiary industries. Such labor loss has led to a shrinkage in the proportion of agricultural labor, which has, in turn, affected agricultural CO₂ eq. emissions as well. Fourthly, with the development of China's economy, residents' incomes have increased substantially, and the growing demand for animal protein has stimulated animal husbandry scale expansion. Finally, the total population of China is still growing, and population growth has caused an increase in the demand for livestock products, which has also led to the expansion of animal husbandry and an increase in CO₂ eq. emissions.

In summary, the changes in animal husbandry carbon emissions are the result of the combined effects of various factors, such as the advancement of technology, agricultural industrial restructuring, economic growth, and population growth.

Therefore, based on the original Kaya identity, the driving factors that may affect China's animal husbandry CO₂ eq. emissions are further decomposed as follows:

$$CO_2 = \frac{CO_2}{GDP_{L,S}} \times \frac{GDP_{L,S}}{GDP_A} \times \frac{GDP_A}{GDP} \times \frac{GDP}{P} \times P = T \cdot S_1 \cdot S_2 \cdot L \cdot P \quad (4)$$

In Formula (4), $T = \frac{CO_2}{GDP_{L,S}}$ represents the CO₂ eq. emissions intensity of unit animal husbandry GDP, which reflects the technological progress of animal husbandry. $S_1 = \frac{GDP_{L,S}}{GDP_A}$ represents the GDP of the livestock sector relative to agricultural GDP, which indicates the structural change in agriculture. $S_2 = \frac{GDP_A}{GDP}$ is the agricultural GDP value relative to the total GDP value, which indicates the structural change in the total economy. $L = \frac{GDP}{P}$ represents GDP per capita, which indicates economic growth or the level of residents' living standards. P represents the total population, reflecting the impact of the population-scale effect on CO₂ eq. emissions from animal husbandry.

3.3. LMDI Decomposition

The Log Mean Divisia Index (LMDI) was first proposed and used by Ang to discover the effect of various driving factors in relation to the total effect [21,22], to reveal the contribution of each factor to GHG emissions, and to find out the deep-seated factors that affect GHG emissions. The LMDI decomposition method has the advantages of complete decomposition without residuals and needs fewer data than other decomposition methods. LMDI has two forms: one is additive decomposition; the other is multiplicative decomposition. These two forms can be converted into each other. According to the characteristics of the LMDI method, we can obtain the following formula according to Formula (3):

(1) Additive Decomposition:

$$\Delta CO_2 = CO_2^t - CO_2^0 = \Delta CO_{2T} + \Delta CO_{2S_1} + \Delta CO_{2S_2} + \Delta CO_{2L} + \Delta CO_{2P} \quad (5)$$

(2) Multiplicative Decomposition:

$$CO_2 = \frac{CO_2^t}{CO_2^0} = CO_{2T} \times CO_{2S_1} \times CO_{2S_2} \times CO_{2L} \times CO_{2P}. \quad (6)$$

In Formulas (5) and (6), ΔCO_{2T} , ΔCO_{2L} , ΔCO_{2S_1} , ΔCO_{2S_2} , and ΔCO_{2P} represent the net contribution of CO₂ eq caused by technological development, structural change in agriculture, structural change in the total economy, living standard improvement, and population growth, respectively. Meanwhile, CO_{2T} , CO_{2S_1} , CO_{2S_2} , CO_{2L} , and CO_{2P} represent the CO₂ eq from husbandry caused by technology development, structural change in agriculture, structural change in the total economy, living standard improvement, and

population growth, respectively. Each driving factor can be rewritten in different forms as follows:

(3) **Additive Decomposition of Animal Husbandry:**

$$\Delta CO_{2T} = \frac{CO_2^t - CO_2^0}{\ln CO_2^t - \ln CO_2^0} \times \ln \frac{T^t}{T^0} \quad (7)$$

$$\Delta CO_{2S_1} = \frac{CO_2^t - CO_2^0}{\ln CO_2^t - \ln CO_2^0} \times \ln \frac{S_1^t}{S_1^0} \quad (8)$$

$$\Delta CO_{2S_2} = \frac{CO_2^t - CO_2^0}{\ln CO_2^t - \ln CO_2^0} \times \ln \frac{S_2^t}{S_2^0} \quad (9)$$

$$\Delta CO_{2L} = \frac{CO_2^t - CO_2^0}{\ln CO_2^t - \ln CO_2^0} \times \ln \frac{L^t}{L^0} \quad (10)$$

$$\Delta CO_{2P} = \frac{CO_2^t - CO_2^0}{\ln CO_2^t - \ln CO_2^0} \times \ln \frac{P^t}{P^0} \quad (11)$$

(4) **Multiplicative Decomposition of Animal Husbandry:**

$$CO_{2T} = \exp \left[\frac{\ln CO_2^t - \ln CO_2^0}{CO_2^t - CO_2^0} \times \Delta CO_{2T} \right] \quad (12)$$

$$CO_{2S_1} = \exp \left[\frac{\ln CO_2^t - \ln CO_2^0}{CO_2^t - CO_2^0} \times \Delta CO_{2S_1} \right] \quad (13)$$

$$CO_{2S_2} = \exp \left[\frac{\ln CO_2^t - \ln CO_2^0}{CO_2^t - CO_2^0} \times \Delta CO_{2S_2} \right] \quad (14)$$

$$CO_{2L} = \exp \left[\frac{\ln CO_2^t - \ln CO_2^0}{CO_2^t - CO_2^0} \times \Delta CO_{2L} \right] \quad (15)$$

$$CO_{2P} = \exp \left[\frac{\ln CO_2^t - \ln CO_2^0}{CO_2^t - CO_2^0} \times \Delta CO_{2P} \right] \quad (16)$$

T , S_1 , S_2 , L , and P in Equations (7)–(11) have the same meanings as the corresponding symbols in Equation (4). Superscript 0 and t represent the beginning and end of the study period, respectively. We use Equations (5)–(16) and the data we described in Section 2 to carry out our research.

4. Results and Analysis

4.1. Animal Husbandry CO₂ eq Emissions and Driving Factor Decomposition

By means of calculations, we found that the total amount of animal husbandry CO₂ eq emissions declined slightly from 2001 to 2019 and that its average annual growth rate was -1.20% , while animal husbandry GDP, agricultural GDP, national total GDP, and total population growth rate were 7.06% , 7.90% , 11.15% , and 5.13% , respectively. To reveal the net influence of the five factors mentioned in Section 3.2—technological advancement, structural change in the agricultural economy, structural change in the total economy, living standard improvement, and population growth on the CO₂ eq emissions changes in China's animal husbandry—we used both additive and multiplicative forms of the LMDI method to decompose the total CO₂ eq emissions.

With calculations, we derived the net effect of each driving factor on CO₂ eq emissions in animal husbandry. Figure 1, below, shows the total effect of each driving factor from 2001 to 2019 separately.

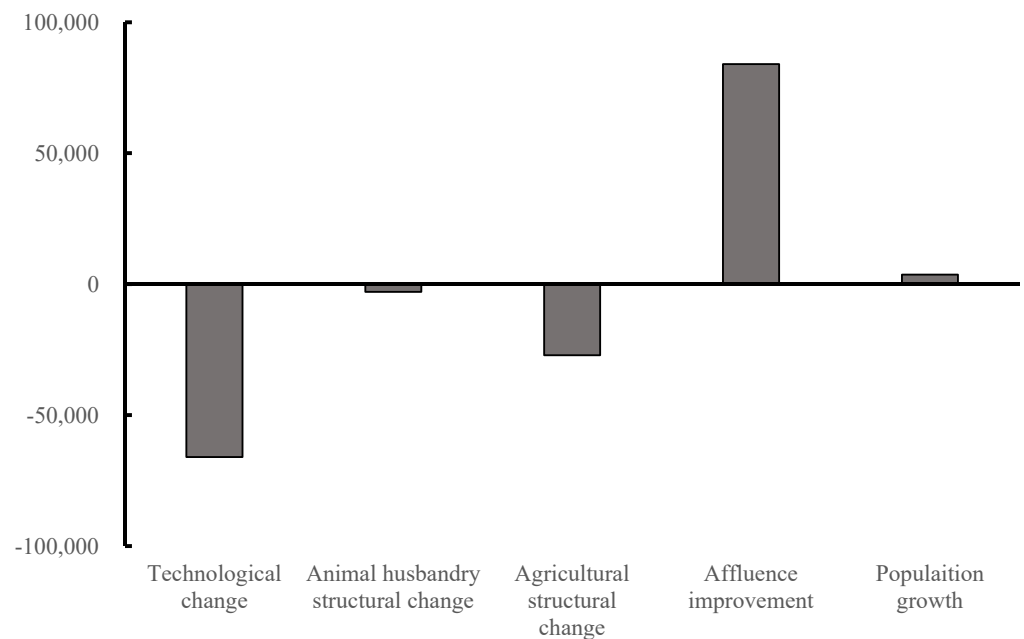


Figure 1. The results of summation and decomposition of total driving effects (units: 10,000 tons).

After analyzing the total effect of each driving factor, using the additive form of the LMDI method, we went on to use a multiplicative form of the LMDI method to analyze the contribution of each driving factor. Figure 2 shows the change in the contribution of each driving factor from 2001 to 2019 in animal husbandry.

(1) The technological advancement effect

According to the analysis, technological advancement has a very strong negative effect on CO₂ eq emissions in animal husbandry. From Figure 2, it can be seen clearly that the CO₂ eq emissions reduction caused by technological advancement effect from 2001 to 2019 has reached a total of 660.0124 million tons. The main reason for this reduction is that China's animal breeding technology has made huge progress during the analysis period and production efficiency has increased, which has led to a significant decrease in CO₂ eq emissions, while production has been maintained or even increased. Although the contribution of the technological upgrade vector has been slightly reduced in recent years, it still has a strong negative effect on CO₂ eq emissions from husbandry.

The average contribution rate of the technological upgrade effect on CO₂ eq emissions reduction from 2001 to 2019 years is 26.49%. This indicates that technological advancement is the most powerful driving factor reducing CO₂ eq emissions from animal husbandry [23]. This fact can also be seen in Figure 2. In the progress of livestock keeping and manure management, appropriate breeding scales and waste recycling systems will help to reduce CO₂ eq emissions from the livestock industry as well [24,25].

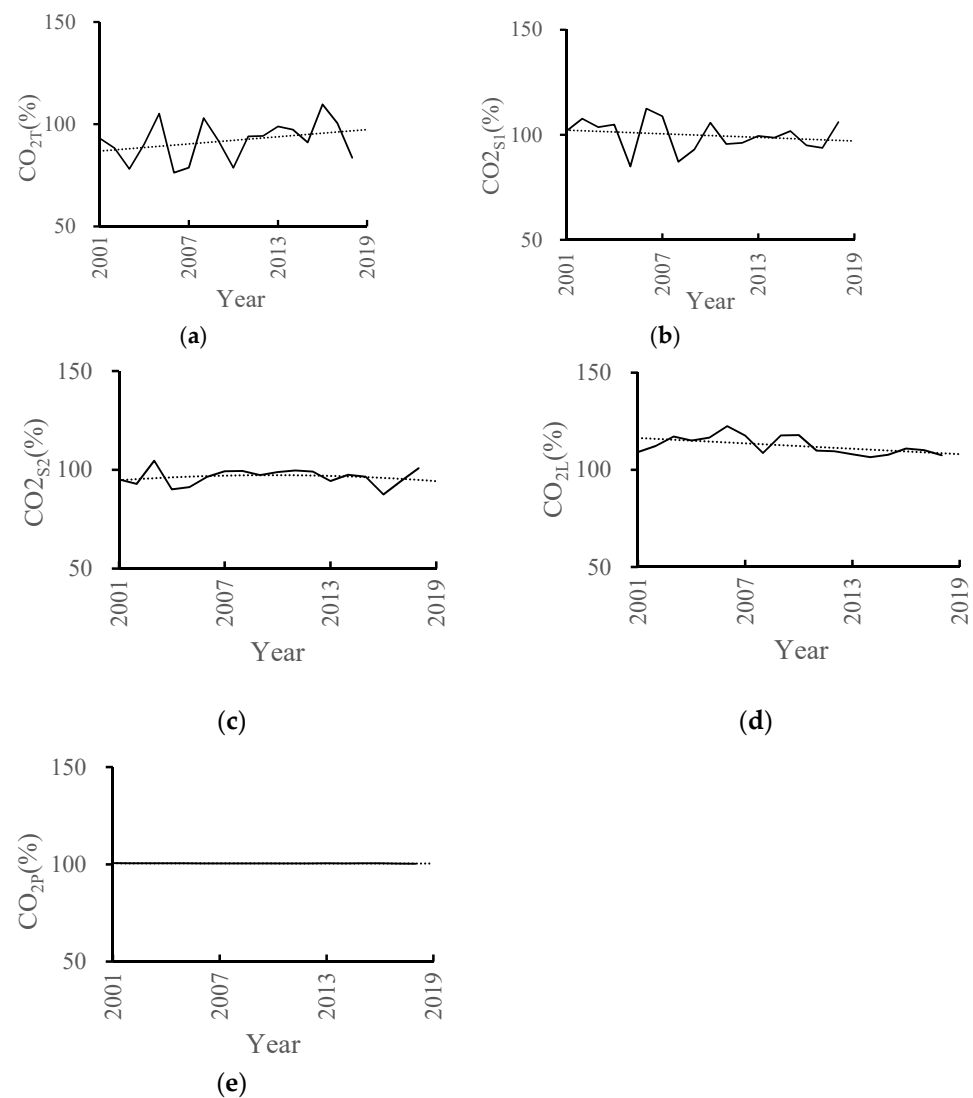


Figure 2. (a) Change in the contribution rate of technological advancement effects. (b) Change in the contribution rate of effects of agricultural structural change. (c) Change in the contribution rate of effects of total economic structural change. (d) Change in the contribution rate of living standard improvement effects. (e) Change in the contribution rate of population growth effects.

(2) The agricultural structural change effect

During the study period, the agricultural structural change effect has the smallest abstract contribution to animal husbandry CO₂ eq emissions, and its overall contribution is negative. From 2001 to 2019, the cumulative CO₂ eq emissions reduction in animal husbandry caused by agricultural structural change was 28.64 million tons. This indicates that the GDP of animal husbandry has accounted for less and less of total agricultural GDP across the country. The main reason for this situation is that, with the development of large-scale and specialized livestock farming and due to the environmental regulatory requirements, most provinces have begun to control the scale of livestock farms and restrict the scale of free-range breeding, which has caused the growth rate of animal husbandry GDP to slow down in relation to overall agricultural GDP, so that, proportionally, animal husbandry GDP shows a downward trend (Figure 2b). With multiplicative decomposition, the contribution rate of the effect of agricultural structural change has declined from 102% in 2001 to 94% in 2019.

Additionally, urbanization and rapid economic growth in China from 2001 to 2019 are also important reasons for the decline in animal husbandry GDP. As urbanization goes on, urban agriculture, aquaculture, agricultural tourism, high value-added agricultural

products, seedlings, and flower planting have received more attention and developed faster [26]. The proportion of the livestock breeding industry, as a traditional agricultural sector under these circumstances has become, relatively, smaller and smaller. According to the data from the *China Statistical Yearbook*, the GDP of animal husbandry in relation to total agricultural GDP from 2001 to 2019 fell from 29.67% to 26.67%. Therefore, the agricultural structural change effect is an important factor in restraining the increase in CO₂ eq emissions in animal husbandry. However, natural resource and environmental conditions in China vary from province to province; therefore, the agricultural structural change effect and the contribution rate in different provinces are different. For example, in Inner Mongolia and Qinghai, the agricultural structural change effect is positive, in contrast to most provinces in China. The driving force in each province and the driving direction will be discussed in the next section.

(3) The effects of total economic structural change

From 2001 to 2019, China's agricultural economy has made a remarkable achievement. The agricultural GDP in 2019 was 4.5 times that of 2001. However, as the agricultural economy grows, agricultural CO₂ eq emissions also increase. Although the effect of agricultural economic development on total CO₂ eq emissions is positive, as the proportion of agricultural GDP of the national total GDP is declining year by year, the effects of total economic structural change appear to have a negative contribution on CO₂ eq emissions in the livestock breeding sector [27]. However, the decrease in relative value does not indicate that the production efficiency of agricultural economic development has increased. On the contrary, it reflects the rapid growth of CO₂ eq emissions from the secondary and tertiary industries, and the problem of high CO₂ eq emissions in secondary and tertiary industries also needs to be solved urgently.

(4) The living standard improvement effect

Economic growth has led to a great improvement in people's living standards. As living standards have risen, people's need for animal protein intake has increased. This demand would have driven CO₂ eq emissions to increase in animal husbandry. From 2001 to 2019, the cumulative increase in CO₂ eq emissions from animal husbandry was 840.63 million tons.

China's rapid economic growth has not only brought about the improvement of people's living standards but also caused the dilemma of environmental degradation. In 1991, Crossman and Krueger proposed the Environmental Kuznets Curve (KEC) [28], describing the relationship between GDP growth and environmental pollution as an inverted U curve. In the first 15 years of the 21st century, China's development pattern has proved the environmental Kuznets Curve, and unsustainable economic development has brought about a sharp increase in CO₂ emissions [29,30].

China joined the WTO in 2001, and in the following 20 years China's secondary and tertiary industries have developed rapidly; incomes continue to rise, dietary requirements have become higher, and the demand for high-quality animal protein has reached unprecedented levels. This has contributed to the flourishing of domestic animal husbandry to a certain extent [31]. As a WTO member, international importation and exportation of animal meat have become more frequent, which has indirectly led to an increase in CO₂ eq emissions from animal husbandry in China.

(5) The population growth effect

Population expansion will bring about a "congestion effect", which will have a positive impact on the growth of CO₂ eq emissions through population urbanization and household consumption effects [32]. The population growth effect has made a positive contribution to CO₂ eq emissions in animal husbandry [33], but the absolute value of the effect is the least of the five driving factors. In Figure 2e, its trend from 2001 to 2019 appears to be a smooth straight line. Our explanation for this is that, with the change in national fertility concepts, the birth rate has decreased such that the positive effect of population growth on CO₂ eq emissions in animal husbandry is no longer obvious. (In fact, the average growth rate of the population from 2001 to 2019 was around 0.51%.) Furthermore, with the continuous

improvement of living standards, people's dietary nutrition is becoming more and more balanced. When people's intake of animal meat protein reaches a certain level, they will inevitably turn to healthier and diversified protein intake, which also limits the animal husbandry industry to a certain extent. This is also the possible reason why the population effect is not obvious from Figures 1 and 2e.

However, as we mentioned, the situation in China varies from province to province since populational growth rates are different in different provinces. As the research progressed, we found that some provinces even underwent negative population growth changes from 2001 to 2019. Research on inter-regional differences in CO₂ eq emissions from animal husbandry will be conducive to our understanding of the current status and reasons for CO₂ eq emission patterns associated with animal husbandry in different regions of China. This research will be explored in the next section.

To sum up, first of all, the effects of technological advancement, agricultural structural change, and total economic structural changes generally have had a negative effect on CO₂ eq emissions from animal husbandry. Living standard improvements and population growth effects have made a positive contribution to CO₂ eq emissions from animal husbandry. Secondly, net total CO₂ eq emissions depend on the absolute value of the sum of the five factors. Finally, the five factors in carbon emissions from animal husbandry show differences within each province, which lead to regional differences. Therefore, it is necessary to continue to explore inter-provincial differences in the total amount of animal husbandry CO₂ eq emissions and the differences in the role of driving factors in different provinces.

Following the same analysis paths as above, we calculated the total CO₂ eq emissions from animal husbandry in 31 provinces and we also used the LMDI method to decompose and observe the driving effects of animal husbandry in 31 provinces, then conducted a comparative analysis. We tried to explore why and how the same five driving factors have led to different driving effects on CO₂ eq emissions from animal husbandry in the different provinces.

4.2. Accounting of Total Carbon Emissions by Provinces and Decomposition of Driving Factors

China has a vast territory. The resource endowments of different provinces are different, which has led to an absolute imbalance in the development of animal husbandry in each province. According to the calculation formulas and provincial data, we can obtain the panel data for the total CO₂ eq emissions of 31 provinces from 2001 to 2019. Due to space limitations, our research only displays data for every two years since 2001. The provincial CO₂ eq emissions data are shown in Table 4.

From Table 4, we can easily find out that the changes in CO₂ eq emissions in different provinces are uneven and that rates of change are also very different. Based on average rates of change in CO₂ eq emissions from the livestock industry from 2001 to 2019, we classified the 31 provinces into four types. First of all, Heilongjiang, Inner Mongolia, Xinjiang, Gansu, Ningxia, Qinghai, and Yunnan show a positive average change rate. They are in the regions where CO₂ eq emissions in animal husbandry are increasing. We define these kinds of areas as CO₂ fluctuating and rising in CO₂ eq emissions regions.

Except for these seven provinces, the average change rate in CO₂ eq emissions from animal husbandry is negative in other provinces. Among these negative change provinces, the average rates of CO₂ eq emissions reduction in animal husbandry in Beijing and Shanghai from 2001 to 2019 exceeded 10%; they are 11.36% and 10.82%, respectively, which represents a rapid decline in CO₂ eq emissions. Thus, Beijing and Shanghai are defined as fast falling in CO₂ eq emissions regions.

Liaoning and Tibet are areas where CO₂ eq emissions from animal husbandry are slowly decreasing, and their average change rate is lower than 1% (−0.48% and −0.06%, respectively); therefore, they are defined as slow falling CO₂ eq emissions regions.

The average change rates in other provinces not mentioned above are between 10% and 1%, and we classify these as steady falling CO₂ eq emissions regions.

Different regions with different change rates in CO₂ eq emissions are shown in Figure 3.

Table 4. The results for total carbon emissions from animal husbandry from 2001 to 2019 (units: 10,000 tons).

Province	2001	2004	2007	2010	2013	2016	2019
China	43,536.67	42,748.72	40,976.61	39,417.81	37,516.41	36,652.90	35,210.42
Beijing	135.27	151.57	104.72	96.83	96.73	82.31	26.33
Tianjin	119.32	173.44	100.85	111.80	114.79	117.53	94.12
Hebei	2757.09	3077.29	1910.18	1672.86	1663.54	1635.14	1395.53
Shanxi	884.89	849.62	529.61	483.67	532.62	558.77	542.33
Inner Mongolia	1783.05	2714.54	2886.51	3104.39	2939.71	3099.89	3091.98
Liaoning	995.79	1375.92	1270.63	1395.90	1399.86	1454.38	1032.60
Jilin	1398.66	1527.09	1655.20	1419.62	1370.05	1337.96	1050.21
Heilongjiang	1519.66	1822.14	1711.66	1777.19	1662.29	1654.26	1560.22
Shanghai	69.07	26.29	41.90	51.80	52.08	36.36	24.50
Jiangsu	751.43	772.19	455.07	479.93	474.69	458.09	250.83
Zhejiang	349.48	348.49	253.97	287.30	287.65	159.88	132.85
Anhui	1799.53	1699.33	706.08	756.79	799.47	818.53	531.58
Fujian	484.58	507.14	394.71	414.10	417.24	361.34	207.09
Jiangxi	1161.73	1173.44	799.88	957.91	1045.58	1032.82	831.28
Shandong	3677.56	3788.83	2425.11	2171.20	2246.04	2216.16	1704.66
Henan	4689.49	5176.26	3729.11	3723.77	3427.90	3359.32	1937.87
Hubei	1378.20	1456.91	1235.24	1319.70	1393.91	1400.33	1005.35
Hunan	1957.57	2336.99	1766.51	1882.74	1911.33	1923.54	1639.20
Guangdong	1442.88	1319.15	941.11	956.30	983.98	939.64	545.85
Guangxi	2503.71	2366.22	1406.79	1576.39	1613.68	1471.66	1165.54
Hainan	444.39	446.72	260.62	314.94	297.64	269.92	169.88
Chongqing	739.66	764.65	504.58	621.35	636.96	647.23	487.44
Sichuan	3765.22	4081.64	3791.09	3706.71	3641.39	3649.30	2989.83
Guizhou	2083.97	2361.55	1635.99	1719.84	1521.60	1653.24	1512.93
Yunnan	2641.12	2645.62	2456.69	2572.88	2525.46	2679.30	2762.42
Tibet	1803.65	1973.17	1969.62	1928.57	1919.83	1870.56	1796.81
Shaanxi	912.15	1101.50	718.40	712.56	660.97	670.14	699.24
Gansu	1295.50	1409.70	1537.47	1623.67	1643.01	1685.48	1698.72
Qinghai	1423.67	1400.17	1483.36	1499.77	1493.96	1555.01	1546.27
Ningxia	270.85	353.40	346.71	350.97	386.19	429.30	495.48
Xinjiang	1967.97	2328.63	1949.93	1641.25	1908.48	2052.84	2284.11

To more intuitively observe the differences in total carbon emissions between various provinces, we have drawn a visual map showing the total carbon emissions from animal husbandry based on the calculated panel data of the total carbon emissions for each province, as shown in Figure 3.

To analyze how the combined effects of various factors have led to the difference in the rates of change in different provinces, based on the panel data of the total CO₂ eq emissions from animal husbandry in each province from 2001 to 2019, we used the multiplicative decomposition method to analyze the driving effects in 31 provinces, as shown in Table 5:

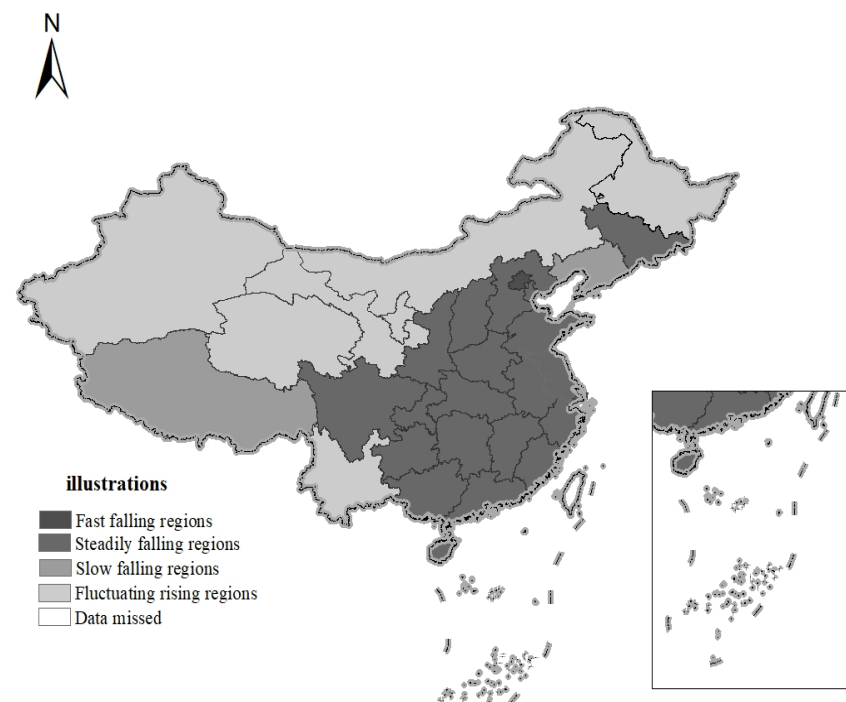


Figure 3. Regional distribution of different types of CO₂ eq emissions changes from animal husbandry in China from 2001 to 2019. Note: This map is based on the standard map downloaded from the standard map service website of the National Bureau of Surveying, Mapping, and Geographic Information with the approval number GS (2016)2556. The base map has not been modified.

Table 5. Decomposition of the driving factors of each province from 2001 to 2019 (%).

Province	CO _{2T}	CO _{2S1}	CO _{2S2}	CO _{2L}	CO _{2P}	Province	CO _{2T}	CO _{2S1}	CO _{2S2}	CO _{2L}	CO _{2P}
Beijing	97	96	88	113	103	Hubei	91	99	97	115	99
Tianjin	96	98	94	110	103	Hunan	93	100	96	114	100
Hebei	91	99	97	111	101	Guangdong	89	99	95	112	102
Shanxi	89	101	97	114	101	Guangxi	89	98	97	114	100
Inner Mongolia	93	101	96	116	100	Hainan	87	100	97	113	101
Liaoning	92	101	99	110	100	Chongqing	91	99	95	117	99
Jilin	90	103	97	112	100	Sichuan	91	100	96	115	99
Heilongjiang	90	100	105	109	99	Guizhou	88	99	97	118	99
Shanghai	102	96	90	110	102	Yunnan	90	101	97	115	101
Jiangsu	90	98	95	114	101	Tibet	92	102	93	114	102
Zhejiang	92	98	94	112	101	Shaanxi	89	100	96	117	100
Anhui	87	101	94	115	100	Gansu	93	100	97	113	100
Fujian	88	101	95	114	101	Qinghai	90	101	98	114	101
Jiangxi	92	100	94	115	101	Ningxia	93	101	96	115	101
Shandong	89	100	96	112	101	Xinjiang	91	101	98	112	102
Henan	89	100	95	114	99						

Note: the data in the table have been converted into percentage values. CO_{2T}, CO_{2S1}, CO_{2S2}, CO_{2L}, and CO_{2P} represent the CO₂ eq emissions from husbandry caused by technological development, structural change in agriculture, structural change in the total economy, living standard improvement, and population growth, respectively.

Based on the data in Table 5 and the contribution of each driving factor to animal husbandry CO₂ eq emissions in different provinces, we classified 31 provinces into 3 driving types. First of all, according to the previous analysis, technological advancement is the most powerful driving force for CO₂ eq emissions reduction in animal husbandry, and living standard improvement is the most powerful driving force for the growth of CO₂ eq emissions in animal husbandry. The abstract value of the positive effects of living standard improvement in Heilongjiang, Inner Mongolia, Xinjiang, Gansu, Ningxia, Qinghai, and

Yunnan province is greater than the absolute value of the negative effects of CO₂ eq emissions caused by factors such as technological advancement in animal husbandry. We define these kinds of provinces as economic growth-driven provinces.

The effects of the adjustments in the agricultural structure and the national industrial structure in Beijing, Shanghai, and Tianjin have had a significant influence on CO₂ eq emissions reduction in animal husbandry, so the three regions are defined as economic restructuring-driven areas. In other provinces, the absolute value of the negative effect caused by technological progress and adjustment in industrial structure is greater than the absolute value of the positive effect caused by living standard improvement; thus, they show a downward trend in total CO₂ eq emissions in animal husbandry from 2001 to 2019. We define these as provinces driven by changes in technology and industrial structure. We drew a visual map of the driving effects of inter-provincial animal husbandry CO₂ eq emissions and CO₂ eq emissions reduction, as shown in Figure 4:

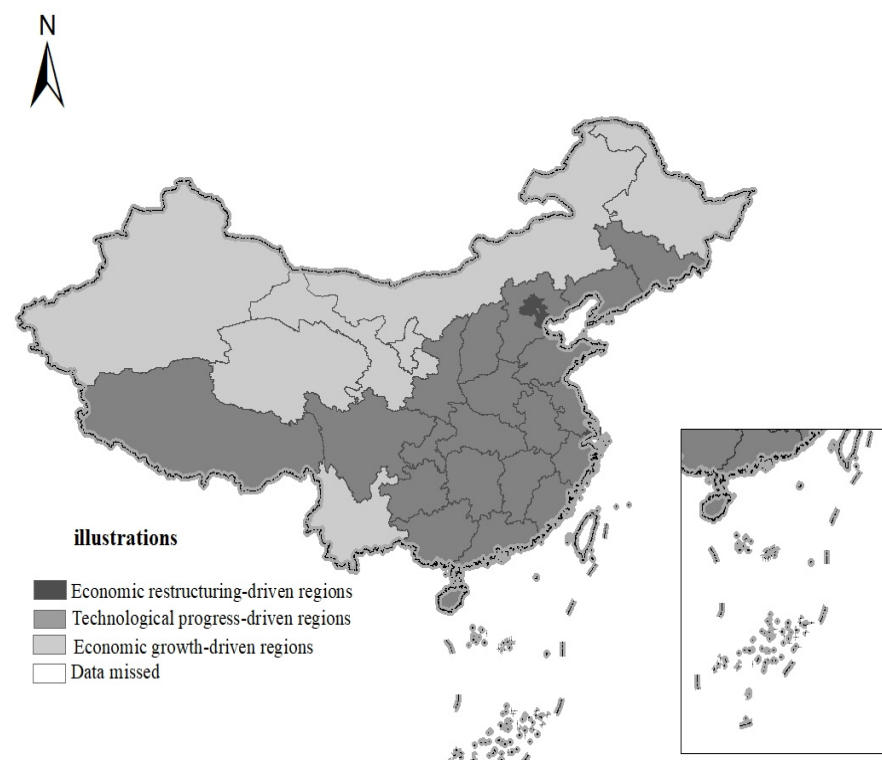


Figure 4. Regions with different types of drivers. Note: This map is based on the standard map downloaded from the standard map service website of the National Bureau of Surveying, Mapping, and Geographic Information with the approval number GS (2016)2556. The base map has not been modified.

With reference to Figures 3 and 4, we can establish the following facts.

First of all, we found that the three regions (Beijing, Tianjin, and Shanghai) that are driven by the effect of technological advancement had high average rates of CO₂ eq emissions reductions from 2001 to 2019. The rapid decline in CO₂ eq emissions from animal husbandry in these three regions in recent years has mainly been due to the relocation and adjustment of industries. Since 2009, Beijing has gradually promoted the relocation of its non-capital functions and promoted the coordinated development of Beijing–Tianjin–Hebei [34,35]. The government transferred part of Beijing’s non-capital functions to neighboring areas, such as Tianjin, Shijiazhuang, and Xiong’an New District [36]. Tianjin also adjusted its development strategy and industrial structure accordingly, while Shanghai focused on integrated digital industries, emerging strategic industries, and modern service industries. In terms of animal husbandry, these three regions have carried out a thorough

modernization of the animal husbandry industry that still exists [37,38]. Due to limited land resources, intensification and high-tech density are important characteristics of animal husbandry in these areas [39]. This is also the reason why the agricultural structural change effects and the effects of total economic structural change have been strong negative driving powers in these three regions. With the development of breeding technology and intensive production, the production efficiency of animal husbandry has increased and the intensity of CO₂ eq emissions has decreased. The total amount of regional animal husbandry CO₂ eq emissions has shown an obvious downward trend.

Secondly, the fluctuating rising regions in Figure 3 correspond to the economic growth-driven regions in Figure 4. In these areas, the agricultural economy has developed rapidly in recent years. The investment in animal husbandry, policy support, and natural geographical advantages have made animal husbandry production more efficient in these regions, and with the development of the economy, farmers' awareness of the market economy has been continuously strengthened. Driven by higher economic benefits, people in these areas are also becoming more motivated to engage in animal husbandry production [40]. In addition, large-scale and mechanized breeding has increased fodder and fuel inputs, which has led to an upward trend in total CO₂ eq emissions from animal husbandry.

Thirdly, based on the data from 2001 to 2019 and the results presented in Figures 3 and 4, we found that the negative growth of CO₂ eq emissions driven by technological advancement effects and total industrial structure change effects will be offset by the positive growth in CO₂ eq emissions driven by living standard development effects. There is an ebb and flow relationship between them. Therefore, when the negative growth rate of CO₂ eq emissions driven by technological advancement effects and total industrial structural change effects is faster than the positive growth rate of CO₂ eq emissions driven by living standard development effects, the total CO₂ eq emissions of the livestock sector shows a net reduction and vice versa. CO₂ eq emissions from animal husbandry in technological progress-driven regions and economic restructuring-driven regions both show a decreasing trend, since these regions' technological advancement effects and total industrial structural change effects are more powerful than the living standard development effects.

It is worth noting that the effects of agricultural structural change and population-scale effects among provinces are not all consistent with the driving effects at the national level. For instance, some provinces, such as Jilin, Liaoning, Shanxi, Shandong, Anhui, Inner Mongolia, Ningxia, Qinghai, Tibet, Yunnan, and Xinjiang, have experienced positive effects from agricultural structural adjustment. The possible reason for this phenomenon is that China has implemented a series of policies to promote the scale and intensification of animal husbandry, and the efficiency of animal husbandry production has increased significantly in recent years. In addition, with economic development, the continuous improvement of residents' living standards has caused the demand and prices of livestock products to rise sharply. Therefore, these provinces use their geographical advantages to expand the scale of animal husbandry and increase economic benefits. The adjustment of agricultural structure has led to an increase in the scale of animal husbandry in these provinces. It needs to be explained again that the data collected in this research reflect total animal husbandry farming at the provincial level and do not represent the differences between small-scale farmers and large-scale farmers at the micro-level. Therefore, we do not consider whether large-scale farming improves the efficiency of CO₂ eq emissions reduction. The total CO₂ eq emissions from animal husbandry are positively correlated with the total amount of livestock breeding. In this research, if the economic growth of animal husbandry is faster than the economic growth of the agricultural sector, animal husbandry will have a positive effect on total CO₂ eq emissions.

Besides the positive effects of the adjustment in agricultural structure, the population scale expansion effect must also be considered. The population scale expansion effect shows a negative effect on CO₂ eq emissions in Heilongjiang, Henan, Hubei, Chongqing, Sichuan, and Guizhou. (The results of their additive decomposition are: −25.15, −22.19, −18.09, −11.83, −151.65, −95.28, separately). Due to the continuous improvement of the

public transportation system, population movement has accelerated. In central and western regions of China, a large number of young and middle-aged laborers gather in a few large cities. Due to the overall economic recession and lower birth rate, population growth in northeast China is lower than the emigration rate. Therefore, in these regions, the population scale expansion effect on CO₂ eq emissions from animal husbandry was negative. Some studies have shown that the inter-provincial floating population in China is still highly concentrated in eastern cities [41–43]. The large number of migrants flowing into the eastern region compensated the population gap caused by the birth rate decline. Therefore, the population scale expansion effect on CO₂ eq emissions from animal husbandry in eastern regions such as Shanghai and Zhejiang was positive. It is foreseeable that as China begins to implement the policy of liberalizing fertility, the population scale of different regions will increase accordingly and the CO₂ eq emissions from animal husbandry caused by this will also increase in the future.

5. Conclusions and Discussion

After more than 40 years of development in reform and opening up, China's economy has made considerable progress, and agricultural production has also undergone tremendous changes. Due to economic development and the improvement of living standards, residents' demands for various livestock products have increased, which has stimulated the development of China's animal husbandry. Yet it has also brought a series of environmental problems. Therefore, it is of great significance to pay attention to the CO₂ eq emissions of animal husbandry and its driving factors. In addition, China has proposed the Carbon Peaking and Neutrality Goals, the aim of which is to fulfill China's international GHG emissions reduction obligations and truly achieve sustainable development. Since CO₂ eq emissions from animal husbandry is the most important source of agricultural CO₂ eq emissions, in the meantime, for food security and to meet market demands for livestock products, animal husbandry in China must make certain changes.

According to the analysis based on the LMDI and spatial analysis, we can make the following conclusions: (1) Similar to previous studies [11,13], the total CO₂ eq emissions of animal husbandry in China showed a gradual decline from 2001 to 2019, and the GDP of animal husbandry, agricultural GDP, total GDP, and population scale showed the opposite trend. Therefore, we decomposed the driving factors of total CO₂ eq emissions from animal husbandry and found that the effect of technological advancement, agricultural structural adjustment, and national industrial structural adjustment have made a negative contribution to CO₂ eq emissions from animal husbandry, while the living standard improvement effect and population-scale expansion effect have made a positive contribution to the CO₂ eq emissions of animal husbandry. (2) According to the average growth rate of CO₂ eq emissions from the livestock industry, we classified China's 31 provinces into four types: fluctuating rising regions, fast falling regions, slow falling regions, and steadily falling regions. At the same time, according to the main driving factors and their magnitudes of CO₂ eq emissions from animal husbandry in different areas, we classified 31 provinces into three types: economic restructuring-driven regions, technological progress-driven regions, and economic growth-driven regions. (3) Economic restructuring-driven regions correspond to regions where total CO₂ eq emissions from animal husbandry are rapidly declining. Economic growth-driven regions correspond to regions where the total CO₂ eq emissions from animal husbandry increase. The combined effect of technological advancement and decline in the ratio of agricultural GDP to total GDP have led to varying degrees of decline in animal husbandry CO₂ eq emissions in the rest of the regions [44]. (4) Compared to previous studies, with the improvement of animal husbandry production efficiency, some provinces have expanded the scale of animal husbandry breeding, and the effect of agricultural industrial structural adjustment in these provinces has shown a positive effect. (5) What has not been noticed before is that the population expansion effect has shown a negative effect in some provinces. This may be explained by the low birth rate in the past decades and continuous population emigration.

Based on these conclusions, we are led to the following insight. First, China's animal husbandry CO₂ eq emissions vary significantly from province to province. Therefore, local governments should pay attention to this fact and formulate policies in line with local conditions to promote animal husbandry CO₂ eq emissions reduction. Secondly, at both the national level and the provincial level, the CO₂ eq emissions from animal husbandry have shown a declining trend, but this decline has fluctuated very sharply. Based on this fact, the central government of China needs to formulate a long-term plan to ensure the stable reduction in animal husbandry CO₂ eq emissions and should formulate individualized policies for different provinces with large animal husbandry CO₂ eq emissions in order to improve their animal husbandry production efficiency while reducing animal husbandry CO₂ eq emissions.

Regarding existing research, we have considered the CO₂ eq emissions of different systems; however, due to the difficulty of obtaining some data and the complicated development status, there are still a few factors that have not been fully considered, such as the CO₂ eq emissions from poultry farming. In addition, this research mainly focuses on the macro-driving factors of animal husbandry CO₂ eq emissions and does not comprehensively cover the relevant micro-factors, such as the different scale of livestock farmers, different livestock breeding methods, animal waste disposal methods, etc. These provide directions for future research. As the issue of agricultural GHG emissions is receiving more and more attention, research on the estimation and trend of GHG emissions from animal husbandry will continue to deepen.

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