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RETRACTED: Decoupling of greenhouse gas emissions from livestock industrial development: Evidence from China Agricultural Green Development Modern Zone

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China Agricultural Green Development Modern Zone (CAGDMZ) constitute a demonstration area for achieving green and sustainable development of Chinese agriculture. It plays a role in demonstrating high-quality agricultural development and environmental protection. As a result, a coordinated interaction among livestock greenhouse gas (GHG) emissions and rapid industrial livestock evolution in the CAGDMZ is of great concern to China's government. In this paper, we were the first to research the decoupling relationship between livestock GHG emissions and industrial development by using data from 165 CAGDMZ of China from 2010 to 2019 at different regional scales and long time series. On this basis, we further explored the factors affecting livestock GHG emissions by using the Logarithmic Mean Divisia Index method (LMDI). Our analysis revealed that the amount of GHG emissions from livestock in the CAGDMZ showed a rising and then declining trend. Pigs, nondairy cattle and sheep were the main targets of livestock GHG emission reductions. There were obvious spatial differences in livestock GHG emissions. 17 provinces' CAGDMZ achieved emissions reductions, but 14 provinces' CAGDMZ increased livestock GHG emissions. The Northeast CAGDMZ had the highest livestock GHG emissions and the Eastern CAGDMZ had the largest livestock GHG deceleration. Furthermore, the decoupling status in the CAGDMZ were unstable. Most provinces or regions of the CAGDMZ maintained the economic growth of livestock while curbing the excessive growth of GHG emissions. Only a few of them achieved a win-win situation of livestock output value increase while GHG emission reduction. Moreover, the comprehensive effect showed an inverted "U" trend. Production efficiency was the most major contributor to livestock GHG emissions reductions. Economic development factor and labor scale factor were the main driving factors for increasing GHG emissions. Industrial structure factor shifted from promotion to suppression of livestock GHG emissions. Therefore, some policies to accomplish the CAGDMZ's long-term development were proposed.

KEYWORDS

livestock industrial development, livestock GHG emissions, decoupling status, LMDI decomposition model, China Agricultural Green Development Modern Zone

1 Introduction

Greenhouse gas (GHG) emissions from agricultural production system cause the issue of climate change (Elahi et al., 2021a; Bai et al., 2021; Elahi et al., 2022b). Reducing GHG emissions has achieved global consensus to protect the environment (Thomas et al., 2004; Elahi et al., 2019a; Elahi et al., 2022a). Agriculture is the second-largest source of GHG emissions. Livestock is the main source of greenhouse gas generation in agriculture and the main source of CH₄ and N₂O emissions (Peng et al., 2016; Buratti et al., 2017; Bai et al., 2018). Thus, adoption strategies are required to increase system efficiency while reducing the GHG emission and health damages (Elahi et al., 2019b; Elahi et al., 2019c; Elahi et al., 2020; Elahi et al., 2021b). Some researches have shown that the global livestock industry emits 710 million tons of carbon dioxide equivalent (CO₂-eq) greenhouse gases each year. Livestock products and their byproducts account for approximately 18% of total global GHG emissions (Gerber et al., 2013). 37% of global CH₄ emissions and 65% of global N₂O emissions come from livestock (Zhuang et al., 2019). Over the past two decades, the global consumption of livestock products has increased sharply due to population growth and higher quality of life. In particular, meat consumption has increased by 56.59% (Elahi et al., 2017; Elahi et al., 2018). It has further led to increase livestock GHG emissions (Chen et al., 2021). At the same time, the OECD predicts that the global demand for livestock products will continue to increase due to population and income growth. Meat consumption will increase by 40 million tons in 2028, especially in developing regions such as Asia and Latin America (OECD, 2019). Therefore, livestock can trigger more GHG emissions as a result of the increasing livestock products and could exert enormous pressure on the global environment.

Since Reform and Opening-up of China, residents' demand for meat, eggs, milk and other livestock products have been increasing due to rapid socio-economic development. Currently, China has become the largest meat consumption market in the world, consuming 46% of pork, 11% of beef, 18% of chicken and 48% of mutton (Zhang et al., 2018). At the same time, in order to satisfy residents' demand for livestock products, the Chinese government has invested many resources to develop the livestock industry and now becomes the world's largest livestock producer (Xue et al., 2019).

The National Bureau of Statistics of China reported that pork, beef and mutton production totaled 42.553, 6.673, and 4.875 million tons, respectively (NBSC, 2020). Milk and egg production was 32.976 and 33.09 million tons, respectively. Nevertheless, accelerated advance of animal husbandry industry has led to significant GHG emissions, such as CH₄,

N₂O and CO₂. According to The Third National Communication on Climate Change of the People's Republic of China, enteric fermentation and manure management produce large amounts of CH₄ and N₂O gases which account for 42.8% of total agricultural emissions in China (NCSC, 2018). Therefore, the livestock industry has become a key field of greenhouse gas emissions reduction in China's agriculture. In particular, as the world's largest developing country, China has actively assumed its international responsibility to reconcile the contradictions among economic development and environmental protection. It has also committed to achieving peak emissions by 2030 and carbon neutrality by 2060 (Zhao et al., 2017; Ma et al., 2019; Dong et al., 2020; Peng et al., 2020; Zhao et al., 2020; Zhao et al., 2021). In order to achieve this goal, Chinese government has emphasized green agricultural development. It takes livestock as an important area for reducing GHG emissions in agriculture and has formulated a series of sustainable development policies. China Agricultural Green Development Modern Zone (CAGDMZ) constitutes a significant agricultural policy to explore sustainable development and to provide typical experiences for green agricultural development in China.

The CAGDMZ is a high-quality development zone representing the environmental protection and modernization of China's livestock industry (Luo et al., 2002; Iarrp, 2020). On the one hand, it has improved the resource utilization rate of livestock manure by adjusting breeding structures and production modes. In this way, the CAGDMZ ultimately reduces greenhouse gas emissions from livestock and even from agriculture. On the other hand, the CAGDMZ pays attention to the livestock output. Therefore, we can propose policy recommendations for livestock sustainable development by studying the relationship between livestock GHG emissions and output value growth in the CAGDMZ.

In theory, an inverted U-shaped curve is demonstrated by researches which reflects the correlation of carbon dioxide emissions and economic and industrial expansion in agriculture (Zhao et al., 2017; Han et al., 2018). Agricultural GHG emissions rise rapidly with agricultural economic growth at first. Subsequently, agricultural carbon dioxide emissions will reach a maximum as the industry expansion and increased output value. Emissions will indeed continue to fall as the agricultural economy expands. Scholars refer to the economic growth of agriculture being faster than the rate of environmental degradation due to GHG emissions as decoupling. It is the ideal state for individual countries pursuing sustainable agricultural development. The concept of decoupling was first proposed by Weizsäcker (1997) in the field of economic research. It reflected the asynchronous relationship among economic development

and carbon emissions. Decoupling indicators were further created by OECD (2002) and applied to agriculture. Tapio (2005) built decoupling elasticity to analyze the relevance among GHG emissions and economic development. Since then, numerous scholars used the decoupling elasticity to explore relationship between environmental pollution and economic growth (GDP), such as agricultural pollutant emissions, agricultural carbon emissions and livestock GHG emissions (Wang and Feng, 2019; Rehman et al., 2020; Bai et al., 2021). They also have researched the influencing factors of greenhouse gases (Ayyildiz and Erdal, 2021; Liu and Feng, 2021; Sun et al., 2022).

The literature has focused on the decoupling between agriculture environment and the agricultural economy. For example, They analyzed the agricultural carbon emissions and agricultural output value's decoupling relationship (Saravia-Matus et al., 2019; Hossain and Chen, 2021; Jiang et al., 2021; Liu et al., 2021; Wang and Lv, 2022). Studies of the estimation and influencing factor decomposition of carbon emissions for different livestock species have also been performed in the literature. For example, some studies have measured the GHG emissions of major livestock, such as pigs and beef cattle. Then they decomposed the drivers of livestock GHG using the Kaya equation and LMDI (Wang and Qiao, 2019; Dai et al., 2021; Zubir et al., 2021). However, there has been a lack of research on the relationship between livestock output value and GHG emissions from livestock in the CAMGDDZ. Against the background of a low-carbon economy, the development of livestock has brought about a series of environmental problems, such as an increase in GHG emissions. As a model zone for agricultural modernization in China, the CAGDMZ has played a critical role in coordinating the relationship among livestock GHG emissions and industrial development. Therefore, this paper focuses on the CAGDMZ, measures the GHG emissions of livestock as well as analyzing the decoupling state among livestock GHG emissions and livestock industrial development.

Numerous researchers have concentrated on the spatial and temporal characteristics of livestock GHG emissions in countries such as China, France, Malaysia and Bangladesh. There are also some literatures that analyze from Asian, European and other intercontinental perspectives (Dangal et al., 2017; Garnier et al., 2019; Siddiki et al., 2021; Zubir et al., 2021). Especially in China's existing studies, scholars have tended to research livestock GHG emissions at the national level, geographical level or province level, such as in Tibet, along the Yangtze River or in Jiangsu Province (Bai et al., 2021; Guo et al., 2021; Xiong et al., 2022). However, there has been a lack of studies on GHG emissions from livestock in different Chinese administrative regions. In particular, administrative regions largely affect the structure of livestock and industrial development, which is influenced by China's state system. Thus, ignoring regional differences

could lead to large deviations between policy-making and reality (Xue et al., 2014; Zhou et al., 2014). Moreover, studies of the long-term trends and spatial characteristics of livestock GHG emissions in the CAGDMZ have been insufficient. Therefore, this study concentrates on the relationship among development of livestock industry and livestock GHG emissions at the national, provincial and administrative regional scales in the CAGDMZ. The main contributions of the study are given as: Firstly, we calculated the livestock GHG emissions in the CAGDMZ at the first time. Secondly, we analyzed the decoupling relationship between livestock industry and livestock GHG emissions by using different regional scales and long time series in the CAGDMZ. This paper has enriched the research field of livestock GHG emissions in China in terms of research objects and research contents.

The general idea of this paper is to analyze the changes in livestock GHG emissions by livestock species and the source structure of GHG emissions. Then, the decoupling relationship among livestock GHG emissions and the development of livestock industry are discussed. Finally, we decompose the influential elements of livestock GHG emissions. The structure of this article is as follows: Section 2 presents the data used and our research methods. Section 3 presents the results and discussion. Section 4 presents the conclusions and suggestions.

2 Methodology and data

2.1 Research methods

2.1.1 Calculation of greenhouse gas emissions from livestock

CH₄ and N₂O emissions from livestock were calculated based on Ipcc (2006) standards at first. In order to convenient analyze, we further converted to CO₂ equivalents (CO₂-eq). Eq. 1 calculated livestock GHG emissions in the CAGDMZ.

$$C = C_{CH_4} + C_{N_2O} = \sum N_i \times \alpha_i \times 25 + \sum N_i \times \beta_i \times 295 \quad (1)$$

where C represents the gross livestock GHG emissions. C_{CH₄} represents CAGDMZ's livestock CH₄ emissions. C_{N₂O} represents CAGDMZ's livestock N₂O emissions. The livestock population is represented by N_i. α_i, and β_i represent the CH₄ and N₂O emission factors of livestock, respectively. To facilitate the analysis, CH₄ and N₂O were converted into CO₂ equivalents with conversion factors of 25 and 295, respectively (Tullberg et al., 2018; Huang et al., 2019). CH₄ and N₂O emissions factors were based on the standards of Ipcc (2006), calculated by the Provincial Greenhouse Gas Emission Inventory Guidelines issued by the Chinese government and study of Hu and Wang (2010) (Table 1).

TABLE 1 GHG emission factors from different emission categories and animal species.

Emissions category	Pigs	Nondairy cattle	Dairy cattle	Sheep	Poultry
Enteric CH ₄	1	51.4	68	8.23	–
Fecal CH ₄	3.5	1.5	16	0.505	0.02
Fecal N ₂ O	0.53	1.37	1	0.064	0.02

The emissions factor for nondairy cattle is the average of the emissions factors for buffalo and yellow cattle. The emissions factor for sheep is the average of the emissions factors for goats and sheep. The emissions factor for poultry is the average of the emissions factors for chickens, geese, ducks and turkeys (Sheng et al., 2015). We adjust the annual livestock population because the livestock population could be changed by breeding and slaughter. In this paper, we follow the method of Hu and Wang (2010) and Xiong et al. (2022):

- (1) When the slaughter rate is greater than or equal to 1, the annual livestock population is adjusted according to the amount of slaughter.

$$N_i = \text{Days_alive}_i \times \frac{M_i}{365} \quad (2)$$

where N_i represents the livestock population. Days_alive_i represents the average lifecycle of livestock. Average life cycle of pigs and poultry is 200 days and 55 days, respectively (Yao et al., 2017). M_i represents the amount of slaughter.

- (2) When the slaughter rate is less than 1, the annual livestock population is adjusted according to the amount of breeding.

$$N_i = (C_{it} + C_{i(t-1)})/2 \quad (3)$$

where N_i represents the livestock population. C_{it} and $C_{i(t-1)}$ represent the amount of breeding for year t and year $t-1$, respectively.

2.1.2 The Tapio decoupling model between livestock greenhouse gas emissions and industrial development

The Tapio decoupling model is used to investigate the decoupling connection among livestock GHG emissions and industrial development as well as economic growth of livestock. The following has been the estimation formula:

$$e = \frac{\% \Delta C / C}{\% \Delta H / H} = \frac{(C_{end} - C_{start}) / C_{start}}{(H_{end} - H_{start}) / H_{start}} \quad (4)$$

where e symbolizes the decoupling elasticity of livestock GHG emissions and livestock industrial development. $\% \Delta C$ is the change in livestock output. $\% \Delta H$ is the change in livestock GHG emissions. Livestock GHG emissions in the first and last

years of a research period are symbolized by C_{start} and C_{end} , respectively. H_{start} and H_{end} are the livestock output value in the first and last years of a research period, respectively.

The value of the Tapio decoupling elasticity is illustrated in Eq. 4. It represents the percentage change in GHG emissions when the output values from livestock change by 1%. When the GHG emissions of livestock no longer increase with the growth of output value, it indicates a decoupling between the two. It identifies the three decoupling types and eight decoupling states to further properly depict the decoupling relationship among livestock GHG emissions and livestock output growth (Luo et al., 2017; Siping et al., 2019), as shown in Table 2.

2.1.3 Decomposition model of factors influencing livestock greenhouse gas emissions

There are many methods to decompose the factors of livestock GHG emissions. But Ang (2004) pointed out that the Logarithmic Mean Divisia Index method (LMDI) method can eliminate the residual term and render the model more convincing based on a comprehensive comparison of various factor decomposition methods. In this paper, we use the LMDI method based on Raupach et al. (2007) who investigated the factors influencing GHG emissions by modified the Kaya identity. They are expressed as follows:

$$C = \sum \frac{C}{H} \times \frac{H}{A} \times \frac{A}{L} \times L \quad (5)$$

$$= \sum U \times S \times R \times P$$

where C is the GHG emissions of livestock in units of 10,000 tons. H is the gross domestic product of livestock in units of 100 million yuan. A is the total agricultural output value in units of 100 million yuan. L is the size of the agricultural labor force in 10,000 people. $U=C/H$ is the GHG emissions per unit output value of livestock, and it represents the production efficiency of livestock. $S=H/A$ is a ratio that represents the value of livestock output towards the entire value of agricultural industry output, it represents the industrial structure. $R=A/L$ is the output value of the unit agricultural labor force, it represents the level of economic development. The scale of labor is indicated by $P=L$, which represents the quantity of the rural labor force.

Additive decomposition is better than multiplicative decomposition in LMDI model decomposition. Therefore, A

TABLE 2 Classification of and criteria for decoupling relationships among livestock GHG emissions and livestock output.

Decoupling types	Decoupling states	% C/C	% H/H	e	Interpretation
Decoupling	Strong decoupling	<0	>0	$(-\infty, 0)$	GHG emissions decreased; output value increased
	Weak decoupling	>0	>0	$[0, 0.8)$	GHG emissions and output value increased simultaneously; GHG emissions grew more slowly
	Recessive decoupling	<0	<0	$(1.2, +\infty)$	GHG emissions and output value decreased simultaneously; GHG emissions decreased faster
Negative decoupling	Strong negative decoupling	>0	<0	$(-\infty, 0)$	GHG emissions increased; output value decreased
	Expansive negative decoupling	>0	>0	$(1.2, +\infty)$	GHG emissions and output value increased at the same time; GHG emissions increased faster
	Weak negative decoupling	<0	<0	$[0, 0.8)$	GHG emissions and output value decreased simultaneously; output value decreased faster
Coupling	Expansive coupling	>0	>0	$[0.8, 1.2]$	GHG emissions and output values increased simultaneously
	Recessive coupling	<0	<0	$[0.8, 1.2]$	GHG emissions and output value decreased simultaneously

decomposition of the elements that influence GHG emissions was performed using an additive decomposition depending on Eq. 6. We define the variations in livestock GHG emissions from based period to the T th period as:

$$\Delta C = C^T - C^0 = \Delta U + \Delta S + \Delta R + \Delta P \quad (6)$$

where ΔC represents the total effects, which is derived by summing the effects of all the factors that influence GHG emissions. C^T is livestock GHG emissions in the T th period. C^0 represents the GHG emissions of livestock in the base period. ΔU is the change in factors associated with production efficiency regarding GHG emissions. ΔS is the change in factors associated with industrial structure regarding GHG emissions. ΔR is the change in factors associated with economic development regarding GHG emissions. ΔP is the change in factors associated with labor scale regarding GHG emissions. The specific calculation formulas are as follows:

$$\Delta U = \sum \frac{C^T - C^0}{\ln(C^T/C^0)} \times \ln \frac{U^T}{U^0} \quad (7)$$

$$\Delta S = \sum \frac{C^T - C^0}{\ln(C^T - C^0)} \times \ln \frac{S^T}{S^0} \quad (8)$$

$$\Delta R = \sum \frac{C^T - C^0}{\ln(C^T - C^0)} \times \ln \frac{R^T}{R^0} \quad (9)$$

$$\Delta P = \sum \frac{C^T - C^0}{\ln(C^T - C^0)} \times \ln \frac{P^T}{P^0} \quad (10)$$

2.2 Data source

The agricultural survey data of the China Agricultural Green Development Modern Zone (CAGDMZ) for this study were collected from the China Agricultural Green

Development Research Association of the Chinese Academy of Agricultural Sciences. The data included the annual slaughter volume of livestock, total agricultural output value, livestock output value, rural labor force and other information for 165 CAGDMZ from 2010 to 2019. To eliminate the influence of inflation, the output value was adjusted according to the constant price in 2010.

3 Results and discussion

3.1 Temporal-spatial characteristics for livestock greenhouse gas emissions in China Agricultural Green Development Modern Zone

3.1.1 Trends of livestock greenhouse gas emissions in China Agricultural Green Development Modern Zone

We calculated the amount of GHG emissions of livestock from 2010 to 2019 in the CAGDMZ based on Eq. 1. Livestock GHG emissions in the CAGDMZ risen at first, then decreased. From 2010 to 2014, GHG emissions from livestock rose from 156.4936 to 179.0853 million tons CO₂-eq with a growth rate of 14.44%. After 2014, the emissions of livestock in the CAGDMZ began to decline. Until 2019, the GHG emissions of livestock decreased to 138.4007 million tons CO₂-eq (Figure 1).

Firstly, among the GHG emissions from different livestock species in the CAGDMZ from 2010 to 2019, pigs were the largest contributors to GHG emissions, followed by non-dairy cattle. Pigs GHG emissions accounted for more than 35 percent of overall livestock GHG emissions, whereas nondairy cattle GHG emissions accounted for more than 20 percent. Secondly, some significant differences were reflected in the GHG emissions

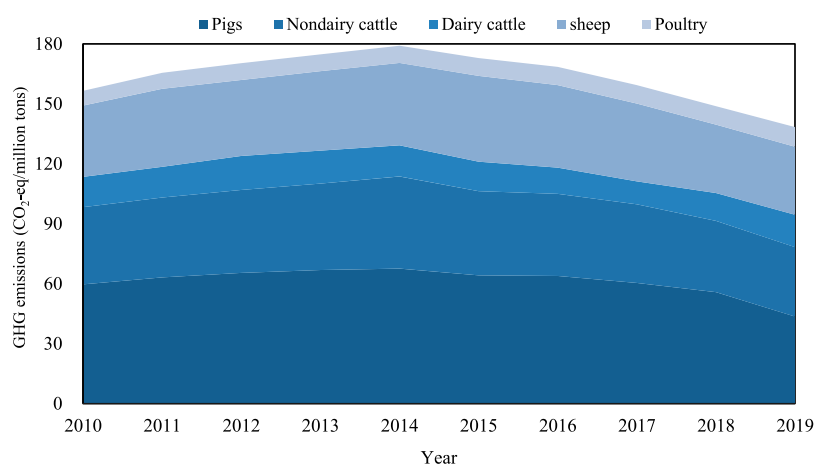


FIGURE 1
GHG emissions from livestock during 2010–2019 in the CAGDMZ.

TABLE 3 GHG emissions in different emission categories from 2010 to 2019 in the CAGDMZ.

Year	CH ₄ emissions			N ₂ O emissions (10 kt)	GHG emissions (10 kt Co ₂ -eq)
	Enteric CH ₄ emissions (10 kt)	Manure CH ₄ emissions (10 kt)	Total emissions (10 kt)		
2010	304.16	100.99	405.15	18.71	15,649.36
2011	321.54	106.67	428.21	19.81	16,548.36
2012	328.05	110.84	438.89	20.53	17,029.83
2013	338.46	112.87	451.34	20.98	17,473.03
2014	349.75	113.80	463.55	21.42	17,908.53
2015	340.21	109.61	449.22	20.54	17,288.79
2016	326.79	107.08	433.87	20.35	16,848.55
2017	307.35	100.85	408.19	19.44	15,940.24
2018	285.13	95.21	380.34	18.20	14,877.23
2019	283.72	80.83	364.55	16.02	13,840.07

tendencies of different livestock species. The GHG emissions of pigs, nondairy cattle and sheep showed an increasing trend at first, then they showed a large decrease. But dairy cattle had a fluctuating trend of “increasing-decreasing-increasing” and poultry always showed an increasing trend.

Thirdly, in terms of the source structure of livestock GHG emissions in the CAGDMZ from 2010 to 2019, the overall trend of livestock CH₄ and N₂O emissions was upward, followed by a downward trend. From 2010 to 2014, CH₄ emissions raised from 4.0515 to 4.6355 million tons and N₂O emissions raised from 0.1871 to 0.2104 million tons. After 2014, CH₄ emissions decreased to 3.6455 million tons while N₂O emissions

decreased to 0.1602 million tons. CH₄ was a major source of total GHG emissions and pigs emitted the most CH₄ gas (Table 3).

Livestock GHG emissions showed obvious stage characteristics in the CAGDMZ. It might have been influenced by the numbers of livestock breeding structure, breeding methods, policies, etc. From 2010 to 2014, China’s Ministry of Agriculture formulated a set of policies to promote the livestock industrial advancement. The supply of livestock products in CAGDMZ had grown steadily. Amount of pigs, sheep and nondairy cattle continued to increase during this period, accompanied by rising GHG emissions (Figures 1, 2).



These policies have affected the breeding quantity of livestock and poultry in the CAGDMZ. From 2015 to 2019, the feeding quantity of pigs, nondairy cattle and sheep declined annually in the CAGDMZ. The quantity of these animals in 2019 decreased by 35.56%, 24.64%, and 20.8% from the peak year, respectively. In addition, the number of dairy cattle started to increase after 2017, while the number of poultry increased, reaching 1691874 million head in 2019. In summary, there was a large

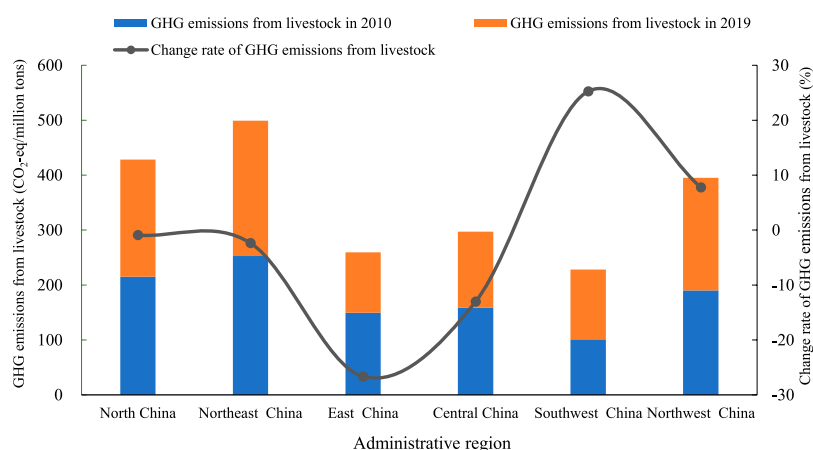


FIGURE 4
GHG emissions from livestock in the CAGDMZ for each administrative region.

difference in livestock GHG emissions in the CAGDMZ from 2010 to 2019.

3.1.2 The spatiotemporal features of livestock greenhouse gas emissions in the China Agricultural Green Development Modern Zone

Significant spatial variation in livestock GHG emissions was observed in different CAGDMZ. Therefore, we calculated the average GHG emissions from livestock in the CAGDMZ for each province.

At the provincial level, Inner Mongolia is the largest greenhouse gas-emitting province in the CAGDMZ. In addition, the CAGDMZ in Xinjiang, Liaoning, Henan, Heilongjiang and Jiangxi Provinces were in the top ten for livestock GHG emissions. Meanwhile, the livestock GHG emissions in the CAGDMZ of these six provinces accounted for 37.61% and 36.30% of the total livestock GHG emissions in 2010 and 2019, respectively (Figure 3).

The CAGDMZ achieved livestock GHG emissions reductions in 17 provinces. The CAGDMZ in Tibet was the largest GHG emissions reduction contributor, with a 92.24% reduction in 2019 compared to 2010, followed by the CAGDMZ in Beijing, Shaanxi, Jiangsu, Zhejiang and Shanghai, with 81.29%, 53.34%, 49.13%, 48.46%, and 48.52% reductions in livestock GHG emissions, respectively. Furthermore, 14 provinces' CAGDMZ increased livestock GHG emissions. Gansu's CAGDMZ was the largest emitter, with a 220.04% increase in 2019 compared to 2010.

Because of the differences in resource endowment and the structure of livestock for each region in China, GHG emissions showed different regional differences in the CAGDMZ. The Northeast, North and Northwest were the main GHG emission areas in the CAGDMZ and the Southwest emitted the least livestock GHG emissions. The Northeastern

CAGDMZ was the greatest contributor to the GHG emissions from livestock in all CAGDMZ, where the regional average GHG emissions generated in 2010 and 2019 were 25,259.52 million tons CO₂-eq and 246,6297 million tons CO₂-eq, respectively. This was followed by the northern and northwestern regions.

However, livestock GHG emissions had different growth rates in these regions (Figure 4). In the Eastern CAGDMZ showed negative growth, decreasing by 26.66% from 2010 to 2019 driven by the decreasing populations of pigs and sheep. However, livestock GHG emissions increased in the southwestern and northwestern CAGDMZ by 25.26% and 7.78%, respectively.

3.2 Decoupling analysis of livestock greenhouse gas emissions and output value in the China Agricultural Green Development Modern Zone

3.2.1 Temporal characteristics of decoupling state

Table 4 depicted the decoupling states between livestock GHG emissions and output values from 2010 to 2019 in the CAGDMZ. The decoupling state could be divided into two stages.

In the first stage of 2010–2014, the CAGDMZ's GHG emissions from livestock increased while industrial output value increased simultaneously. It underwent the change process of “expansive coupling → weak decoupling → expansive negative decoupling.” Although GHG emissions and output value increased simultaneously in the CAGDMZ, there was a significant difference in their change rates. From 2010 to 2012, the increasing in livestock output was faster than the

TABLE 4 Decoupling the relationship between livestock GHG emissions and output value in the CAGDMZ.

Year	Change rate of livestock GHG emissions	Change rate of livestock output value	Decoupling elasticity	Decoupling state
2010–2011	0.0574	0.0589	0.9760	Expansive coupling
2011–2012	0.0291	0.0365	0.7964	Weak decoupling
2012–2013	0.0260	0.0216	1.2037	Expansive negative decoupling
2013–2014	0.0249	0.0104	2.3904	Expansive negative decoupling
2014–2015	−0.0346	−0.0493	0.7022	Weak negative decoupling
2015–2016	−0.0255	−0.0056	4.5071	Recessive decoupling
2016–2017	−0.0539	−0.0546	0.9878	Recessive coupling
2017–2018	−0.0667	−0.0758	0.8799	Recessive coupling
2018–2019	−0.0697	−0.2198	0.3172	Weak negative decoupling

increasing in livestock GHG emissions. However, this situation reversed after 2012. Livestock GHG emissions were growing faster than livestock output value. Thus, the decoupling elasticity rose rapidly from 0.9760 to 2.3904, it indicated that the livestock industry in the CAGDMZ was under greater environmental pressure at this stage.

In the second stage of 2014–2019, the CAGDMZ's GHG emissions from livestock and industrial output value decreased simultaneously. The decoupling elasticity had a rising trend at first, followed by a steady decline. It underwent a change process of “weak negative decoupling → recessive decoupling → recessive coupling → weak negative decoupling.” Around 2015, the change in the rate of GHG emissions from livestock in the CAGDMZ went from increasing to decreasing. These changes were related to a series of environmental protection policies for livestock to adjust the feeding structure and then influence GHG emissions from livestock. In addition, the decline in the CAGDMZ's livestock output value from 2016 to 2019 was largely caused by the African swine fever epidemic and the impact of environmental protection policies. It resulted in a significant decrease in the number of livestock.

3.2.2 Regional analysis of decoupling states

To further investigate the spatial differences in decoupling status, this section analyzes the elasticity and states of decoupling for provincial and regional CAGDMZ. There were five types of decoupling states between livestock GHG emissions and industrial development in the CAGDMZ of each province from 2010 to 2019 (Table 5): recessive decoupling, weak decoupling, strong decoupling, expansive negative decoupling and recessive coupling.

Firstly, there were 12 provinces' CAGDMZ, including Hunan, Shanghai, Jiangsu, Yunnan, etc., in a state of “strong decoupling.” The result indicated that the livestock production value of these provinces' CAGDMZ rose and livestock GHG emissions gradually decreased. They achieved the emissions reduction target of the livestock industry.

Secondly, there were 13 provinces' CAGDMZ, such as Gansu, Hebei, and Ningxia, in a state of “weak decoupling.”

The result indicated that the GHG emissions from livestock increased simultaneously with the output value in the CAGDMZ of these provinces, but the increase in GHG emissions from livestock was less than the increase in livestock output value. Although these regional examinations focus on environmental protection in the livestock industry, there was enormous environmental pressure in the CAGDMZ.

Thirdly, there were four provinces' CAGDMZ—Shaanxi, Zhejiang, Tibet and Tianjin—in a state of “recessive decoupling.” This result indicated that both GHG emissions and output value from livestock in these provinces underwent a negative growth rate. Livestock GHG emissions declined faster than livestock output.

Finally, the CAGDMZ of Beijing was in a state of “recessive decoupling.” It obviously indicated that both GHG emissions and output value from livestock in the CAGDMZ of Beijing underwent negative growth and at a similar rate. GHG emissions decreased at a slightly faster rate than livestock output value decreased in Beijing. In addition, the CAGDMZ of Sichuan Province was in “expansive negative decoupling.” The result indicated that both GHG emissions and output value from livestock rose. The increasing in GHG emissions was faster than the increasing in output value from livestock. There was greater environmental pressure in Sichuan Province's CAGDMZ.

Overall, more than 80.64% of the provinces' CAGDMZ curbed the excessive growth of GHG emissions while maintaining the growth of livestock output value. 38.7% of the provincial CAGDMZ within these provinces achieved a win-win situation between livestock GHG emissions reduction and industrial development of livestock.

To further research the regional differences in the CAGDMZ's decoupling status, this study also analyzed the decoupling status among both livestock GHG emissions and the livestock industry's economic growth in the CAGDMZ in different administrative regions from 2010 to 2019 (Table 6).

First, the CAGDMZ in North China, Northeast China, East China and Central China were in a state of “strong decoupling” from 2010 to 2019. It indicated that livestock output value increased while

TABLE 5 Decoupling relationship between livestock GHG emissions and output value in the different provinces' CAGDMZ from 2010 to 2019.

Province	Change rate of livestock GHG emissions	Change rate of livestock output value	Decoupling elasticity	Decoupling state
Beijing	−0.81	−0.76	1.06	Recessive coupling
Tianjin	−0.40	−0.17	2.41	Recessive decoupling
Hebei	0.31	0.78	0.40	Weak decoupling
Shanxi	−0.03	0.77	−0.04	Strong decoupling
Inner Mongolia	0.26	1.56	0.17	Weak decoupling
Liaoning	0.06	1.01	0.06	Weak decoupling
Jilin	−0.07	0.80	−0.09	Strong decoupling
Heilongjiang	−0.08	0.63	−0.12	Strong decoupling
Shanghai	−0.48	0.07	−7.07	Strong decoupling
Jiangsu	−0.49	0.20	−2.44	Strong decoupling
Zhejiang	−0.49	−0.10	5.00	Recessive decoupling
Anhui	−0.18	1.06	−0.17	Strong decoupling
Fujian	0.03	1.60	0.02	Weak decoupling
Jiangxi	0.01	0.69	0.01	Weak decoupling
Shandong	−0.26	0.89	−0.29	Strong decoupling
Henan	−0.28	1.21	−0.23	Strong decoupling
Hubei	0.12	1.04	0.11	Weak decoupling
Hunan	−0.34	0.04	−8.73	Strong decoupling
Guangdong	0.34	1.27	0.26	Weak decoupling
Guangxi	0.10	1.24	0.08	Weak decoupling
Hainan	0.07	0.88	0.08	Weak decoupling
Chongqing	0.11	0.86	0.12	Weak decoupling
Sichuan	1.96	0.28	6.96	Expansive negative decoupling
Guizhou	0.41	1.37	0.30	Weak decoupling
Yunnan	−0.17	0.32	−0.54	Strong decoupling
Xizang	−0.92	−0.30	3.04	Recessive decoupling
Shaanxi	−0.53	−0.08	6.84	Recessive decoupling
Gansu	2.20	4.92	0.45	Weak decoupling
Qinghai	−0.08	1.32	−0.06	Strong decoupling
Ningxia	0.35	1.04	0.33	Weak decoupling
Xinjiang	−0.39	0.90	−0.43	Strong decoupling

TABLE 6 The decoupling effects of livestock GHG emissions for regional CAGDMZ from 2010 to 2019.

Administrative region	Change rate of livestock GHG emissions	Change rate of livestock output value	Decoupling elasticity	Decoupling state
North China	−0.01	0.37	−0.03	Strong decoupling
Northeast China	−0.02	0.85	−0.03	Strong decoupling
East China	−0.27	0.75	−0.36	Strong decoupling
Central China	−0.13	1.01	−0.13	Strong decoupling
Southwest China	0.25	0.55	0.46	Weak decoupling
Northwest China	0.08	1.42	0.05	Weak decoupling

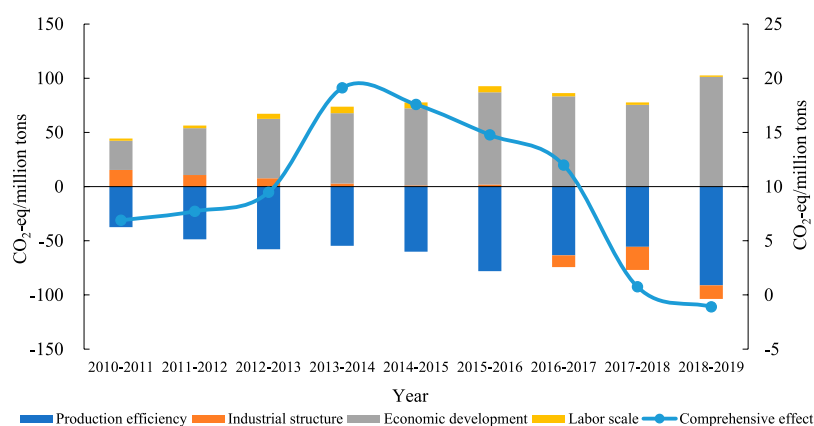


FIGURE 5

Factors driving GHG emissions from livestock in the CAGDMZ.

livestock GHG emissions grew negatively in the regional CAGDMZ. These regional CAGDMZ effectively curbed GHG emissions and reached their emission reduction targets with a growth output value from livestock. Among them, the Eastern CAGDMZ had the largest reduction in GHG emissions from livestock and the decoupling elasticity was -0.36 . Such a decoupling state was influenced by the advanced livestock breeding technology and adequate economic and social conditions in East China.

Second, the CAGDMZ in the southwest and northwest China was in a state of “weak decoupling.” The result indicated that the GHG emissions from livestock increased simultaneously with the output value in the CAGDMZ of these regions, but the increase in GHG emissions from livestock was less than the increase in livestock output value. Such a decoupled state could be associated with changes in the structure and quantity of livestock feeding. For example, the Northwest CAGDMZ had become the main production area of dairy cattle, sheep and nondairy cattle. The increase in livestock feeding had led to more GHG emissions from livestock. Since 2015 a set of environmental protection policies for livestock was implemented by government, it also reduced GHG emissions to some degree. But there was still greater environmental pressure in the CAGDMZ.

3.3 Influencing factors of livestock greenhouse gas emissions in the China Agricultural Green Development Modern Zone

3.3.1 Temporal characteristics of influencing factors

According to Eqs 5–10, we decomposed the effects of production efficiency, industrial structure, economic

development and labor scale on livestock GHG emissions in the CAGDMZ from 2010 to 2019 (Figure 5). The conclusions were as follows:

First, the production efficiency was a most important contributor to decline livestock GHG emissions. The production efficiency effect was negative and consistently promotes the reduction of livestock GHG emissions. CAGDMZ's livestock GHG emissions were reduced by 91.07 million tons $\text{CO}_2\text{-eq}$ due to the production efficiency factor from 2010 to 2019. The explanation for this result was the construction of a livestock breeding system, a high-efficiency technology system and a livestock waste utilization system were in the CAGDMZ from 2010 to 2019. This system promoted the large-scale and intensification of livestock breeding, improved livestock production efficiency and influenced livestock GHG emissions reductions.

Second, the industrial structure factor was a major contributor to the livestock GHG emissions in the CAGDMZ, but this effect turned into a negative effect after 2016. After livestock GHG emissions declined from 2010 to 1.9802 million tons of $\text{CO}_2\text{-eq}$ in 2016 caused by industrial structures, the industrial structure effect became negative from 2016 to 2017. The negative effect reached its maximum from 2017 to 2018 at -21.374 million tons of $\text{CO}_2\text{-eq}$. The impact of industrial structures produces fundamental changes which could be related to the adjustment of livestock industrial structure in the CAGDMZ. The feeding of pigs, non-dairy cattle and sheep decreased and the feeding of poultry increased.

Third, the economic development factor was the most important elements that increase livestock GHG emissions in the CAGDMZ. The economic development factor was positive from 2010 to 2019, and it consistently promoted GHG emissions from livestock. The economic development effect of promoting

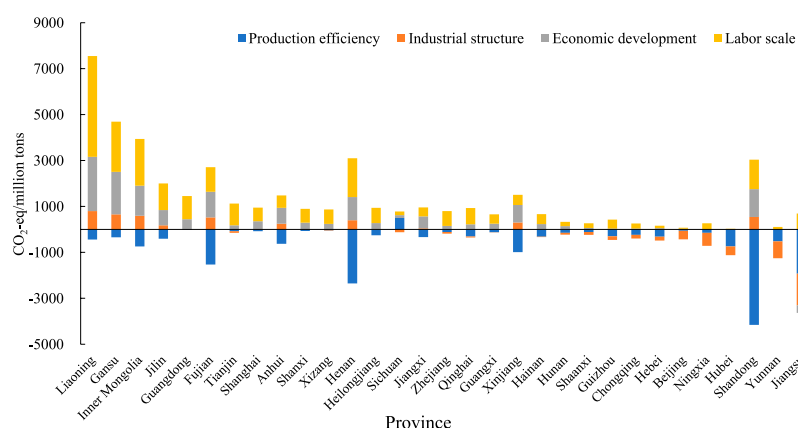


FIGURE 6

Factors driving GHG emissions from livestock in the CAGDMZ of each province.

GHG emissions from livestock increased by 101.3149 million tons CO₂-eq. It increased by 74.235 million tons CO₂-eq compared to 2010–2011. Residents of the CAGDMZ upgraded their diets because of the increase in income. Therefore, the demand for livestock products grown. The increase in the number of livestock products further led to higher GHG emissions in the CAGDMZ.

Fourth, the labor scale was a major contributor to promote livestock GHG emissions. It reached a maximum value of 5.9716 million tons CO₂-eq in 2013–2014. Then it reached a minimum value of 1.1781 million tons CO₂-eq in 2018–2019. With the improvements in inbreeding scale and breeding technology in the livestock industry in the CAGDMZ, the level of capability of animal husbandry practitioners and production efficiency improved. GHG emissions decreased while resource consumption decreased in livestock. Furthermore, urbanization reduced the agricultural labor force in the CAGDMZ, at the same time it diminished the contribution of labor factors to GHG emissions.

Finally, the comprehensive effect showed an inverted “U” trend and peaked at 19.1128 million tons of CO₂-eq in 2013–2014, and GHG emissions achieved negative growth in 2018–2019. This result indicated that the livestock reduction policies implemented after 2014 began to take effect which led to impressive emission reductions.

Overall, the production efficiency was the most crucial factor in reducing GHG emissions from livestock in the CAGDMZ. The industrial structure factors regarding livestock GHG emissions experienced a shift from promotion to suppression. The factors of economic development and labor scale promoted livestock GHG emissions. Among them, economic development had the greatest impact on the increase in livestock GHG emissions of CAGDMZ.

3.3.2 Spatial characteristics of factors influencing livestock in the China Agricultural Green Development Modern Zone

In order to further study the spatial differences, this section analyzed the influencing factors of GHG emissions for provincial and regional CAGDMZ. We derived the effects of the driving factors of GHG emissions from livestock for the CAGDMZ of each province as follows in Figure 6.

First, the production efficiency factor suppressed livestock GHG emissions in the CAGDMZ of each province. Except for Sichuan Province, the production efficiency effect in the CAGDMZ of each province was negative. It indicated that production efficiency makes a great contribution to the reduction of livestock GHG emissions. Among them, the CAGDMZ in Shandong was decreased by 4,159.82 million tons CO₂-eq by production efficiency. This result showed that the production efficiency of livestock in the CAGDMZ of each province was improved by large-scale production and advanced technology. It reduced GHG emissions in all aspects of the livestock industry.

Second, the industrial structure factor had different effects on livestock GHG emissions in different provinces' CAGDMZ. The livestock GHG emissions in 14 provinces such as Liaoning, Gansu and Inner Mongolia were increased by industrial structure factors. GHG emissions from livestock were curbed in 17 provinces' CAGDMZ, including Jiangsu, Yunnan and Hubei. Due to the different degrees of development of the livestock industries, there are differences in GHG emissions in each provincial CAGDMZ. For example, GHG emissions from livestock would gradually increase as the agricultural structure tilts toward the livestock industry in developed provinces' CAGDMZ.

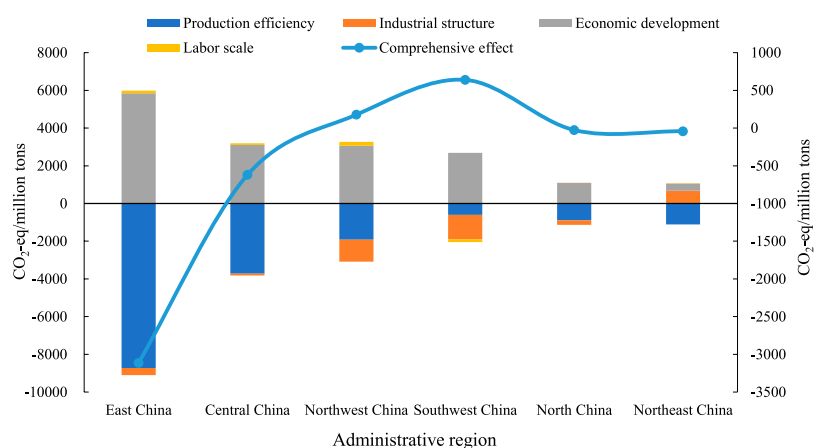


FIGURE 7

Factors driving GHG emissions from livestock in the CAGDMZ for each administrative region.

Third, the factors of economic development and labor scale were the main drivers of increasing livestock GHGs in the CAGDMZ of each province. The effects of economic development and labor scale in the CAGDMZ of each province were positive. It indicated that these factors promoted GHG emissions. Among them, the CAGDMZ in Liaoning emitted the largest GHG emissions, and it influenced by the factors of economic development and labor scale.

Figure 7 depicted the factors affecting livestock GHG emissions in each administrative region's CAGDMZ. First, the factors of production efficiency and industrial structure were the main factors that reduced livestock GHG emissions in each regional CAGDMZ. On the one hand, the production efficiency effect was negative in each regional CAGDMZ. The Eastern CAGDMZ had the largest livestock GHG emissions reduction caused by production efficiency which is related to the wealthy socioeconomic conditions and advanced agricultural technology. On the other hand, except for the northeast CAGDMZ, the effect of industrial structures in each regional CAGDMZ was negative. The CAGDMZ of Northwest China was decreased by 1,168.4546 million tons CO₂-eq due to the influence of industrial restructuring of livestock industry in Northwest China in recent years.

Second, the factors of economic development and labor scale were the main factors that increased livestock GHG emissions in each regional CAGDMZ. Regarding the economic development factor, the Eastern CAGDMZ emitted the largest GHG emissions influenced by economic development. For the labor scale factor, the Northwestern

CAGDMZ emitted the largest GHG emissions influenced by the labor scale factor. The explanation for this situation was that the Northwest CAGDMZ was a major producer of dairy cattle, sheep and nondairy cattle as well as a relatively economically underdeveloped region of China. Due to the labor-intensive characteristics of the livestock industry, more labor might be needed. It resulted in more GHG emissions from livestock.

4 Conclusion and policy implications

4.1 Conclusion

This paper used data of 165 China Agricultural Green Development Modern Zone (CAGDMZ) from 2010 to 2019. GHG emissions from livestock were calculated. The decoupling between livestock GHG emissions and industrial development was investigated. The influencing factors affecting livestock GHG emissions were further decomposed. The following conclusions were mainly drawn.

First, the overall trend of GHG emissions from livestock in the CAGDMZ increased and then decreased from 2010 to 2019. In terms of different livestock species, pigs were still the most important source of GHG emissions among livestock in the CAGDMZ, followed by non-dairy cattle, sheep, dairy cattle and poultry. In terms of the structure of different sources of GHG emissions, CH₄ and N₂O emissions of each major livestock showed a same trend of increasing and then decreasing.

Second, there were significant spatial differences in livestock GHG emissions in the CAGDMZ. Among them,

17 provinces' CAGDMZ achieved livestock GHG emission reductions. In particular, the CAGDMZ in Tibet had the most significant GHG emission reductions. A total of 14 provinces' CAGDMZ increased livestock GHG emissions. Gansu province was the largest contributor to livestock GHG emissions. A further study of GHG emissions from different regional CAGDMZ showed that the Northeast CAGDMZ had the highest livestock GHG emissions, and the Southwest CAGDMZ had the lowest livestock GHG emissions. However, the East CAGDMZ had the largest livestock GHG deceleration with a decrease of 26.66%. The Southwest CAGDMZ had the largest livestock GHG emission growth rate with an increase of 25.26%.

Third, the decoupling status between livestock GHG emissions and livestock output value in the CAGDMZ was unstable from 2010 to 2019. It could be divided into two stages and six states, which included weak decoupling, expansive negative decoupling and expansive coupling. It illustrated the decoupling relationship among livestock GHG emissions and livestock output value. However, the decoupling status of CAGDMZ from 2010 to 2019 varied significantly between provinces and regions. There were five decoupling states for provincial CAGDMZ: recessive decoupling, weak decoupling, strong decoupling, expansive negative decoupling and recessive coupling. Hunan, Shanghai and 12 other provinces' CAGDMZ were in "strong decoupling." Gansu, Hebei and 13 other provinces' CAGDMZ were in "weak decoupling." In addition, the CAGDMZ in North, Northeast, East and Central China were in "strong decoupling." The CAGDMZ in Southwest and Northwest China were in "weak decoupling." In general, majority of provinces and regions in the CAGDMZ maintained the economic growth of livestock while curbing the excessive growth of GHG emissions. However, only a few of them had achieved a win-win situation for both economic development and GHG emissions reduction.

Finally, the comprehensive effect showed an inverted "U" trend. Production efficiency was the most important factor in livestock emissions reduction. Industrial structure factors in livestock GHG emissions underwent a shift from promotion to suppression. Economic development and labor scale were important factors in promoting livestock GHG emissions. Especially economic development effect was the most important. However, there are spatial differences in the influencing factors of livestock GHG emissions in the CAGDMZ. Production efficiency inhibits livestock GHG emissions in the CAGDMZ for each province and each administrative region. The industrial structure factor in livestock GHG emissions in the CAGDMZ for each province is uncertain and varies according to province, but it promotes the livestock GHG emissions reduction in each regional CAGDMZ. Economic development factors and labor scale factors were the main contributors to increasing livestock GHG emissions in the CAGDMZ for each province and each administrative region.

4.2 Suggestions

According to the above conclusions, the following suggestions are proposed. Firstly, the Chinese government should formulate livestock GHG emissions reduction policies according to the conditions of each province and region's CAGDMZ. For the CAGDMZ in the "weak decoupling" state, the CAGDMZ could reduce the intensity of livestock GHG emissions by cultivating excellent varieties of livestock and promoting clean breeding technologies. For the CAGDMZ in the "strong decoupling" state, the government could improve the laws for livestock management and regulations to further consolidate the existing achievements. For the CAGDMZ in the "recessive decoupling" state should improve the technology level and breeding level of the livestock industry. They could improve production efficiency and maintain GHG emission reduction while increasing the economic growth of the industry. For the CAGDMZ in the "expansive negative decoupling" state, the government could adjust the breeding structure according to market demand and improve the intensification level of livestock. GHG emissions reduction targets and policies for livestock in the CAGDMZ also could be formulated.

Secondly, the CAGDMZ should balance the relationship among economic development in the livestock industry and GHG emissions from livestock. Livestock industry should make an effort to achieve a win-win situation by lowering emissions while increasing output value. On the one hand, the government in the CAGDMZ should adjust the industrial structure in time. The agricultural sector in the CAGDMZ should optimize the breeding management mode and improve technological inputs of livestock to reduce the GHG emissions from livestock, such as non-dairy cattle, pigs and sheep. On the other hand, the government in the CAGDMZ should promote the high-quality development of livestock industry by improving the professional quality of livestock practitioners and promoting the transfer of employment of rural labor.

Data availability statement

The original contributions presented in the study are included in the article/supplementary files, further inquiries can be directed to the corresponding authors.

Author contributions

ZL: methodology, formal analysis, writing—original draft, writing—review. MA: conceptualization and editing. GL: software and validation. QL: supervision and

project administration. YL: data curation and supervision. YY and MG: supervision and editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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