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Greenhouse gas emissions from Chinese livestock sector can be decreased by one third in 2030 by the improvement in management

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Abstract

China is one of the largest contributors to global greenhouse gas (GHG) emissions, and the livestock sector is a major source of non-CO₂ GHG emissions. Mitigation of GHG emissions from the livestock sector is beneficial to the sustainable development of the livestock sector in China. This study investigated the provincial level of GHG emissions from the livestock sector between 2000 and 2020 in China, to determine the driving factors affecting the provincial-level GHG emissions from the livestock sector, based on the logarithmic mean Divisia index (LMDI) model, which took into account of technological progress, livestock structure, economic factor, and agricultural population. Moreover, a gray model GM (1, 1) was used to predict livestock GHG emissions in each province until 2030 in China. The results showed that the GHG of Chinese livestock sector was decreased from 195.1 million tons (MT) CO₂e in 2000 to 157.2 MT CO₂e in 2020. Henan, Shandong, and Hebei provinces were the main contributors to the reduction in Chinese livestock GHG emissions, with their livestock GHG emissions reduced by 60.1%, 53.5% and 45.5%, respectively, in 2020 as compared to 2000. The reduction in GHG emissions from the Chinese livestock sector can be attributed to two main factors: technological progress and the shrinking of the agricultural laborers. In contrast, the agricultural economic development model with high input and high emissions showed a negative impact on GHG emission reduction in China's livestock sector. Furthermore, the different livestock structure in each province led to different GHG reduction effects on the livestock sector. Under the gray model GM (1,1), the GHG emissions of the livestock sector will be reduced by 33.7% in 2030 as compared with 2020 in China, and the efficiency factor will account for 76.6% of the positive effect of GHG reduction in 2030. The eastern coastal region will be the main contributor to the reduction of GHG emissions from the Chinese livestock sector in 2030. Moreover, recommendations (such as upgrading livestock management methods and promoting carbon emission mitigation industries) should be proposed for the environmentally sustainable development of the livestock sector in the future.

Highlights

- Inner Mongolia was a major contributor to increase GHG emissions from the livestock sector in China.
- Henan played a dominant position in decreasing GHG emissions of the Chinese livestock sector due to the efficiency factor.
- The GHG emissions of the Chinese livestock sector will be reduced by 33.7% in 2030 compared with 2020.

Keywords Gray model, Greenhouse gas, Livestock sector, Logarithmic mean Divisia index, Provincial level

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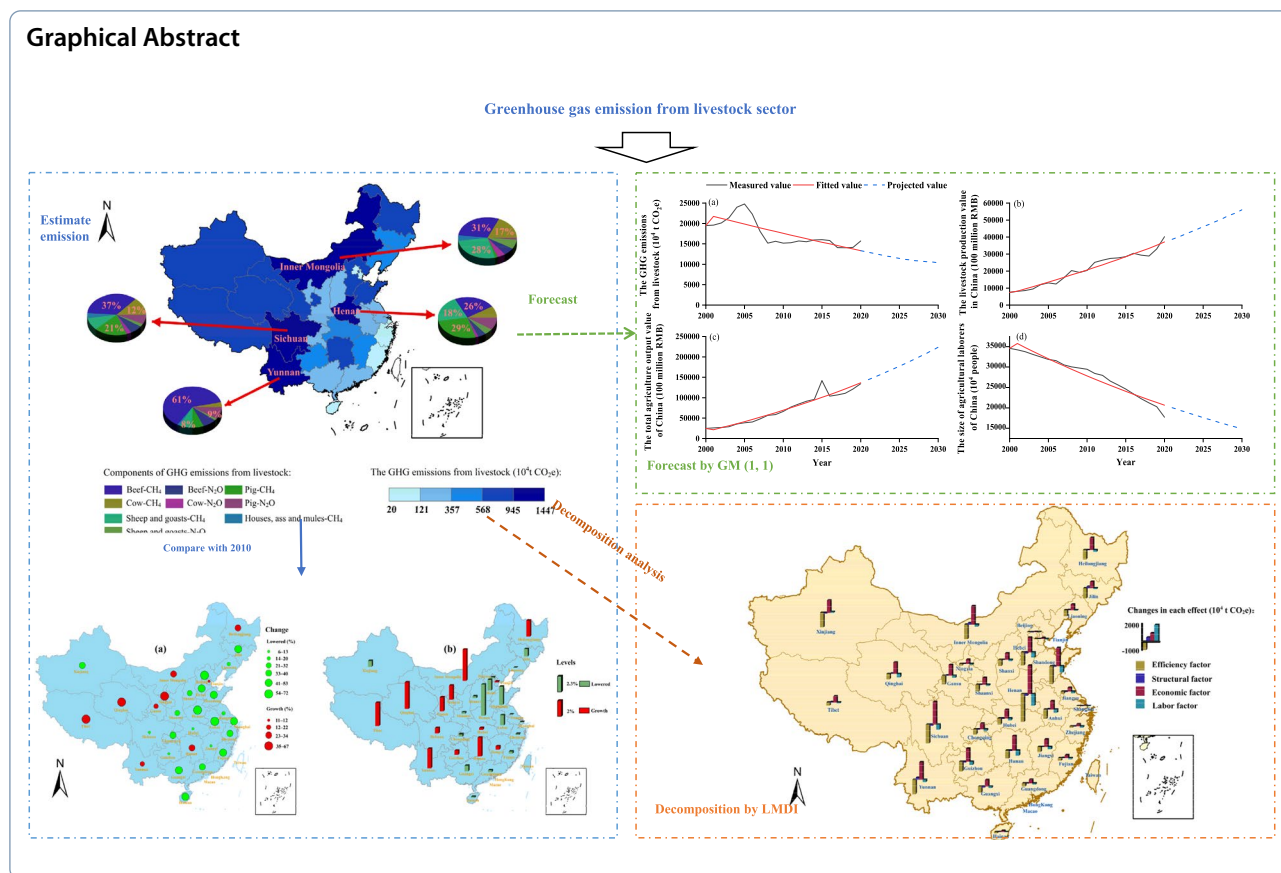
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1 Introduction

Twenty billion animals make use of 30% of the terrestrial land for grazing, and livestock production accounts for 33–50% of the gross domestic product of agriculture, which has a significant impact on human livelihoods and the environment (Herrero et al. 2016; Li and Jiang 2021; Otte et al. 2019). Livestock contributes to the livelihoods of 100 million of the poorest people worldwide, employing nearly 100 million people (Hurst et al. 2005). Moreover, livestock is undergoing a “livestock revolution” due to increased demand for livestock products resulting from increased population, urbanization rates, and population incomes (Thornton 2010). The issue of greenhouse gas (GHG) emissions from livestock sector has a variety of significant environmental impacts that are widely considered to be a “long shadow” concern (Steinfeld et al. 2006). The topic of global warming and climate change has become a major issue in the twenty-first century, and animal husbandry accounts for 14.5% of global GHG emissions, with livestock contributing 37% of global methane emissions and 65% of global nitrous oxide emissions (Raihan 2024; Gerber et al. 2013a; Steinfeld et al. 2006).

At the same time, livestock production is a major source of other pollutants, makes major demands on scarce water resources in some areas, and can exacerbate soil erosion (Godfray et al. 2018).

China ranks among the top GHG emitters globally, with livestock contributing to 42.8% of the country’s total agricultural emissions through the release of methane (CH₄) and nitrous oxide (N₂O) gases from enteric fermentation and manure management (NCSC 2018). A lot of studies have investigated the GHG emissions in the livestock sector. Wang et al. (2017a) found that the total GHG emissions from both pigs and poultry increased between 1961 to 2010. Yu et al. (2018) found that the annual CH₄ emissions by livestock in China increased by 61.9% in 2013 (11.80 Tg) as compared with 1980 (4.5 Tg). However, He et al. (2023) found that GHG emissions from livestock products decreased from 535.5MT CO₂e in 2000 to 532.2MT CO₂e in 2020 using life cycle assessment. According to Zhuang et al. (2019), Henan, Sichuan, Inner Mongolia, Shandong, Yunnan, and Hunan provinces ranked among the six high-ranking GHG emitters from the

livestock sector in 2015. The above studies quantified the trend of GHG changes of the livestock sector in China. However, the mechanisms of long-term trends for the changes in provincial level GHG emissions from livestock sector have been rarely discussed. This problem can be solved well by the decomposition analysis method, which breaks down a complex event into several relatively independent and readily understandable factors to study the nature of change (Su and Ang 2012). In addition, decomposing indicator changes is often done using methods such as Structure Decomposition Analysis (SDA) and Index Decomposition Analysis (IDA). The Logarithmic Mean Divisor Index (LMDI) is a wide choice in IDA due to its exceptional decomposition, consistent aggregation, and capability to handle zero values without any unexplained residual terms (Ang et al. 2003). Dai et al. (2022) found that GHG emissions from animal husbandry in China generally decreased from 2001 to 2009, and the technological progress and industrial structure adjustment of agriculture have a significant effect on emission reduction in Beijing, Tianjin, and Shanghai. Conversely, provinces driven by economic growth, such as Heilongjiang, Inner Mongolia, and Xinjiang, among others, showed a facilitating influence on driving GHG emissions, driven by rising living standards. Cai et al. (2019) found that the GHG emission intensity of Chinese livestock decreased by 80.02% from 1998 to 2016. Animal husbandry regions (e.g., Inner Mongolia and Xinjiang) lagged behind agricultural regions (e.g., Henan and Hebei) in terms of environmental and economic levels because of low productivity and economic benefits. The GHG emissions of the livestock sector had several challenges due to the impact of dynamic factors, including economic, anthropogenic, and natural environments (Ye et al. 2022). The gray model was a method for predicting systems containing uncertain characteristics and was first proposed by Deng (1982), owing to its simple structure, minimal parameters, and independence from the need to consider the probability distribution of data, which makes the results strongly interpretable. Furthermore, gray prediction proves highly effective in situations where system data is limited or information is incomplete (Zeng and Li 2016).

The gray model has been applied in urban planning (Chen et al. 2010), sewage treatment (Liu and Yu 2007), environmental pollution (Liu et al. 2023), energy consumption (Wang and Cao 2021), ecological protection (Yu and Zhao 2012), and other related fields in the past 20 years. However, few studies reported that the GHG emission of livestock sector was predicted by the gray model. Therefore, the objectives of this study were (1) to

investigate the provincial GHG emissions from the livestock sector in China from 2000 to 2020, (2) to examine how the effect factors affect the GHG emissions of livestock sector from 2000 to 2020 by LMDI model, (3) to predict the GHG emissions of livestock sector in China in 2030 by the gray model GM (1, 1) and to conduct spatial distribution analysis of the factors affecting greenhouse gas emissions in the livestock sector in 2030.

2 Materials and methods

2.1 Calculation of GHG emissions in the livestock sector

The total emissions of livestock (E_{GHG}) specific calculation principle were as follows:

$$E_{GHG} = \sum EF_{(T)} \times N_{(T)} \times GWP/10^3 \quad (1)$$

, where E_{GHG} includes intestinal CH_4 emissions, manure CH_4 emissions, and manure N_2O emissions. $EF_{(T)}$ is the emissions factor. $N_{(T)}$ (head) corresponds to the number of animals within each studied species. T is the type of livestock, including cows, beefs, horses, ass, mules, camels, sheep, goats, and pigs. Due to insufficient further delineation of subclasses of livestock populations in the data sources and the difficulty of obtaining the various coefficients of total energy, the estimation of livestock populations and emission factors following Tier 1 in IPCC. GWP is the global warming potential corresponding to CH_4 and N_2O .

Due to the different feeding cycles of various types of livestock, the average annual number of livestock was adjusted based on the IPCC:

$$APP = Days_alive \cdot \left(\frac{NAPA}{365} \right) \quad (2)$$

, where AAP is the average annual number of livestock. NAPA is the average annual number of feeding days for livestock. For livestock with an average number of days of feeding less than 365 days, the average annual number is raised to the number of days required for slaughter or death.

The emissions factor of intestinal CH_4 for livestock was inferred from the 2006 IPCC Guidelines for the Preparation of National Greenhouse Gas Inventories (Hu and Wang 2010). The CH_4 and N_2O emissions factors from manure management for livestock were calculated based on the Guidelines for Provincial Greenhouse Gas Inventory System (NDRC 2011), as shown in Table S1 (Supplementary materials).

2.2 Data collection

This study involved 31 provincial-level administrative regions in China, excluding Hong Kong, Macao, and Taiwan because of the difficulty of obtaining data, and the

study period spanned from 2000 to 2020. The number of livestock was collected from the *Animal Husbandry and Veterinary Yearbook of China* (CAHVY 2021). The average feeding cycle of different livestock in each province was collected from the *National Data Compilation of Revenue and Cost of Agricultural Products* (NDRC 2019). The emissions factors of the populations of cows, beef, horses, ass, mules, camels, sheep, goats, and pigs were inferred from the *Guidelines for Provincial Greenhouse Gas Inventory System*. The data on the output value of livestock and the total output value of agriculture were from the *China Statistical Yearbook* (CSY 2021). The number of agricultural laborers was from the *China Labor Statistical Yearbook* (CLSY 2021), the *China Population and Employment Statistical Yearbook* (CPESY 2021), and the statistical yearbooks of provinces, municipalities, and autonomous regions.

2.3 Influence factors of GHG emissions in livestock sector

In this study, the emission intensity, production scale, economic level and agricultural population size that affect livestock emissions were included in the decomposition of GHG emissions in livestock sector, and the drivers were decomposed into four categories (Ang 2015):

- (1) The production efficiency in livestock sector (PE, which is livestock GHG emissions per unit of output value, a lower value of PE means higher production efficiency and a higher PE value means lower production efficiency) represents the technical level of livestock production.
- (2) The industrial structure of livestock sector (IS, which is the ratio of the livestock industry output value to the agricultural industry output value) represents the production scale level of livestock.
- (3) The agricultural economic development (ED, which is the output value per unit of agricultural labor force) represents the level of agricultural development and technological upgrading.
- (4) The size of agricultural laborers (AL, which is the number of workers engaged in agricultural production) represents the level of agricultural labor force.

Based on the concepts proposed above, the GHG emissions of livestock sector were decomposed into carbon emissions caused by PE, IS, ED and AL under the LMDI framework:

$$C = \frac{C}{LS} \times \frac{LS}{AGRI} \times \frac{AGRI}{AL} \times AL = PE \times IS \times ED \times AL \quad (3)$$

, where C (CO₂e) is the total carbon emissions of livestock sector, LS (100 million RMB) is the livestock production

value, AGRI (100 million RMB) is the total agriculture output value, and AL (10⁴ people) is the size of agricultural laborers. PE=C/LS is the GHG emissions per unit output value of livestock sector, and it represents the production efficiency of livestock sector. IS=LS/AGRI is a ratio that represents the value of livestock output relative to the entire value of agricultural industry output, and it means the industrial structure. ED=AGRI/AL is the output value of the unit agricultural labor force, and it means the level of economic development. The scale of labor is indicated by AL. The LMDI method decomposes the carbon emission changes of GHG emissions from the livestock sector into efficiency (PE), structural (IS), economic (ED), and labor (AL) factors.

Additional decomposition was better than multiple decomposition in LMDI model decomposition. Therefore, a decomposition of the element that influences the GHG emissions of livestock sector was performed as follows (Ang and Liu 2001):

$$\Delta C = C^t - C^0 = \Delta PE + \Delta IS + \Delta ED + \Delta AL \quad (4)$$

, where ΔC (CO₂e) is the change of the total GHG emissions in livestock sector, C^t (CO₂e) is the GHG emissions from the livestock sector in the period of t, i.e., the target year of calculation. C^0 (CO₂e) is the GHG emissions from the livestock sector in the base period, i.e., 2000. ΔPE is the change in factors related to production efficiency regarding GHG emissions. $\Delta IS = \Delta LS / \Delta AGRI$ is the change in factors associated with industrial structure regarding GHG emissions; $\Delta ED = \Delta AGRI / \Delta AL$ is the change in factors associated with economic development regarding GHG emissions. ΔAL is the change in factors associated with labor scale regarding GHG emissions. The specific expressions are as follows (Dai et al. 2022):

$$\Delta PE = \frac{C^t - C^0}{LnC^t - LnC^0} \times Ln \frac{PE^t}{PE^0} \quad (5)$$

$$\Delta IS = \frac{C^t - C^0}{LnC^t - LnC^0} \times Ln \frac{IS^t}{IS^0} \quad (6)$$

$$\Delta ED = \frac{C^t - C^0}{LnC^t - LnC^0} \times Ln \frac{ED^t}{ED^0} \quad (7)$$

$$\Delta AL = \frac{C^t - C^0}{LnC^t - LnC^0} \times Ln \frac{AL^t}{AL^0} \quad (8)$$

, where C, t, 0 in Eqs. (5, 6, 7 and 8) have the same meaning as in Eq. (4). If the coefficients of ΔPE , ΔIS , ΔED , and ΔAL were positive, the effect contributed to GHG emissions in livestock sector. If those coefficients were

negative, the effect mitigated the GHG emissions of livestock sector.

2.4 Prediction of GHG emissions in the livestock sector

A gray model was used to predict GHG emissions (based on the GHG emissions from livestock sector in each province of China from 2000 to 2020), livestock output value, total agricultural output value, and the number of agricultural laborers in each province in 2030 in this study. The sum of the GHG emission in livestock sector in each province comprises the total Chinese GHG emission, livestock output value, total agricultural output value, and agricultural labor force of China’s livestock industry in 2030, respectively. The principle of GM (1, 1) was to use the accumulation to make the initial data in an exponential law, establish the first-order differential equations, and then solve the equations to get the gray prediction value (Zhao 2015).

The initial non-negative sequence $X^{(0)}$ was calculated as follows:

$$X^{(0)} = \{x^{(0)}(1), x^{(0)}(2), \dots, x^{(0)}(n)\} \tag{9}$$

, where $x^{(0)}(1), x^{(0)}(2), \dots, x^{(0)}(n)$ are the initial data.

Accumulation on the initial data gave the data an exponential regularity, and yielded a new non-negative sequence $X^{(1)}$:

$$X^{(1)} = \{x^{(1)}(1), x^{(1)}(2), \dots, x^{(1)}(n)\} \tag{10}$$

$$x^{(1)}(k) = \sum_{i=1}^k x^{(0)}(i), k = 1, 2 \dots n \tag{11}$$

, where $x^{(1)}(k), x^{(1)}(2), \dots, x^{(1)}(n)$ are the new exponential data after initial data accumulation. Equation (11) can also be written:

$$x^{(0)}(k) = x^{(1)}(k) - x^{(1)}(k - 1) \tag{12}$$

$Z^{(1)}$ was a sequence generated by the nearest neighbor mean of $X^{(1)}$:

$$Z^{(1)} = \{z^{(1)}(2), z^{(1)}(3), \dots, z^{(1)}(n)\} \tag{13}$$

$$z^{(1)}(k) = \frac{1}{2}(x^{(1)}(k) + x^{(1)}(k - 1)) \tag{14}$$

A first-order mono-differential equation was established:

$$x^{(0)}(k) + az^{(1)}(k) = b \tag{15}$$

, where a is the development coefficient, which mainly controls the development trend of the system, and b

is the gray action, whose size reflects the relationship between data changes. Equation (15) is referred to as the gray differential equation of GM (1, 1).

To address the unknown parameters, least squares equations were constructed:

$$[ab]^T = (B^T B)^{-1} B^T Y \tag{16}$$

$$B = \begin{bmatrix} -z^{(1)}(2) & 1 \\ -z^{(1)}(3) & 1 \\ \vdots & \vdots \\ -z^{(1)}(n) & 1 \end{bmatrix} Y = \begin{bmatrix} x^{(0)}(2) \\ x^{(0)}(3) \\ \vdots \\ x^{(0)}(n) \end{bmatrix} \tag{17}$$

, where B is the matrix form containing $z^{(1)}(k)$, and Y is the matrix form containing $x^{(0)}(k)$.

For the gray differential equation model of Eq. (15), $x^{(0)}(k)$ was treated as a function of the variable t, and $x^{(1)}(k)$ was treated as a function of the variable t. The GM (1, 1) gray differential equation corresponds to the white differential equation:

$$\frac{dx^{(1)}(t)}{dt} + ax^{(1)}(t) = b \tag{18}$$

Therefore, the equation was as follows:

$$x^{(1)}(t) = (x^{(0)}(1) - \frac{b}{a})e^{-a(t-1)} + \frac{b}{a} \tag{19}$$

The results in the cumulative predicted value were:

$$\hat{x}^{(1)}(k) = [x^{(0)}(1) - \frac{b}{a}]e^{-a(k-1)} + \frac{b}{a}, k = 1, 2, \dots, n \tag{20}$$

Reduction yields the corresponding predicted values were:

$$\hat{x}^{(0)}(k + 1) = \hat{x}^{(1)}(k + 1) - \hat{x}^{(1)}(k), k = 1, 2, \dots, n - 1 \tag{21}$$

The operations were performed on the SPSSPRO website (<https://www.spsspro.com/introduction/>).

2.5 Examination of model accuracy

The critical issue was selecting appropriate criteria to assess the validity of the model. To accurately measure the error between the estimated values and the actual observations, root mean square error (RMSE), mean absolute error (MAE), and mean absolute percentage error (MAPE) were applied for error assessment. In addition, the prediction accuracy of the model could be assessed based on MAPE (Qian and Sui 2021). Here, the criteria were showed in Table S2.

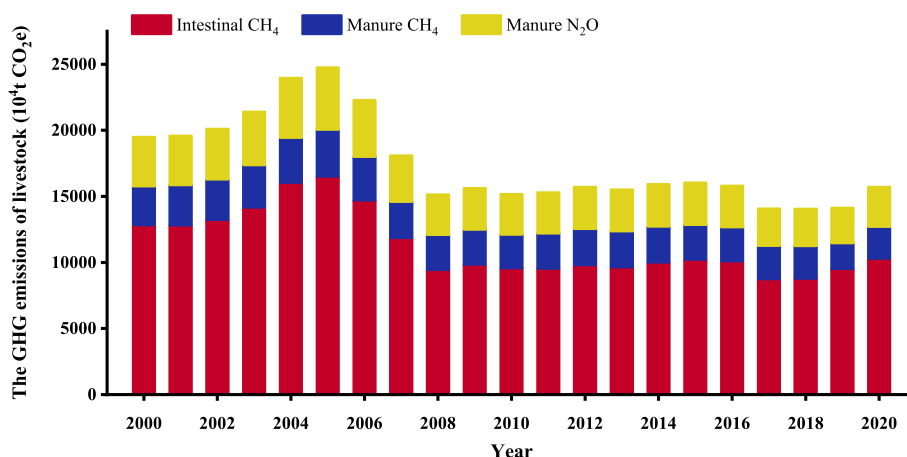


Fig. 1 The GHG emissions from livestock sector (including intestinal CH₄, manure CH₄, and manure N₂O emissions) in China from 2000 to 2020

3 Results and discussion

3.1 Trends of GHG emissions from Chinese livestock sector

The GHG emissions from livestock sector in China were reduced over the two decades. The intestinal CH₄ emissions, manure CH₄, and N₂O emissions decreased by 19.8%, 17.7%, and 19.3%, respectively, in 2020 as compared to 2000 (Fig. 1). The GHG emissions of livestock sector increased from 195.1 million tons (MT) CO₂e in 2000 to a peak of 247.6 MT CO₂e in 2005, the average annual growth rate of 5.4%. The rapid expansion of the GHG emissions during this period was due to the gradual elimination of agricultural taxes (Wang et al. 2023). The abolition of agricultural taxes increased the specialization of livestock breeding and the commercialization of meat products. The GHG emissions of livestock sector have decreased rapidly since 2008, which was related to the decrease in livestock population. The decline in livestock production was because of the decline in meat prices in 2006 and the outbreak of avian influenza in 2007 (Xu et al. 2017). This was also related to changes in the Chinese livestock industry system. As traditional agricultural labor animals in China, beef has gradually been replaced by modern agricultural machines, and the number of beefs has sharply decreased since 2005 (Xue et al. 2014).

3.2 Provincial and temporal characteristics of GHG emissions in Chinese livestock sector

Nationwide, the GHG emissions from livestock sector in China have been shifted to the northwest and southwest (Fig. 2). The four provinces with the higher emissions were Inner Mongolia, Sichuan, Yunnan, and Henan, which emitted 14.5 MT CO₂e, 12.8 MT CO₂e, 10.9 MT CO₂e, and 9.5 MT CO₂e, respectively, in 2020,

accounting for 30.3% of total GHG emissions from livestock sector in China. This was because the number of livestock raised in these provinces was very high (Zhao and Xiong 2022). In Inner Mongolia, Sichuan, and Yunnan, the CH₄ emissions from beef accounted for 31.1%, 36.9%, and 60.9% of the total GHG emissions from the livestock sector, respectively. In Henan province, the CH₄ emission from pigs occupied 28.5% of the total GHG emissions from the livestock sector. This was because Inner Mongolia, Sichuan, Yunnan, and Henan provinces were historically the main areas for livestock production (He et al. 2016), and the consumption market for meat trade has shifted to these areas where livestock production has advantages, resulting in sustained growth of GHG emissions from the livestock sector in these regions (Li et al. 2024). The GHG emissions of livestock sector increased by 52.7% and 34.1%, respectively, in Tibet and Inner Mongolia in 2020 as compared to 2000 (Fig. 3a). The proportion of the GHG emissions in Tibet and Inner Mongolia from China also increased (Fig. 3b). Livestock production was the primary source of income for almost 76% of the population (Bai et al. 2021). However, overgrazing may be the main reason for increased GHG emissions by the livestock sector (Feng et al. 2023). Furthermore, the low level of education has made the local population subject to traditional livestock management and techniques, which has indirectly contributed to the high level of GHG emissions from the livestock sector (Zhang et al. 2019). Although Henan (60.9%) had lower GHG emissions mitigation than Beijing (71.0%) in 2020 as compared to 2000 (Fig. 3a), Henan contributed more than Beijing to Chinese GHG emissions reduction in the livestock sector. Over the past 20 years, the share of GHG emissions in livestock sector in China decreased

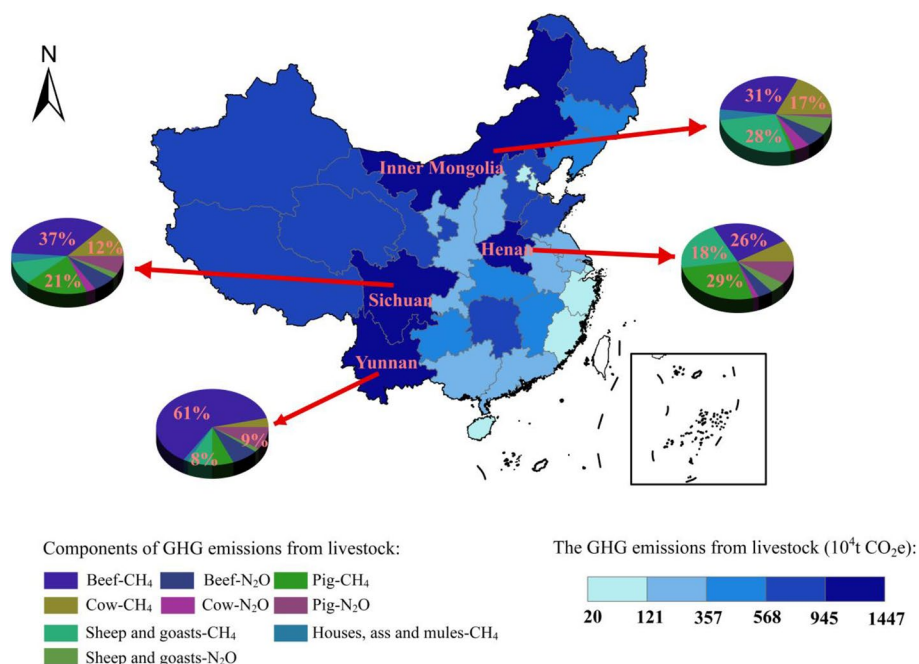


Fig. 2 Livestock GHG emissions in four provinces of China in 2020 with higher emissions than other provinces. The main emission sources of different livestock types are presented in the pie chart for these four provinces

by 6.4% in Henan (Fig. 3b). This was due to the fact that Henan was a typical food production base in China, with a large number of people engaged in agricultural activities and much higher GHG emissions from the livestock sector compared to Beijing (Wang et al. 2018). The transition from traditional style to energy utilization in Henan province included increased recycling and utilizing animal manure, resulting in a decrease in GHG emissions from the livestock sector in Henan (Si et al. 2019; Wang 2021).

3.3 Contribution of different factors to the GHG emissions of Chinese livestock sector

3.3.1 Efficiency factor

The efficiency effect was occupied by 42.2% of the total efficiency effect in the top five provinces, including Henan, Shandong, Sichuan, Xinjiang, and Inner Mongolia (Table 2). In contrast to economically advanced regions (such as Beijing, Shanghai, Tianjin, and Zhejiang), the GHG emission reduction of livestock sector in traditional farming and animal husbandry areas was more significant by efficiency factor. For example, Henan

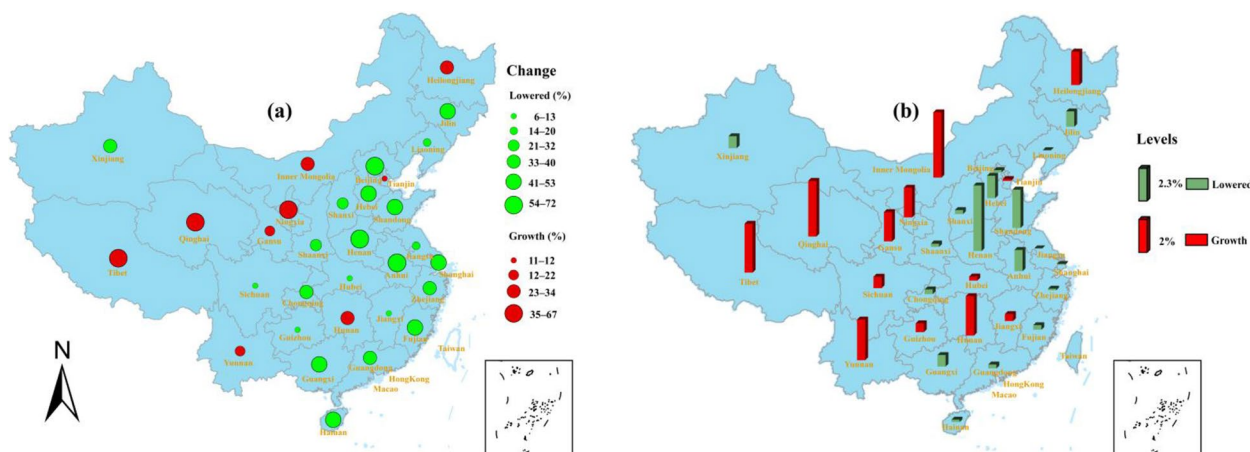


Fig. 3 The change of GHG emissions in Chinese livestock sector in each province in 2020 as compared with those in 2000 (a) and changes in the contribution of each province to the national GHG emissions from the livestock sector in 2020 as compared with those in 2000 (b)

Province held a prominent position among Chinese provinces known for their traditional animal husbandry. With the technology development and policy innovation, the output of livestock products has been increased in Henan (Wang et al. 2014). Compared to 2000, the LS in Henan increased by 2.2 billion RMB in 2020 (Table 1). Furthermore, Henan province has witnessed a substantial enhancement in livestock management, attributable to the gradual shift in animal husbandry production methods from traditional family-based to modern intensive approaches over the past two decades (Qian et al. 2018). As a result, the reduction of GHG emissions in livestock sector in Henan from the efficiency factor was increased by 39.0 MT CO₂e in 2020 as compared to 2000 (Fig. 4). In contrast, as the capital of China, Beijing is an ecological protection zone in urban zone, with few livestock production value and employees (BMCRA et al. 2012). In addition, with the acceleration of urbanization, the scale of the livestock industry decreased in Beijing (Wei et al. 2018). As a result, the LS has shrunk by 4.2 billion RMB in Beijing over the last 20 years (Table 1). Nevertheless, the contribution of the efficiency factor to Beijing's GHG reduction in livestock sector only increased by 0.2 MT CO₂e in 2020 compared to 2000, and this represented a mere 0.005% of the emissions reduction observed in Henan during the same period. This was due to the fact that the urban agriculture in Beijing was the most developed in China, which reduced the effect of efficiency factor in GHG emissions reduction from Beijing's livestock sector. Meanwhile, the land carrying capacity in Beijing was not conducive to the development of animal husbandry, contributing to a subsequent contraction in its scale (Zheng et al. 2019).

The efficiency factor played a significant role in mitigating GHG emissions of the livestock sector in traditional agricultural provinces (e.g., Henan), but the benefit declined rapidly when the management level was stabilized (e.g., Beijing). More technology and management innovation for GHG emissions reduction in the livestock sector should be used to increase the efficiency (He et al. 2023). For example, adding fat to the diet can reduce animal intestinal CH₄ emissions (Gerber et al. 2013b). In addition, specialized planting and livestock farm cooperation can reduce the carbon footprint of the entire agricultural production chain (Chen et al. 2023). Moreover, solid–liquid separation systems instead of liquid systems in fecal management can alleviate pig N₂O emissions (Wang et al. 2017b).

3.3.2 Structural factor

Structural factor was different in different provinces (Table 2). The structural factor had a positive driver on

Table 1 The change in output value and the number of employees in the main industry in the provinces in 2020 compared with 2000

Province	LS (100 million RMB)	AGRI (100 million RMB)	AL (10 ⁴ people)
Beijing	-42.3	74.80	-31.6
Tianjin	93.7	320.1	-0.9
Hebei	1696.0	5197.8	-863.1
Shanxi	516.7	1613.5	-239.0
Inner Mongolia	1397.9	2929.2	-110.7
Liaoning	1300.5	3615.2	-54.4
Jilin	1278.7	2366.6	-112.3
Heilongjiang	1737.3	5813.0	-265.7
Shanghai	-32.3	63.32	-50.2
Jiangsu	885.3	6082.9	-1215.7
Zhejiang	288.7	2439.9	-762.0
Anhui	1550.8	4461.0	-1203.9
Fujian	932.9	3863.8	-517.0
Jiangxi	903.6	3079.4	-505.9
Shandong	1972.7	7896.2	-1434.5
Henan	2214.3	7974.8	-2341.0
Hubei	1526.0	6178.0	-28.1
Hunan	2235.5	6260.1	-1285.0
Guangdong	1328.0	6200.7	-826.7
Guangxi	1148.4	5084.3	-705.0
Hainan	324.2	1509.1	-33.1
Chongqing	729.9	2336.4	-542.9
Sichuan	3002.1	7732.9	-1101.4
Guizhou	908.3	3945.7	-743.9
Yunnan	2113.9	5239.7	-469.9
Tibet	96.2	182.3	-22.0
Shaanxi	787.0	3591.7	-378.0
Gansu	426.5	1783.5	-283.6
Qinghai	264.6	450.1	-87.4
Ningxia	220.8	625.3	-75.6
Xinjiang	923.6	3828.4	72.1

LS (100 million RMB) is the livestock production value, AGRI (100 million RMB) is the total agriculture output value, and AL (10⁴ people) is the size of agricultural laborers

GHG emission reductions in the fifteen provinces of Hunan, Hebei, Gansu, Hubei, Jiangsu, Guangxi, Jiangxi, Shanghai, Guangdong, Chongqing, Ningxia, Beijing, Fujian, Qinghai, and Tianjin over the past 20 years (Table 2). In these provinces where animal husbandry did not dominate, the LS constituted a relatively small portion of the AGRI, and the structural factor played an inhibitory role in mitigating GHG emissions from the livestock sector (Table 1). On the contrary, Inner Mongolia, as one of the important pastoral areas in China, farmers and herders were highly dependent on animal husbandry for their income (Liu et al. 2022), which has led to a 34.0% increase

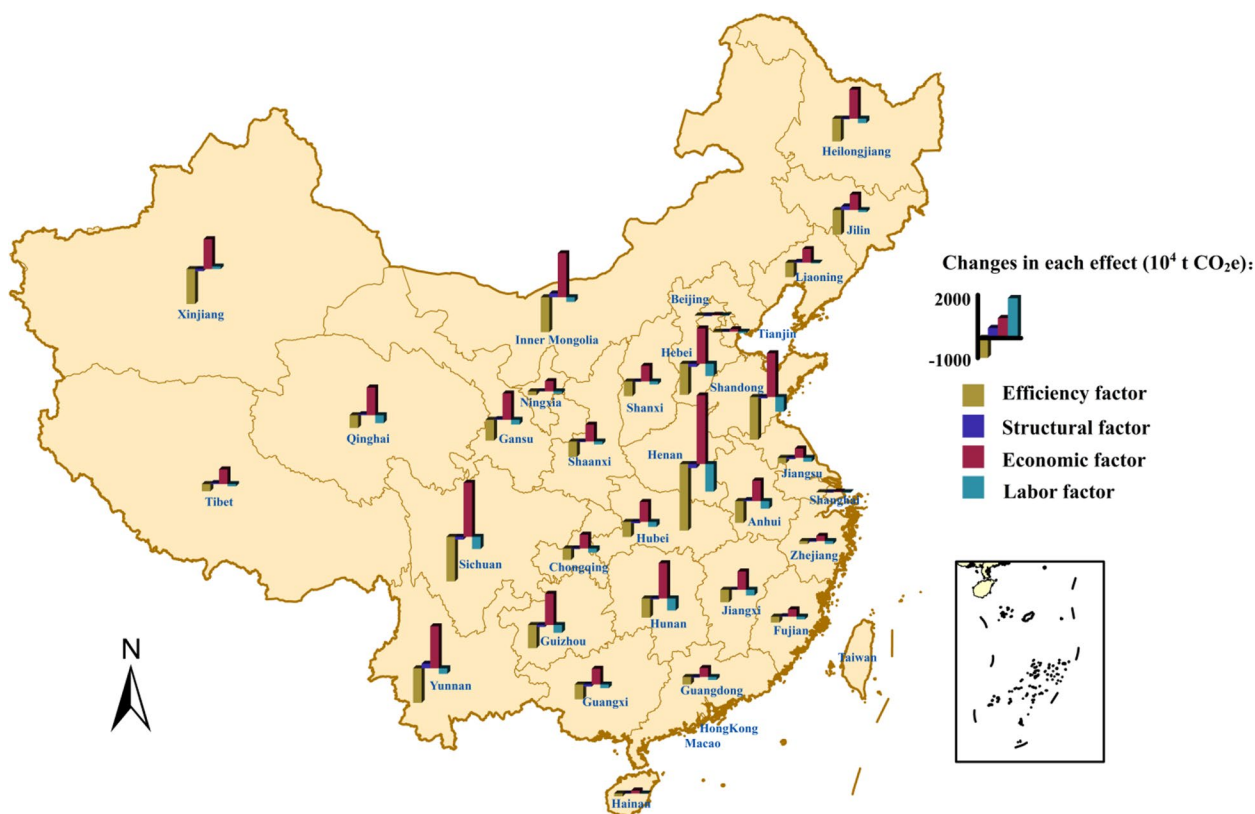


Fig. 4 The changes in the contribution of each factor (efficiency, structural, economic and labor factors) to GHG emissions from the livestock sector in different provinces in 2020 compared to 2000

in GHG emissions from the livestock sector over the past 20 years (Fig. 3a). Specifically, the structural factor contributed 2.2 MT CO₂e to the increase of GHG from livestock sector in Inner Mongolia (Fig. 4), accounting for 60.3% of the total increase. This was because the proportion of LS in AGRI was also increased in the past 20 years in Inner Mongolia (Table 1), which resulted in the negative effect of structural factor on the emission reduction of livestock sector in Inner Mongolia.

The transformation of Chinese animal husbandry was necessary because of the large number of the GHG emissions in the livestock sector. Therefore, dietary balance should be encouraged, such as reducing the consumption of food of animal origin and increasing the cereals and beans (Ma et al. 2013; Hedenus et al. 2014). In addition, some dairy products can be imported to alleviate domestic GHG emission reduction pressure (Bai et al. 2018). Furthermore, low-carbon industries such as forestry and fishery can be encouraged to develop in the future (Tian et al. 2014).

3.3.3 Economic factor

The economic factor was the main driver of GHG emissions from the livestock sector in China, both at the

national and provincial levels (Table 2). This was because the increase in income was accompanied by an increase in meat protein consumption, which also increased the demand for GHG emissions reduction (Ren et al. 2019). Traditional agricultural provinces with higher AGRI had a greater driving effect on GHG emissions in the livestock sector, while economically developed provinces had relatively weaker economic effect (Fig. 4). Sichuan and Shanghai were taken as examples to illustrate the differences in the contribution of economic factors. The livestock GHG emissions in Sichuan were 12.8 MT CO₂e in 2020 (Fig. 2), 12.5% lower as compared with that in 2000 (Fig. 3a). Nevertheless, economic factor was still the main driver of high GHG emissions from Sichuan's livestock sector. The economic effect of Sichuan's livestock GHG emissions was increased to 32.5 MT CO₂e, with the increase of 31.7 MT CO₂e in 2020 compared to that in 2000 (Fig. 4). With its fertile land and abundant water resources, Sichuan province was the major grain-producing region in southwest China (Yan et al. 2020). Simultaneously, Sichuan province was also a large consumer of livestock products with high economic benefits for the products. However, due to the inadequate use of manure in livestock sector, Sichuan has become the most

Table 2 The average annual contribution of efficiency, structural, economic, and labor factors on GHG emissions of the livestock sector from 2000 to 2020 in different provinces (MT CO₂e)

Province	The driving force			
	Efficiency factor	Structural factor	Economic factor	Labor factor
Beijing	-0.3	-0.1	0.4	-0.2
Tianjin	-0.2	0.0	0.7	-0.3
Hebei	-11.5	-1.1	11.5	-2.2
Shanxi	-5.2	0.0	4.2	-0.4
Inner Mongolia	-12.1	1.6	13.9	0.3
Liaoning	-6.5	0.8	5.2	0.1
Jilin	-8.0	0.0	6.2	-0.2
Heilongjiang	-7.9	1.1	8.9	-0.5
Shanghai	0.0	-0.2	0.3	-0.2
Jiangsu	-1.6	-0.3	3.4	-1.4
Zhejiang	-1.1	0.1	1.6	-0.8
Anhui	-8.1	0.4	5.8	-1.5
Fujian	-2.2	0.0	2.2	-0.7
Jiangxi	-4.5	-0.2	4.9	-1.1
Shandong	-19.4	0.9	16.3	-3.7
Henan	-24.1	0.6	25.9	-8.5
Hubei	-5.0	-0.5	5.8	-0.5
Hunan	-5.0	-1.8	9.7	-1.8
Guangdong	-2.4	-0.2	2.6	-0.6
Guangxi	-6.0	-0.3	5.0	-0.5
Hainan	-2.2	0.8	0.9	0.0
Chongqing	-3.8	-0.1	4.5	-1.6
Sichuan	-14.9	0.3	17.3	-3.6
Guizhou	-5.9	0.4	7.0	-1.1
Yunnan	-11.1	0.8	10.5	-0.7
Tibet	-1.3	0.2	3.4	-0.1
Shaanxi	-5.7	0.5	5.2	-0.6
Gansu	-5.3	-0.9	6.8	-0.1
Qinghai	-3.4	0.0	7.0	-1.3
Ningxia	-1.1	-0.1	2.4	-0.3
Xinjiang	-13.7	0.1	9.1	2.0
Total	-199.7	2.5	208.8	-32.4

notable area of livestock pollution in China (Kang et al. 2023; Zheng et al. 2019). The high-input and high-emission development mode of livestock sector in Sichuan had high emission reduction potential (Zhu et al. 2022). On the contrary, the livestock GHG emissions in Shanghai were only 0.2 MT CO₂e in 2020 (Fig. 2). Although Shanghai was one of the most developed cities in China, the economic effect of GHG emissions from the livestock sector has only increased by 0.4 MT CO₂e in the past 20 years (Fig. 4), the increase speed in Shanghai was just 0.01% of that in Sichuan. The production of animal waste in Shanghai was the lowest, and strict environmental regulations limited the scope of livestock farming, so the

livestock sector in Shanghai became more intensive (Bao et al. 2019; Hou et al. 2018).

The growth of economic effects was positively correlated with GHG emissions from the livestock sector, so sustainable intensification was a good way to reduce costs without using more land, water, and other inputs (Herrero et al. 2016), such as improving the efficiency and resilience of food systems to reduce food waste (Knorr and Augustin 2022); declining the demand for resource-intensive foods such as meat and dairy products (Thyberg and Tonjes 2016); applying traditional and modern breeding techniques to improve yields of crop and livestock species (Garnett et al. 2013). In

addition, governments need to develop policies to promote the professionalization of livestock sector (Herrero et al. 2010).

3.3.4 Labor factor

The labor factor was the second most important factor in reducing national GHG emissions in the livestock sector, trailing only the intensity effect. In the past 20 years, the labor factor drove livestock GHG emissions only in Xinjiang, Inner Mongolia, Liaoning, and Hainan (Table 2). The GHG emissions of livestock sector in Xinjiang decreased by 4.0 Mt CO₂e in 2020, a 36.4% reduction in emissions compared to 2000 (Fig. 3a), but there was still 1.5 Mt CO₂e emission pressure due to the labor factor (Fig. 4). This was because the animal husbandry industry was the labor-extensive type in Xinjiang, and the increase in labor input had a significant impact on the GHG emissions of livestock sector (Liao et al. 2014, 2015). Besides, Dai et al. (2020) found that Xinjiang was a concentration of Uyghur minorities, and that language has become the biggest obstacle to outward labor mobility, leading to a large number of laborers moving to the countryside. However, a large-scale transfer of agricultural labor to off-farm industries seems to be a major trend because of advances in agricultural technology, the expansion of agricultural scale, and the increase in off-farm employment opportunities (Zhang et al. 2022). He et al. (2023) found that the development of urbanization and industrialization led to a decrease in rural farmers, which indirectly mitigated GHG emissions from the livestock sector in China. Therefore, with the expansion of the

breeding scale and the improvement of labor productivity, the emission reduction ability of the labor factor will be further enhanced, and the labor factor may also be an important driving factor for GHG emissions in the Chinese future livestock industry.

3.4 Gray prediction of GHG emissions from livestock sector in China

The MAPE for GHG emissions of livestock sector, livestock production value, total agriculture output value, and agricultural laborers were 8.6%, 0.07%, 0.07%, and 0.03%, respectively (Table S3). According to Qian and Sui (2021), this indicates that the model has high predictive ability (Table S2). In 2030, the GHG emissions from the Chinese livestock sector will be 33.7% lower compared with 2020, predicted by GM (1, 1) (Fig. 5). The efficiency factor will continue to be the main driver of GHG emission reductions, accounting for 76.6% of all positive emission reductions (Table S4). The eastern coastal region will be the main contributor to the reduction of GHG emissions from the Chinese livestock sector (Fig. 6a), the reason may be that more environmental protection policies (such as environmental protection fee-to-tax) have been taken in eastern coastal regions to reduce the GHG emissions (Jiang et al. 2023). Besides, with socio-economic development, land use in the eastern coastal areas was gradually changing from agricultural land to construction land (Zhou et al. 2020). According to Xiong et al. (2022), building and improving the low-carbon industrial chain of animal husbandry, and promoting low carbon technology research and development and introduction would be the two main focuses of non-CO₂ GHG

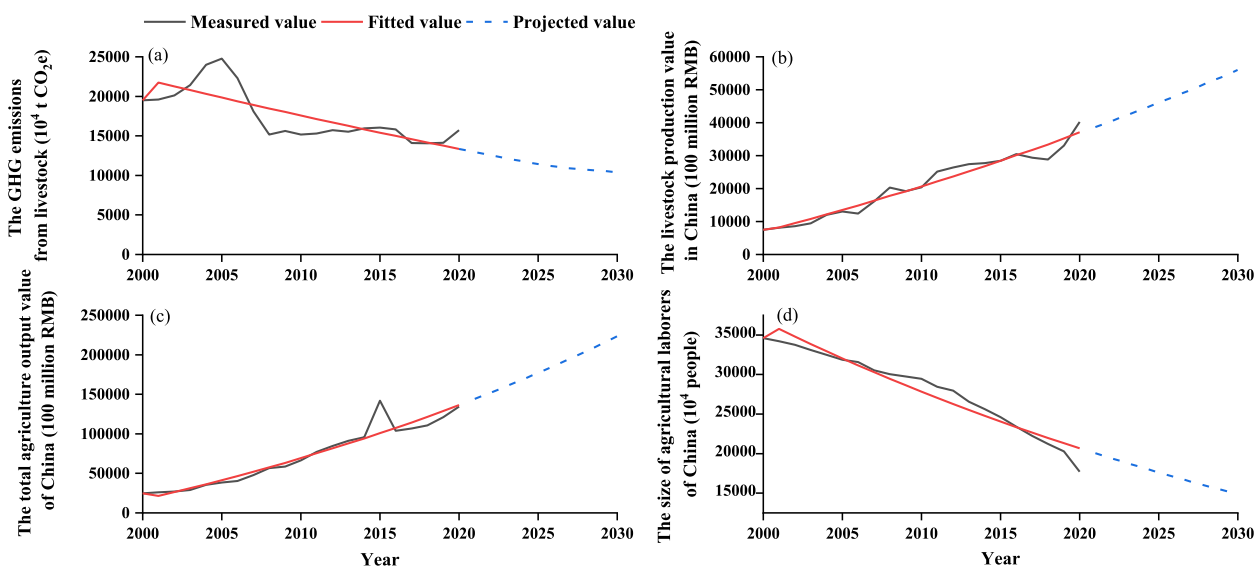


Fig. 5 The GHG emissions of livestock, the livestock production value, the total output value of agriculture, and the size of agricultural laborers in China in 2030 based on GM (1, 1)

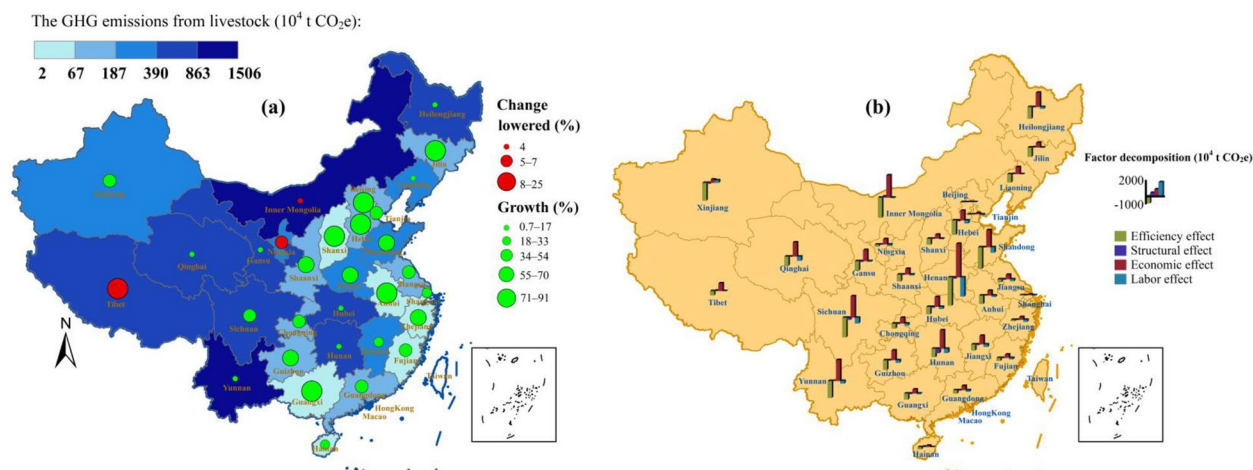


Fig. 6 The prediction of GHG emissions (a) and the contribution of each factor (b) (efficiency, structural, economic and labor factors) from the livestock sector in each province of China in 2030. The color of the bubbles represents the change of increase or decrease in livestock GHG emissions in 2030 compared with 2020. The size of the bubbles represents the change of the percentage in livestock GHG emissions in 2030 compared with 2020

emission reduction in the eastern developed regions. Moreover, the GHG emissions in livestock sector will be decreased in the major provinces of animal husbandry in central China (Fig. 6a). For example, the GHG emissions from livestock in Henan, Shandong, and Sichuan will be decreased by 69.7%, 65.2%, and 52.6%, respectively, in 2030 as compared to 2020 (Fig. 6a). The main reason is that the number of agricultural laborers will be decreased 15.8% in 2030 as compared to 2020, which will have a significant impact on these agricultural provinces (Fig. 5d). The GHG emissions in Tibet, Ningxia and Inner Mongolia will be increased by 24.6%, 6.3% and 3.9%, respectively, in 2030 compared with 2020 (Fig. 6a). Inner Mongolia is also the highest proportion of GHG emissions from livestock sector, accounting for 14.4% of the GHG emissions of Chinese livestock sector in 2030 (Fig. 6a). The main factor contributed to the increase of the emissions in these provinces will be the development of the economy. Specifically, the economic effect will contribute 10.9 MT CO₂e, 7.7 MT CO₂e, and 31.5 MT CO₂e to the growth of GHG emissions in livestock sector in Tibet, Ningxia and Inner Mongolia, respectively in 2030 (Table S4). The increases will be 21.2%, 21.4%, and 18.2%, respectively, lower in Tibet, Ningxia, and Inner Mongolia as compared with 2020, respectively, which means that the negative impact of economic growth on the GHG reduction in livestock sector has slowed down in Tibet, Ningxia, and Inner Mongolia (Fig. 4).

3.5 Limitations and uncertainties

The GHG emissions of livestock sector were changed due to the differences in emission factors, livestock feeding cycles, livestock numbers, calculation methodologies,

global warming potential values, and regional categorization. He et al. (2023) and Wang et al. (2023) both calculated the GHG emissions of livestock sector in 2020, one was 532.2 MT CO₂e (He et al. 2023), and the other is 173.9 MT CO₂e (Wang et al. 2023). The reason for the difference was because that Wang et al. (2023) focused on direct emissions related to livestock, while He et al. (2023) considered emissions from the production process of livestock products. In addition, He et al. (2023) adjusted livestock numbers according to the IPCC, while Wang et al. (2023) adjusted livestock numbers according to consumption and trade diversion. Moreover, the GHG emissions of livestock sector in China were different from 2000 to 2020. During this period, He et al. (2023) found that GHG emissions decreased from 535.5 Mt CO₂e to 532.2 Mt CO₂e, while Wang et al. (2023) found that GHG emissions increased from 144.9 Mt CO₂e to 173.9 MtCO₂e.

The GHG emissions in livestock sector of this study focused more on grazing livestock and pigs in China, which was different from other studies. In this study, intestinal CH₄ management accounted for the largest proportion of GHG emissions (Fig. 1), which was basically consistent with the findings of Herrero et al. (2013). Herrero et al. (2013) found that intestinal CH₄ was the largest contribution of GHG emissions, accounting for about 64.0% of the total GHG in livestock sector, which was slightly lower than that in this study (71.9%). In the provincial scale GHG emissions of livestock sector, the three provinces (Inner Mongolia, Sichuan, and Yunnan) had the largest emissions in 2020 in this study, which was consistent with the study of Yan and Zhang (2023). Inner Mongolia was the province with the largest contribution

to livestock GHG growth from 2000 to 2020, which was also proved by other studies (He et al. 2023). Compared with Zhuang et al. (2019), the study adjusted the number of different livestock species per province per year according to the breeding cycle, which helped to more accurately estimate the GHG emissions in livestock sector at the provincial level. The GHG emission reduction of livestock sector in China in 2030 in this study was the driving factor of emission reduction discussed under the decomposition of LMDI, based on the GHG trends of the past 20 years. Future studies should take into account such factors as land carrying capacity, changes in diet structure and livestock feeding costs.

4 Conclusions and recommendations

4.1 Conclusions

The GHG emissions of Chinese livestock sector were peaked in 2005 and were sharply decreased, which stabilized from 2008 to 2020. Inner Mongolia, Sichuan, Yunnan, and Henan were the four provinces with the highest GHG emissions from the livestock sector in 2020, totally accounting for 30% of Chinese livestock sector. Henan province had the greatest reduction in GHG emissions from livestock sector in 2020 compared with 2000. The efficiency and labor factors were favorable for mitigating GHG emissions from the livestock sector. In contrast, the structural and economic factors were averse to mitigating GHG emissions from the livestock sector. In 2030, the GHG emissions from Chinese livestock sector will be 34% lower compared with 2020. Driven by the efficiency factor, the center and east will be the regions with the most significant GHG reductions in the livestock sector. The livestock GHG emissions in Tibet, the highest increase province in the GHG emissions of Chinese livestock sector, will be increased by 25% in 2030 compared with 2020, driven by the economic factor.

4.2 Recommendations

The GHG reduction in livestock sector benefits can be achieved through large-scale intensive development, improving the efficiency of livestock management and technological innovation. Industrial diversification will help to mitigate the GHG emissions of livestock sector through structural factor in China. Livestock developing provinces (Inner Mongolia, Tibet, Xinjiang, Qinghai, Gansu, Ningxia, Yunnan, Heilongjiang, Jiangxi) should change traditional high-input, high-emissions livestock and poultry farming methods, reduce labor inputs and cost inputs, and change rough to intensive farming production. Livestock mature provinces (e.g., Beijing, Tianjin, Shanghai, Zhejiang, Guangdong, Jiangsu, Hubei, Hunan, Anhui, Fujian, and Hainan) should not take livestock husbandry as their main industry due to limited

land resources. Therefore, innovative development is the direction of livestock husbandry in these regions. The provinces of main GHG emissions in livestock sector (e.g., Henan, Shandong, Sichuan, Hebei, Jilin, Guangxi, Chongqing, Guizhou, and Shaanxi) should consider developing forestry and fisheries to achieve emission reduction. Due to the limitation of this study, further research should focus on how to reduce the GHG emissions of livestock sector considering the diversity of external factors, and should provide more concrete policy suggestions.

Abbreviations

GHG	Greenhouse gas
LMDI	Logarithmic mean Divisia index
GM	Gray model
GDP	Gross domestic product
CH ₄	Methane
N ₂ O	Nitrous oxide
SDA	Structure Decomposition Analysis
IDA	Index Decomposition Analysis
IPCC	The Intergovernmental Panel on Climate Change
AAP	The average annual number of livestock
NAPA	The average annual number of feeding days for livestock
LS	The livestock production value
AGRI	The total agriculture output value
AL	The size of agricultural laborers
PE	The production efficiency of livestock
IS	The industrial structure
ED	The level of economic development
RMSE	Root mean square error
MAE	Mean absolute error
MAPE	Mean absolute percentage error

Supplementary Information

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Supplementary Material 1

Authors' contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Yulong Chen. The draft of the manuscript was written by Yulong Chen and Le Qi and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests

The authors have no competing interests to declare that are relevant to the content of this article.

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References

- Ang BW (2015) LMDI decomposition approach: a guide for implementation. *Energy Policy* 86:233–238. <https://doi.org/10.1016/j.enpol.2015.07.007>
- Ang BW, Liu FL (2001) A new energy decomposition method: perfect in decomposition and consistent in aggregation. *Energy* 26:537–548. [https://doi.org/10.1016/S0360-5442\(01\)00022-6](https://doi.org/10.1016/S0360-5442(01)00022-6)
- Ang BW, Liu FL, Chew EP (2003) Perfect decomposition techniques in energy and environmental analysis. *Energy Policy* 31:1561–1566. [https://doi.org/10.1016/S0301-4215\(02\)00206-9](https://doi.org/10.1016/S0301-4215(02)00206-9)
- Bai Y, Guo C, Li S, Degen AA, Ahmad AA, Wang W, Zhang T, Huang M, Shang Z (2021) Instability of decoupling livestock greenhouse gas emissions from economic growth in livestock products in the Tibetan highland. *J Environ Manage* 287:112334. <https://doi.org/10.1016/j.jenvman.2021.112334>
- Bao W, Yang Y, Fu T, Xie G (2019) Estimation of livestock excrement and its biogas production potential in China. *J Clean Prod* 229:1158–1166. <https://doi.org/10.1016/j.jclepro.2019.05.059>
- CAHYV (2021) China animal husbandry and veterinary yearbook. <https://data.cnki.net/yearBook/single?id=N2022030153>
- Cai T, Xia F, Yang D, Huo J, Zhang Y (2019) Decomposition of factors affecting changes in non-CO₂ greenhouse gas emission intensity of China's livestock sector based on the concept of "environment–food–economy." *Sci Total Environ* 691:611–620. <https://doi.org/10.1016/j.scitotenv.2019.07.020>
- Chen H, Yu R, Ning S, Huang H (2010) Forecasting effluent quality of an industry wastewater treatment plant by evolutionary grey dynamic model. *Resour Conserv Recy* 54:235–241. <https://doi.org/10.1016/j.resconrec.2009.08.005>
- Chen X, Lin J, Tan K, Pei Y, Wang X (2023) Cooperation between specialized cropping and livestock farms at local level reduces carbon footprint of agricultural system: a case study of recoupling maize-cow system in South China. *Agr Ecosyst Environ* 348:108406. <https://doi.org/10.1016/j.agee.2023.108406>
- CLSY (2021) China Labor Statistical Yearbook. <https://data.cnki.net/yearBook/single?id=N2022020102>
- CPESY (2021) China population and employment statistical yearbook. <https://data.cnki.net/yearBook/single?id=N2022040097>
- CSY (2021) China statistical yearbook. Available at: <https://data.cnki.net/yearBook/single?id=N2021110004>
- Dai X, Li B, Wu Z, Nan B, Ren Z, Fan Y, Zhang X (2020) Pastoral livelihood transition via divergent pathways: a case study in northern Xinjiang, China. *J Arid Environ* 174:104083. <https://doi.org/10.1016/j.jaridenv.2019.104083>
- Dai X, Wu X, Chen Y, He Y, Wang F, Liu Y (2022) Real drivers and spatial characteristics of CO₂ emissions from animal husbandry: a regional empirical study of China. *Agriculture* 12:510. <https://doi.org/10.3390/agriculture12040510>
- Deng JL (1982) Control problems of grey systems. *Syst Control Lett* 1:288–294. [https://doi.org/10.1016/S0167-6911\(82\)80025-X](https://doi.org/10.1016/S0167-6911(82)80025-X)
- Feng X, Zhao Q, Li J, Qiu H (2023) The impact of political status and social capital on herders' overgrazing behaviors in the pastoral areas of China. *J Environ Manage* 327:116861. <https://doi.org/10.1016/j.jenvman.2022.116861>
- Garnett T, Appleby MC, Balmford A, Bateman IJ, Benton TG, Bloomer P, Burlingame B, Dawkins M, Dolan L, Fraser D, Herrero M, Hoffmann I, Smith P, Thornton PK, Toulmin C, Vermeulen SJ, Godfray HCJ (2013) Sustainable Intensification in agriculture: premises and policies. *Science* 341:33–34. <https://doi.org/10.1126/science.1234485>
- Gerber PJ, Hristov AN, Henderson B, Makkar H, Oh J, Lee C, Meinen R, Montes F, Ott T, Firkins J, Rotz A, Dell C, Adesogan AT, Yang WZ, Tricarico JM, Kebreab E, Waghorn G, Dijkstra J, Oosting S (2013a) Technical options for the mitigation of direct methane and nitrous oxide emissions from livestock: a review. *Animal* 7:220–234. <https://doi.org/10.1017/S1751731113000876>
- Gerber PJ, Steinfeld H, Henderson B, Mottet A, Opio C, Dijkman J, Falcucci A, Tempio G (2013b) Tackling climate change through livestock: A global assessment of emissions and mitigation opportunities. FAO, Rome
- Godfray HCJ, Aveyard P, Garnett T, Hall JW, Key TJ, Lorimer J, Pierrehumbert RT, Scarborough P, Springmann M, Jebb SA (2018) Meat consumption, health, and the environment. *Science* 361:eaam5324. <https://doi.org/10.1126/science.aam5324>
- He D, Deng X, Wang X, Zhang F (2023) Livestock greenhouse gas emission and mitigation potential in China. *J Environ Manage* 348:119494. <https://doi.org/10.1016/j.jenvman.2023.119494>
- He Y, Yang X, Xia J, Zhao L, Yang Y (2016) Consumption of meat and dairy products in China: a review. *P Nutr Soc* 75:385–391. <https://doi.org/10.1017/S0029665116000641>
- Hedenus F, Wirsenius S, Johansson DJA (2014) The importance of reduced meat and dairy consumption for meeting stringent climate change targets. *Clim Change* 124:79–91. <https://doi.org/10.1007/s10584-014-1104-5>
- Herrero M, Havlík P, Valin H, Notenbaert A, Rufino M, Thornton P, Blümmel M, Weiss F, Grace D, Obersteiner M (2013) Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. *Proc Natl Acad Sci* 110:20888–20893. <https://doi.org/10.1073/pnas.1308149110>
- Herrero M, Henderson B, Havlík P, Thornton PK, Conant RT, Smith P, Wirsenius S, Hristov AN, Gerber P, Gill M, Butterbach-Bahl K, Valin H, Garnett T, Stehfest E (2016) Greenhouse gas mitigation potentials in the livestock sector. *Nat Clim Change* 6:452–461. <https://doi.org/10.1038/nclimate2925>
- Herrero M, Thornton PK, Notenbaert AM, Wood S, Msangi S, Freeman HA, Bossio D, Dixon J, Peters M, van de Steeg J, Lynam J, Rao PP, Macmillan S, Gerard B, McDermott J, Seré C, Rosegrant M (2010) Smart investments in sustainable food production: revisiting mixed crop-livestock systems. *Science* 327:822–825. <https://doi.org/10.1126/science.1183725>
- Hou Y, Wei S, Ma W, Roelcke M, Nieder R, Shi S, Wu J, Zhang F (2018) Changes in nitrogen and phosphorus flows and losses in agricultural systems of three megacities of China, 1990–2014. *Resour Conserv Recy* 139:64–75. <https://doi.org/10.1016/j.resconrec.2018.07.030>
- Hu X, Wang J (2010) Estimation of livestock greenhouse gases discharge in China. *Trans CSAE* 26:247–252 (In Chinese with English Abstract)
- Hurst P, Termine P, Karl M (2005) Agricultural workers and their contribution to sustainable agriculture and rural development. FAO, Rome. <ftp://ftp.fao.org/docrep/fao/008/af164e/af164e00.pdf>
- Jiang X, Li G, Fan X (2023) Environmental protection fee-to-tax and corporate environmental social responsibility: a test based on corporate life cycle theory. *Sustainability* 15:2128. <https://doi.org/10.3390/su15032128>
- Kang X, Du M, Liu Q, Du H, Zou W, Zhao L, Yin Y, Cui Z (2023) City-level decoupling between livestock and crop production and its effect on fertilizer usage: evidence from China. *Sci Total Environ* 905:167115. <https://doi.org/10.1016/j.scitotenv.2023.167115>
- Knorr D, Augustin MA (2022) From food to gods to food to waste. *Crit Rev Food Sci* 12:1–19. <https://doi.org/10.1080/10408398.2022.2153795>
- Li B, Jiang B (2021) Responses of forest structure, functions, and biodiversity to livestock disturbances: a global meta-analysis. *Glob Change Biol* 27:4745–4757. <https://doi.org/10.1111/gcb.15781>
- Li M, Wang Y, Chen W, Sun Y, Hou H, Liu Y (2024) Assessing GHG emissions of food consumption towards low-carbon transformation in China. *Environ Impact Assess* 105:107408. <https://doi.org/10.1016/j.eiar.2023.107408>
- Liao C, Barrett CB, Kassam K-A S (2014) Does diversification translate into Improved Livelihoods? Evidence from pastoral households in the Altay and Tianshan Mountains of Xinjiang, China. *SSRN Electron J*. <https://doi.org/10.2139/ssrn.2628701>
- Liao C, Barrett C, Kassam K-A (2015) Does diversification improve livelihoods? Pastoral households in Xinjiang, China. *Dev Change* 46:1302–1330. <https://doi.org/10.1111/dech.12201>
- Liu G, Yu J (2007) Gray correlation analysis and prediction models of living refuse generation in Shanghai city. *Waste Manage* 27:345–351. <https://doi.org/10.1016/j.wasman.2006.03.010>
- Liu Y, Wang C, Wang H, Chang Y, Yang X, Zang F, Liu X, Zhao C (2023) An integrated ecological security early-warning framework in the national nature reserve based on the gray model. *J Nat Conserv* 73:126394. <https://doi.org/10.1016/j.jnc.2023.126394>

- Liu Z, Ahmad M, Li G, Yang Y, Liu Y, Gao M, Luo Q (2022) Decoupling of greenhouse gas emissions from livestock industrial development: evidence from China agricultural green development modern zone. *Front Environ Sci* 10:979129. <https://doi.org/10.3389/fenvs.2022.979129>
- Ma L, Wang F, Zhang W, Ma W, Velthof G, Qin W, Oenema O, Zhang F (2013) Environmental assessment of management options for nutrient flows in the food chain in China. *Environ Sci Technol* 47:7260–7268. <https://doi.org/10.1021/es400456u>
- NCSC (2018) The Third national communication on climate change of the People's Republic of China. https://unfccc.int/sites/default/files/resource/China_NC3_Chinese_0.pdf
- NDRC (2019) Compilation of Cost-benefit Data of National Agricultural Products. http://www.stats.gov.cn/zs/tjwh/tjkw/tjzl/202302/t20230215_1907941.html
- NDRC (2011) Guidelines for the preparation of provincial greenhouse gas inventories. <http://www.cbcsd.org.cn/sjk/nengyuan/standard/home/20140113/download/shengjiwenshiqiti.pdf>
- Otte Y, Pica-Ciamarra U, Morzaria S (2019) A comparative overview of the livestock-environment interactions in Asia and sub-saharan Africa. *Front Vet Sci* 6:37. <https://doi.org/10.3389/fvets.2019.00037>
- Qian W, Sui A (2021) A novel structural adaptive discrete grey prediction model and its application in forecasting renewable energy generation. *Expert Syst Appl* 186:115761. <https://doi.org/10.1016/j.eswa.2021.115761>
- Qian Y, Song K, Hu T, Ying T (2018) Environmental status of livestock and poultry sectors in China under current transformation stage. *Sci Total Environ* 622–623:702–709. <https://doi.org/10.1016/j.scitotenv.2017.12.045>
- Raihan A (2024) The interrelationship amid carbon emissions, tourism, economy, and energy use in Brazil. *Carbon Res* 3:11. <https://doi.org/10.1007/s44246-023-00084-y>
- Ren Y, Li H, Wang X (2019) Family income and nutrition-related health: evidence from food consumption in China. *Soc Sci Med* 232:58–76. <https://doi.org/10.1016/j.socscimed.2019.04.016>
- Si R, Pan S, Yuan Y, Lu Q, Zhang S (2019) Assessing the impact of environmental regulation on livestock manure waste recycling: empirical evidence from households in China. *Sustainability* 11:5737. <https://doi.org/10.3390/su11205737>
- Steinfeld H, Gerber P, Wassenaar T, Castel V, Rosales M, de Haan C (2006) Livestock's long shadow. <https://www.fao.org/3/a0701e/a0701e00>
- Su B, Ang BW (2012) Structural decomposition analysis applied to energy and emissions: some methodological developments. *Energy Econ* 34:177–188. <https://doi.org/10.1016/j.eneco.2011.10.009>
- Thornton P (2010) Livestock production: recent trends, future prospects. *Phil Trans R Soc B Philos Trans R Soc Lond B Biol Sci* 365:2853–2867. <https://doi.org/10.1098/rstb.2010.0134>
- Thyberg K, Tonjes D (2016) Drivers of food waste and their implications for sustainable policy development. *Resour Conserv Recycl* 106:110–123. <https://doi.org/10.1016/j.resconrec.2015.11.016>
- Tian Y, Zhang J, He Y (2014) Research on spatial-temporal characteristics and driving factor of agricultural carbon emissions in China. *J Integr Agric* 13:1393–1403. [https://doi.org/10.1016/S2095-3119\(13\)60624-3](https://doi.org/10.1016/S2095-3119(13)60624-3)
- Wang C, Cao Y (2021) Forecasting Chinese economic growth, Energ consumption, and urbanization using two novel grey multivariable forecasting models. *J Clean Prod* 299:126863. <https://doi.org/10.1016/j.jclepro.2021.126863>
- Wang C, Yin S, Bai L, Zhang X, Gu X, Zhang H, Lu Q, Zhang R (2018) High-resolution ammonia emission inventories with comprehensive analysis and evaluation in Henan, China, 2006–2016. *Atmos Environ* 193:11–23. <https://doi.org/10.1016/j.atmosenv.2018.08.063>
- Wang G, Wang M, Yang C (2014) The geographical agglomeration characteristics and evolution mechanism of animal husbandry in China. *J Nat Resour* 29:2137–2146 (In Chinese with English Abstract)
- Wang L, Xue B, Yan T (2017a) Greenhouse gas emissions from pig and poultry production sectors in China from 1960 to 2010. *J Integr Agric* 16:221–228. [https://doi.org/10.1016/S2095-3119\(16\)61372-2](https://doi.org/10.1016/S2095-3119(16)61372-2)
- Wang W, Deng X, Wang Y (2023) Changes in non-CO₂ greenhouse gas emissions from livestock production, meat consumption and trade in China. *Sustain Prod Consump* 42:281–291. <https://doi.org/10.1016/j.spc.2023.09.021>
- Wang Y, Dong H, Zhu Z, Gerber PJ, Xin H, Smith P, Opio C, Steinfeld H, Chadwick D (2017b) Mitigating greenhouse gas and ammonia emissions from swine manure management: a system analysis. *Environ Sci Technol* 51:4503–4511. <https://doi.org/10.1021/acs.est.6b06430>
- Wang Y (2021) Research on the relationship between green energy use, carbon emissions and economic growth in Henan Province. *Front Energy Res* 9:701551. <https://doi.org/10.3389/fenrg.2021.701551>
- Wei S, Bai ZH, Chadwick D, Hou Y, Qin W, Zhao ZQ, Jiang RF, Ma L (2018) Greenhouse gas and ammonia emissions and mitigation options from livestock production in peri-urban agriculture: Beijing – a case study. *J Clean Prod* 178:515–525. <https://doi.org/10.1016/j.jclepro.2017.12.257>
- Xiong C, Su W, Li H, Guo Z (2022) Influencing mechanism of non-CO₂ greenhouse gas emissions and mitigation strategies of livestock sector in developed regions of eastern China: a case study of Jiangsu province. *Environ Sci Pollut R* 29:39937–39947
- Xu P, Koloutsou-Vakakis S, Rood MJ, Luan S (2017) Projections of NH₃ emissions from manure generated by livestock production in China to 2030 under six mitigation scenarios. *Sci Total Environ* 607–608:78–86. <https://doi.org/10.1016/j.scitotenv.2017.06.258>
- Xue B, Wang LZ, Yan T (2014) Methane emission inventories for enteric fermentation and manure management of yak, buffalo and dairy and beef cattle in China from 1988 to 2009. *Agr Ecosyst Environ* 195:202–210. <https://doi.org/10.1016/j.agee.2014.06.002>
- Yan B, Yan J, Shi W, Li Y (2020) Study on the comprehensive comparative advantages of pig production and development in China based on geographic information system. *Clean Technol Envir* 22:105–117. <https://doi.org/10.1007/s10098-019-01772-3>
- Yan J, Zhang Y (2023) Quantitative assessment, spatial and temporal characteristics, and dynamic evolution of carbon emissions from animal husbandry in China: 2001–2020. *Environ Sci Pollut Res* 30:116186–116201. <https://doi.org/10.1007/s11356-023-30548-y>
- Ye L, Yang D, Dang Y, Wang J (2022) An enhanced multivariable dynamic time-delay discrete grey forecasting model for predicting China's carbon emissions. *Energy* 249:123681. <https://doi.org/10.1016/j.energy.2022.123681>
- Yu A, Zhao C (2012) Evaluation on the highway asphalt pavement runoff with the gray correlation model. *Proc Environ Sci* 13:1827–1835. <https://doi.org/10.1016/j.proenv.2012.01.176>
- Yu J, Peng S, Chang J, Ciais P, Dumas P, Lin X, Piao S (2018) Inventory of methane emissions from livestock in China from 1980 to 2013. *Atmos Environ* 184:69–76. <https://doi.org/10.1016/j.atmosenv.2018.04.029>
- Zeng B, Li C (2016) Forecasting the natural gas demand in China using a self-adapting intelligent grey model. *Energy* 112:810–25. <https://doi.org/10.1016/j.energy.2016.06.090>
- Zhang H, Zhang J, Song J (2022) Analysis of the threshold effect of agricultural industrial agglomeration and industrial structure upgrading on sustainable agricultural development in China. *J Clean Prod* 341:130818. <https://doi.org/10.1016/j.jclepro.2022.130818>
- Zhang Q, Zhao Y, Li F (2019) Optimal herdsman household management modes in a typical steppe region of Inner Mongolia, China. *J Clean Prod* 231:1–9. <https://doi.org/10.1016/j.jclepro.2019.05.205>
- Zhao X, Xiong C (2022) Spatial and temporal characteristics, evolution law and improvement path of China's animal husbandry production pattern. *Sustainability* 14:15794. <https://doi.org/10.3390/su142315794>
- Zheng L, Zhang Q, Zhang A, Hussain HA, Liu X, Yang Z (2019) Spatiotemporal characteristics of the bearing capacity of cropland based on manure nitrogen and phosphorus load in mainland China. *J Clean Prod* 233:601–610. <https://doi.org/10.1016/j.jclepro.2019.06.049>
- Zhou Y, Li X, Liu Y (2020) Land use change and driving factors in rural China during the period 1995–2015. *Land Use Policy* 99:105048. <https://doi.org/10.1016/j.landusepol.2020.105048>
- Zhu Z, Zhang X, Dong H, Wang S, Reis S, Li Y, Gu B (2022) Integrated livestock sector nitrogen pollution abatement measures could generate net benefits for human and ecosystem health in China. *Nat Food* 3:161–168. <https://doi.org/10.1038/s43016-022-00462-6>
- Zhuang M, Lu X, Caro D, Gao J, Zhang J, Cullen B, Li Q (2019) Emissions of non-CO₂ greenhouse gases from livestock in China during 2000–2015: magnitude, trends and spatiotemporal patterns. *J Environ Manage* 242:40–45. <https://doi.org/10.1016/j.jenvman.2019.04.079>

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