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REVIEW

Low-carbon development policies and achievements in the context of the livestock sector in China

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KEYWORDS

Low carbon livestock development, policy recommendations, divergence, carbon market

HIGHLIGHTS

- The main impediments to low-carbon development of livestock sector are recognized.
- The divergence between the existing policies and actual practices are explained.
- Policy should focus on establishing standards, database and monitoring network.

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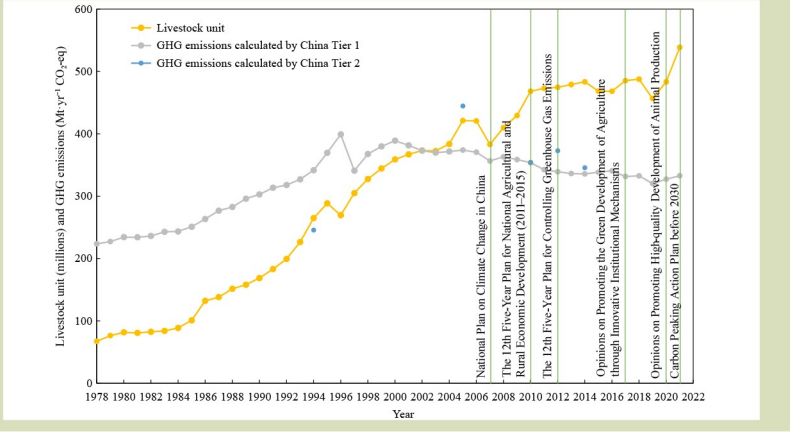
GRAPHICAL ABSTRACT



ABSTRACT

Rapid growth and a vast transition of Chinese livestock industry driven by economic incentives make it become an important contributor on climate change over the last four decades. This study first analyzes the evolving low-carbon livestock development policies and regulations, then an assessment and explanations of the achievements and non-achievements are provided. The findings reveal that China began to pay attention to low-carbon development policy starting in the early 1990s. However, only after the *cyclic and green* concept became the main sustainable development policy, China began to move seriously toward low-carbon livestock development. Several policy instruments were introduced, including moderate scale, feed optimization, manure resource utilization, facility and equipment allocation rate, energy conservation and substitution. Overall, achievements were made in introducing such policies. However, due to the large share of standard agriculture and regional resources, and environmental diversity, such policies may have little effect in practice. The divergence between the policies and actual practices are explained, and important policies applicable to all developing countries are also recommended.

1 Introduction

The livestock sector is important in climate change, representing 14.5% of human-induced greenhouse gas (GHG) emissions[1]. Although the per capita rate of consumption of livestock products in developed countries is plateauing, the consumption of livestock products (and hence livestock production) is rising fueled by population growth, higher incomes and urbanization in developing countries[2–4]. GHG emissions from livestock production will be increased by 60% by 2030, and the agricultural source N_2O emissions will increase by 35% to 60% without additional effective policy and technical measures[5]. Due to this existing increase trend, 92 countries have included the livestock sector in their nationally determined commitments as a means to achieve their national reduction targets under the Paris Agreement[6]. Globally, the livestock sector has great potential to reduce emissions. According to estimates by Havlik et al.[7] the upgrading of the global livestock system will contribute 736 Mt·yr^{-1} CO_2-eq to emissions reductions by 2030. By promoting the use of existing best practices and advanced technologies in feeding, grazing and manure management, the livestock sector can reduce GHG emissions by up to 30%[2]. In the context of food security, the peak of agricultural carbon and the process of reaching the peak largely depend on the development level of low-carbon livestock production.

The livestock industry in China has undergone rapid growth and a vast transition driven by economic incentives over the past 40 years[4,8]. China exceeded Europe and the USA as the world's largest livestock producer[9]. The number of livestock has increased threefold between 1980 and 2020.

The greenhouse gas emissions caused by the rapid development of livestock production have increased rapidly (Fig. 1). GHG emissions from livestock sector (including enteric fermentation and manure management) increased 1.4 times over the past 40 years, and emission proportion of livestock sector to agricultural source emissions remained above 40% over the last 20 year[10,11]. It is indicated that livestock production has become an important source of GHG emissions in the agricultural field in China. Research indicates that daily per capita consumption of animal-derived foods is projected to increase by 59% in 2050 under a business-as-usual scenario compared with 2018, and this will increase the consequent GHG emissions up to 463 Mt·yr^{-1} CO_2-eq by 2050 and present a challenge for achieving carbon neutrality in China[12].

The proportion of enteric fermentation and manure management contribution to global livestock GHG emissions is 68:32 (excluding GHG emissions associated with feed production), and this proportion in China is different from that in the world, which is 57:43[13]. It is worth noting that the proportion of GHG emissions from manure management is gradually increasing in the past 20 years, from 13% in 1994 to

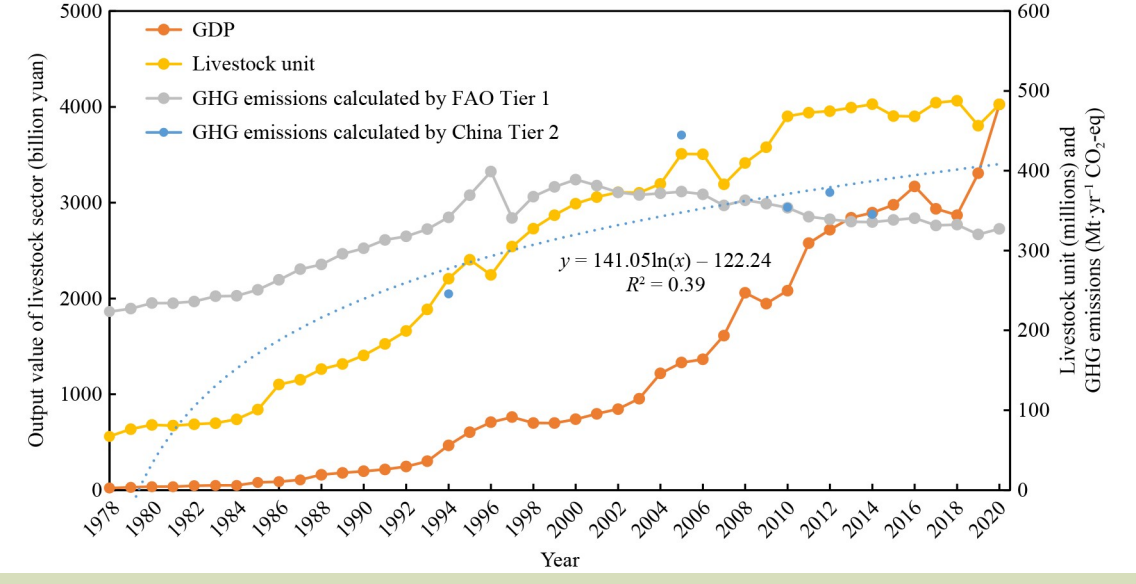


Fig. 1 Output value, livestock unit and GHG emissions of enteric fermentation and manure management of Chinese livestock sector from 1978 to 2020.

40% in 2014, becoming as important a contributor as methane emissions from enteric fermentation[10,11]. This is because pig production is the largest component of the Chinese livestock industry due to the local custom of pork consumption. As a non-ruminant animal, pigs emit little GHGs from intestinal fermentation. However, due to the large water content, large and concentrated production of pig manure, large GHG emissions from pig manure management will increase the contribution of manure management to GHG emissions in the livestock sector in China. Therefore, in addition to some policies on optimizing feed and improving the efficiency of animal production, China has put forward more comprehensive policies, laws and regulations, standards and norms focusing on improving recycling efficiency and reducing emissions in manure management.

Many government policies have been released, but only a few deal with GHG emission mitigation. This paper reviews the objectives and targets of agri-environment policies and regulations in China and assesses their impact on low-carbon livestock development. Based on the review, we make a number of recommendations to further improve low-carbon production. These recommendations provide a reference for the low-carbon development of livestock production in developing countries including China.

2 Challenges of low-carbon livestock production in China

2.1 Losing the links within and between livestock and crop system

The industrialization of livestock production has accelerated the separation of materials and energy within the livestock system and between livestock and crop system. Separation of crop and livestock production both in space and scale is mainly due to the mismatch in land carrying capacity between small-scale cropping farms and large livestock production operations, and lack of third-party services for applying manure to fields in China[14]. Although the proportion of resource utilization of livestock manure (such as using manure to product biogas, solid and liquid organic fertilizer and bedding material) in China reached 75% in 2020[14], the proportion of manure applied to cropping fields only accounts for half of the manure production[15]. Only 30% of total excreted N and 48% of excreted P are returned to the land via manure application[16]. Low recycling rates means that more external substances are added to the production system, and the byproducts or wastes generated by the system go directly into the environment. This not only increases GHG emissions from the external materials production, but also increases GHG emissions from the improper disposal of waste.

Maintaining appropriate conditions in industrial livestock production requires large amounts of exogenous operating energy (i.e., electricity and fossil fuels), including feed, manure delivery/removal, heating and cooling, ventilation, lighting, sanitation in housing, feed process and manure treatment on site[17]. Energy consumption on farm may account for up to 1% to 70% of some of the life-cycle impacts of livestock production[18,19]. The current situation of excessive and non-renewable energy consumption makes energy consumption in animal production another key contributor to GHG emissions.

2.2 Lack of appropriate emission mitigation technology

Optimize the existing technology system is need in low-carbon transition for Chinese livestock sector and innovate multi-objective collaborative emission reduction technologies to achieve both carbon emission reduction and economic growth.

The transition from traditional high carbon agriculture to low-carbon agriculture requires application of technologies and economic incentives, given that agricultural producers are most concerned about the feasibility and profitability of these GHG reduction measures. For example, although the biogas project that China has been vigorously promoting is a carbon emission reduction and carbon recovery technology, its utilization rate is low in small- and medium-scale production due to the high investment, difficult operation and uncertain economic income from byproducts[20]. The small biogas system developed for small- and medium-scale production contexts has problems such as high failure rate, low gas production rate and gas leakage, which does not effectively use biogas and can also cause methane to be directly emitted into the atmosphere. Therefore, the operability, construction and operation costs of these mitigation measures have become the difficulties of the implementation of existing low-carbon technologies in livestock farm.

Series of measures (e.g., low protein diet, covering storage of liquid manure, liquid manure acidification storage, closed composting and liquid manure injected application) have been developed to address manure-related emissions and enteric fermentation emission, and some have been implemented successfully in practice. However, many of the measures are aimed at reducing nitrogen emissions and preventing water pollution[14]. Also, effects of these measures are typically

considered for a specific gas or emission source only[21]. Change in management or introduction of a technology for reducing gas emissions at one stage may affect emissions downstream in the manure management chain or can cause unintended environmental side-effects on other gaseous emissions[22], such as trade-off between emissions of CH_4 and N_2O[23] and interactions between N_2O and NH_3[24].

2.3 Data gaps of livestock-derived GHG emissions assessment

Lift-cycle analysis is the main tool for global assessments of livestock-related climate impact. All the inputs and outputs in a production system was assess by such analyses to show a measure of emissions, sometimes extending to transportation and consumption. Poor quality (inaccuracy, absence and invalidity) data and inappropriate assessment models may eventually lead to inaccuracy and an inability to distinguish between different livestock production systems. When empirical studies are undertaken on local animals, the assessment results could vary widely due to the physiologically adapted, feed selectively and manure management feasibility. As a result, such animals produce far fewer emissions than usually assumed in standard models. Such as GHG emissions from the Chinese livestock sector in 1994 published by FAOSTAT was 342 Mt CO_2-eq[25] (Fig. 1) based on IPCC Tier 1, which is much higher than that of calculated by China (246 Mt CO_2-eq) based on IPCC Tier 2[10]. The biggest difference between the two methods is that the Tier 2 method uses local activity data and emission factors, which can better reflect the actual situation of the assessed area than Tier 1 method.

After realizing this, although China has conducted a certain sample activity data survey and emission factor data monitoring for typical production areas and breeds in recent years, data gaps still exist due to complex livestock system, regional differences in natural conditions, and incomplete monitoring networks, which can reflect both the impacts and benefits of different systems of livestock production[26–29]. The data gap includes feed intake, feed formal, feeding management, manure excretion and management systems, production systems, climate, emission factors, eta. Comparing between the calculation results of FAO Tier 1 and Chinese Tier 2, these gaps will result in persistent biases (–16% to 39%) in aggregate national assessments of the climate impacts of livestock.

2.4 Lack of capacity building for livestock sector to enter the carbon market

China has established a unified national carbon emission trading market. Only few sectors (mostly the power sector) are included in the carbon market and carbon prices are low Chinese emission allowances (CEA) was about 55.3 CNY·t^{-1}[30]. In the construction of China's carbon market, various capacity building activities have been carried out at the national and industry levels. However, the current capacity of different stakeholders to participate in carbon markets is uneven, and the need for capacity building in the livestock sector to participate in carbon markets will be more urgent.

In 2021, the number farmyard operations in China accounted for about 93.6% of the total number of livestock operations[31]. It is difficult to organize dispersed production operations and encourage them to participate in a carbon market. In addition, the restriction of entry threshold, the uncertainty of income, the single form of carbon trading and the lack of greenhouse gas pricing in livestock sector have led to the lack of ability of livestock sector to enter the carbon market. The decentralized farmyard and small-scale agricultural production system require the improvement of carbon emission reduction and carbon sink capacity building for individual operations.

With the release of the industry standard of carbon emission accounting methodology in animal production[32], there is a maturing opportunity for livestock sector to enter the carbon market.

3 Policy and measures for low-carbon livestock production

Many governmental policy measures have been released, but only a few deal with GHG emission mitigation. Until 2007, China put forward a series of policies, regulations and actions for biogas projects, based on commitments under signed international conventions, voluntary compliance programs, CDM and CCER projects (Table 1). From 2007 to 2017, with the GHG emission reduction requirements put forward in the Eleventh Five-Year Plan work program, a series of command-and-control policies, regulations and actions were mainly introduced in this stage for pollution prevention and control, manure resource utilization, and large-scale production facilities (Table 1). High-quality and low-carbon development of livestock production has become a priority with the proposal of agricultural green development policy in 2017 (Table 1). From 2017 to 2020, China put forward policies, regulations and opinions that combine administrative orders and market mechanisms from system construction and technological innovation (Table 1). After 2021, the Chinese Government gradually began to pay attention to the driving role of market

Table 1 Chinese Government laws, regulations, policies and actions promoting the low-carbon development of livestock production

Issue date	Issuing agency	Policy name	Target year	Relevant measures
2007–2017——Emphasis on resource utilization				
2007	General Office of the State Council	Notice on the Chinese National Program on Climate Change		
2007	Ministry of Agriculture	Opinions on Strengthening Energy Conservation and Emission Reduction in Agriculture and Rural Areas	2010	• Vigorously promote feeding livestock with crop straw to reduce feed and energy consumption • Promote energy saving of livestock production • 4700 large and medium-sized biogas projects have been carried out in livestock and poultry production • Promoting the diversion of rain and waste, dry and wet separation, and the installation treatment technologies
2010	Ministry of Environmental Protection	Technical Policy of pollution control in livestock and poultry production industry		• Promote the intensive and large-scale development of livestock and poultry production, and pay attention to the greenhouse gas emission reduction in livestock and poultry production • Pay attention to the environmental protection requirements of enclosure structure, manure cleaning, feed ratio and other links • Gradually promote the dry waste cleaning method, and encourage the energy utilization and fertilizer utilization of livestock wastes
2011	State Council	Outline of the 12th Five-Year Plan for National Economic and Social Development of the People's Republic of China	2015	• For the first time, addressing climate change has been included in the national development plan, clearly setting the target of reducing CO_2 emissions • Put forward for controlling GHG emissions from agriculture • Explore ways to establish standards, labeling and certification systems for low-carbon products, and to establish and improve a statistical and accounting system for GHG emissions, and gradually establish a carbon emission trading market
2011	State Council	The 12th Five-Year Plan for Controlling Greenhouse Gas Emissions	2015	• Control the growth of methane and other greenhouse gas emissions • A statistical and accounting system for GHG emissions has been basically established, and a carbon emission trading market has gradually taken shape • Control carbon dioxide emissions from non-energy activities and greenhouse gases such as methane and nitrous oxide
2012	Ministry of Agriculture, Ministry of Environmental Protection	National 12th Five-Year Plan for Pollution Control of Livestock and Poultry Production	2015	• Quantitative requirements for carbon reduction targets in animal production have been proposed for the first time at the national level
2015	Ministry of Agriculture	Implementation Opinions on fighting the battle of preventing and controlling agricultural non-point source pollution	2020	• One core policy of the livestock carbon emission reduction • Promote the recycling and utilization of agricultural waste, and ensure that the proportion of manure treatment facilities in large-scale livestock production reaches over 75%
After 2017——Emphasis on green and low-carbon development				
2017	General Office of the State Council	Opinions on Accelerating the Resource Utilization of Livestock and Poultry Production Waste	2020	• Support carbon trading projects for biogas projects
2017	General Office of the CPC Central Committee and General Office of the State Council	Opinions on Promoting Green Agricultural Development through Innovation System and Mechanism	2020	• Establish a green, circular and low-carbon agricultural production system.
2018	Ministry of Agriculture and Rural Affairs	Technical Guidelines for Green Agricultural Development (2018–2030)	2030	• Increase feed conversion rate of livestock production by more than 10% • The energy consumption per unit output value of products processing will be reduced by more than 20% • Reduce GHG emission intensity and energy consumption by more than 30% per unit of agricultural added value • Innovate green and low-carbon production structure and technology models
2020	Ministry of Agriculture and Rural Affairs	Opinions on Accelerating the Mechanization Development of Animal Production	2025	• By 2025, the overall mechanization rate of livestock production should reach more than 50% • Promote energy conservation of livestock machinery and equipment

(Continued)

Issue date	Issuing agency	Policy name	Target year	Relevant measures
2020	General Office of the State Council	Opinions on Promoting High-quality Development of Animal Production	2030	• By 2025, the scale rate of livestock production and the comprehensive utilization rate of livestock manure shall reach over 70% and over 80% respectively • By 2030, the scale rate of livestock production and the comprehensive utilization rate of livestock manure shall reach over 75% and over 85% respectively
2021	Ministry of Agriculture and Rural Affairs General Office of Finance	Implementation Guidelines on Subsidies for the Purchase of Agricultural Machinery from 2021 to 2023	2023	• Subsidy equipment includes manure cleaning machine, manure solid liquid separator, waste treatment equipment (biogas slurry extraction equipment, organic waste aerobic fermentation pile turning machine, organic waste dry anaerobic fermentation equipment, biogas generator set, organic fertilizer processing equipment)
2021	General Office of the CPC Central Committee and General Office of the State Council	Opinions on the Complete, Accurate and Comprehensive Implementation of the New Development Concept for Carbon Peak Carbon Neutrality Work		• Established "1+N" policy system, which is the top-level design of carbon peaking and carbon neutrality
2021	General Office of the State Council	Action Plan for Carbon Peak before 2030	2030	• Establish a unified and standardized statistical accounting system for carbon emissions • Establish a tax policy system conducive to green and low-carbon development, and implement tax policies for energy conservation, water conservation and comprehensive resources utilization • Improving the role of the national carbon emission rights trading market
2021	National Development and Reform Commission and other 10 departments	Implementation Plan of National Cleaner Production in "14th Five-Year Plan"	2025	• Significantly improve the efficiency of energy and resources utilization, and significantly reduce the emission intensity of major pollutants and carbon dioxide in key industries • Comprehensive utilization rate of livestock manure has reached more than 80% by composting, organic fertilizer production, biogas production and bio-natural gas production according to local conditions
2022	Ministry of Agriculture and Rural Affairs, National Development and Reform Commission	Implementation Plan of Agricultural and Rural Carbon Emission Reduction and Sequestration	2025 and 2030	• By 2025, the unit agricultural product emission intensity of livestock industry will be stable and decreasing • By 2030, the intensity of GHG emissions from enteric fermentation of ruminant animal and manure management should be further reduced
2022	State Administration of Market Regulation, National Development and Reform Commission and other 9 departments	Notice on the Issuance of the Implementation Plan for Establishing and Improving the Standard Measurement System of Carbon Peaking Carbon Neutrality	2025	• Formulate and revise technical standards for carbon emission reduction in animal production, such as livestock production environment, methane control of enteric fermentation and livestock manure treatment • Promote the standards for energy-saving and low-consumption intelligent machinery and equipment, enclosures, and green inputs in livestock sector

mechanisms on carbon emission reduction, and policy measures such as carbon emission taxation and carbon market have become another key point (Table 1). Therefore, carbon accounting methods, low-carbon standard system construction and carbon trading have become the starting point for realizing low-carbon livestock development.

Signing of the United Nations Framework Convention on Climate Change in 1992 and the Kyoto Protocol in 1998 (approved by China in 2002), which was the first international legal form to limit greenhouse gas emissions, have caused the thinking on GHG emission control in China. In response, the Government has gradually implemented policies and regulations related to livestock sector on GHG emission control from 1992. Until 2007 the main objective of government policies, laws and regulations related to livestock production in China was mainly concentrated in rural biogas energy replacement.

With the signing of the Paris Agreement, the Chinese Government issued two policies from 2007 to 2017: *National Plan on Climate Change in China*[33] and *Outline of the 12th Five-Year Plan for National Economic and Social Development of the People's Republic of China*[34]. These polices for the first time include GHG emission reduction in the national development goal and plan. The Government has also provided one opinion, one technical policy and one work program to support the achievement of these goals and plans. *Opinions on*

Strengthening Energy Conservation and Emission Reduction Work in Agriculture and Rural Areas issued by Ministry of Agriculture and Rural Affairs in 2007[35] specified requirements on carbon emission reduction in livestock sector. *Technical Policy on Pollution Prevention and Control of Livestock and Poultry Industry* issued by the Ministry of Ecology and Environment in 2010[36] proposed to promote intensive development of livestock sector, and emphasized the implementation of the whole-chain technical route of "Source reduction–Clean production–Resource utilization–Secondary pollution prevention" in manure treatment. *The 12th Five-Year Plan for Controlling Greenhouse Gas Emissions* issued by the State Council in 2012[37] clearly specified the control methane emission in livestock sector and emphasized the treatment and comprehensive utilization of livestock manure.

With the release of two key national policies in 2017, *Opinions on Promoting the Green Development of Agriculture through Innovative institutional Mechanisms*[38] and *Opinions on Implementing the Strategy of Rural Revitalization*"[39], the Chinese Government has clarified the comprehensive development stage of animal production with the goal of green, circular and low-carbon development, as the main contribution sector of agricultural output value and the key implementation sector for realizing the green transformation of agriculture. *Opinions on Promoting High-quality Development of Animal Husbandry* issued by the State Council in 2020[40] marks the transformation of animal production in China from focusing on quantity development to emphasizing quality development. The Chinese Government has issued four major policies on the utilization of livestock and poultry waste resources, production mechanization, green technology and social capital investment.

Opinions on Accelerating the Resource utilization of Livestock and Poultry Breeding Waste[41] required that by 2020, the comprehensive utilization rate of livestock and poultry waste reach more than 75%, the equipment allocation rate of large-scale livestock and poultry waste treatment facilities reach more than 95%, and the equipment allocation rate of large-scale livestock and poultry waste treatment facilities reach 100% one year in advance. A series of circular development mechanisms and subsidy and tax policies are proposed to promote the resource utilization of livestock waste (Table 1). *Opinions on Accelerating the Mechanization Development of Animal Husbandry*[42] proposed that by 2025, the overall mechanization rate of animal production will reach more than 50%, and the mechanization of main livestock and poultry production has achieved remarkable results, promoting energy conservation and consumption reduction of livestock machinery and equipment. *Technical Guidelines for Green Agricultural Development (2018–2030)*[43] specified technical requirements from the entire scope of livestock and poultry production. The guidelines required the conversion rate of livestock and poultry feed to be increased by more than 10%, the energy consumption per unit of output value of agricultural processing to be reduced by more than 20%, and the greenhouse gas emission intensity and energy consumption per unit of agricultural added value in the technical model to be reduced by more than 30%. *Measures for the Management of Funds for the Development of Agricultural Production* and *Guidelines for Social Capital Investment in Agriculture and Rural Areas*[44] are management policies to provide financial support for the high-quality development goals of animal production from the central financial public budget and social capital respectively. The funding will focus on supporting large-scale production facilities, the utilization of livestock and poultry waste resources, the revitalization of the dairy industry, the production of high-yield and high-quality alfalfa, and biogas supply and heating. This will support the participation of social capital in the utilization of livestock and poultry waste resources, and increase the collection, storage, transportation and treatment system and return to farmland pipeline network.

Under the promotion of nearly 30 years of policies, regulations and actions, in 2020, China for the first time explicitly established the goal of carbon peak and carbon neutrality. To achieve this goal, in 2021, the State Council issued *Opinions on the Complete, Accurate and Comprehensive Implementation of the New Development Concept to do a Good Job of Carbon Peaking and Carbon Neutrality*[45], which together with the *Carbon Peaking Action Plan before 2030*[46] constitute the top-level design of the Chinese carbon peaking and carbon neutrality 1 + N policy system. The plan, *Implementation Plan of Agricultural and Rural Carbon Emission Reduction and Sequestration*[47], which aims at achieving peak carbon neutrality in agriculture, requires that by 2030, the intensity of greenhouse gas emissions from enteric fermentation of ruminants and manure management in livestock should be further reduced.

In addition, the carbon market, as a market mechanism, has officially become an important policy tool to achieve carbon neutrality. In 2021, the online trading of the carbon market in China will be officially launched, covering about 4.5 Gt of carbon dioxide emissions, making it the largest carbon market in the world covering greenhouse gas emissions. Carbon market function to improve the low-carbon livestock production were issued in 2022, Carbon Market function to

improve the low-carbon livestock Production were issued in 2022, and it is the first national level regulation to organize and standardize the national carbon emission rights registration system and the national carbon emission rights trading system. To ensure the fairness of carbon market trading, the Chinese Government issued *Notice on the Issuance of the Implementation Plan for Establishing and Improving the Carbon Peaking Carbon Neutral Standard Measurement System*[48] in 2022, requiring that by 2025, on the basis of national and provincial carbon emissions accounting, further establish regional, industrial, enterprise, product and other carbon emissions accounting systems and verification accounting reporting standards. This supports the expansion of the national carbon market. The 2022 agricultural industry standard, *Greenhouse Gas Emissions Accounting Method for Livestock and Poultry Farms (NY/T 4243-2022)*[32], provides a standard accounting method for carbon emissions from livestock and poultry production facilities to enter the carbon market, and stipulates the accounting boundaries and contents, accounting steps and methods, data quality management and other contents of greenhouse gas emissions for livestock and poultry production facilities. The carbon trading market for livestock manure management sector in China is in its initial stage but has great potential for future development. In China, the research on livestock manure management methodologies is relatively limited. Therefore, the Chinese Government has been placing increasing importance to livestock manure management and the carbon trading market. The Climate Bureau of the National Development and Reform Commission (a part of the newly established Ministry of Ecology and Environment since 2018, when China undertook institutional reform) released in 2016 a list of voluntary emission reduction methodologies, including centralized treatment of dispersed manure, integrated treatment methodology of livestock and poultry manure from different facilities, CH_4 recovery in manure treatment system, and CH_4 emission reduction by composting, which are all manure treatment methodologies. Livestock waste can be used to produce biogas or incinerated to generate electricity, and its carbon emission reduction can enter the carbon market to achieve economic value. For example, the 20,000 m^3 biogas project in China produced biogas from chicken manure, which reduced greenhouse gas emissions by 67 kt CO_2-eq, and was purchased by the World Bank[49]. The largest chicken manure biomass power project in the Netherlands, can reduce greenhouse gas emissions by 88% through chicken manure incineration[50]. Carbon trading in the livestock and poultry industry will have great potential and significance through the gradual improvement of market conditions and the increase in social awareness.

4 Assessment and effects of the policies

4.1 Main effects

After analyzing the existing policies, regulations standards and actions, the measures to promote the low-carbon development of the livestock production in China mainly include five aspects, namely, appropriate increase in production facility size, feed optimization, manure resource utilization, facility and equipment allocation rate, energy conservation and substitution. Economic means such as economic subsidies and taxes promote the implementation of low-carbon policies. Since 2017, a total of 4.6 billion US dollars of central funds has been allocated to support 723 counties to promote the resource utilization of livestock waste, and all 585 major livestock counties have been covered. The funds focus on supporting the construction of facilities for the manure treatment and application to fields to promote the local and nearby utilization of livestock manure, and to promote the improvement of soil organic matter in farmland.

Industrialization of livestock production can help reduce GHG emissions (associated with enteric fermentation and manure management). The proportion of large-scale livestock production in China increased from 35% in 1994 to 51.5% in 2014[51], and then continued to increase to 71.5% in 2022[52], doubling in nearly 30 years. With the increase of large-scale production, GHG emissions from the livestock production in China trended to first increase and then decrease[10,11] (Fig. 2). The reason for this trend is that before 2005, while animal production in China encouraged large-scale development, there were not the corresponding encouragements for pollution prevention and appropriate management measures

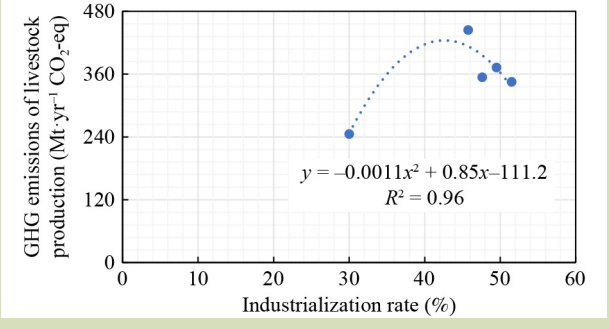


Fig. 2 Relationship between percentage of intensive production and GHG emissions from livestock sector from 1994 to 2014.

for large-scale production. The rapid increase in intensive production with the disorderly manure management has led to a rapid increase in GHG emissions from livestock production in China before 2005 due to the lack the pollution prevention policies and regulations. With the proposed requirements for pollution control in large-scale production facilities and energy conservation and emission reduction in agriculture and rural areas after 2005, the total GHG emissions of livestock industry began to steadily decrease despite the increasing number of production facilities (Fig. 1). This is mainly due to the significant reduction in GHG emission intensity.

The average protein content of feed for fattening pigs in China was 15.7% in 2021 according to monitoring by the Ministry of Agriculture and Rural Affairs. The feed protein content of fattening pigs in large pig enterprises has been reduced to 13.6% through the low protein diet policy in China, but in small- and medium-scale operations (households) this is still maintained at more than 15%. With the implementation of the soybean meal reduction and replacement policy[52], the proportion of soybean meal in livestock diet decreased from about 17.7% in 2021 to 14.5% in 2022. The amount of feed needed to produce 1 g of edible animal protein in 2010 was nearly threefold less than in 1980 (decreased from 357 to 116 g), and the requirement for arable land decreased by about 46% per unit of edible animal protein produced[8]. Average nitrogen use efficiency at herd level increased from 4.4% in 1980 to 11.5% in 2010[8]. Improving feed efficiency can reduce GHG emission intensity by increasing productivity animal product yield per head of animal, which is calculated by dividing the total amount of animal products by the number of animals)[10,11,53,54].

Improving utilization of manure and increasing the equipment allocation rate of manure treatment can standardize the manure treatment and utilization process, and control the disorderly GHG emissions from manure treatment (139 Mt·yr^{-1} CO_2-eq in 2014), which accounted for 40% of the total GHG emissions (associated with enteric fermentation and manure management)[11]). Dry collection of manure, separating animal solid manure and urine immediately after extension by mechanical or manual collection without or less flushing water, not only reduces the amount of liquid manure, but can also improve the collection rate of manure and reduce the total amount of organic matter entering the anaerobic treatment to effectively reduce GHG emissions from manure management process[55]. According to the results of the census of pollution sources in the Chinese livestock industry in 2007 and 2017, the proportion of dry collection of manure used in large-scale pig production in 2017 increased by 46.1% compared with 2007, from 55.7% to 81.4% (Table 2). Matching proportion of manure facilities for large-scale production were < 20% in 2000, subsequently increasing to 63% in 2008 and reaching 97% in 2022 (Table 2). With the standardized construction of manure facilities and equipment, the proportion and standardization of resource utilization of livestock manure have increased greatly. The resource utilization rate of livestock manure increased from 37% in 2010 to 60% in 2015, and then continued to increase to 75% in 2020, with the target of 85% in 2030 (Table 2). The proportion of liquid manure treatment and resource utilization has increased significantly, especially the proportion of field-applied manure and biogas produced by anaerobic fermentation. The sum ratio of these two utilization methods has increased by more than 50% compared with 2007, while the proportion of manure discharge has decreased significantly, from 74% to 19.3% (Table 2). Applying manure to fields also contributes to the improvement of agricultural product quality and the increase of soil organic matter content[64,65], which can increase soil carbon sequestration.

Anaerobic fermentation of manure is an important way to achieve carbon neutrality in livestock production. With the supporting by livestock biogas project policies, the construction of large and medium-sized biogas projects in livestock production has increased rapidly, from more than 400 in 1994 to more than 6970 in 2015, a 17-fold increase in 20 years[66]. Operation of biogas projects in livestock production not only reduces GHG emissions in the manure treatment process, but can also reduce GHG emissions from external energy consumption on site by generating heat or electricity from biogas.

4.2 Divergence between policy and practice

Policies for low-carbon livestock production in China are mainly implied in the national environmental strategic policy or agricultural policy. There are few low-carbon laws, regulations norms and technical guidelines related to livestock sector. At present, a series of policies have been implemented to strengthen the sustainable development of livestock production from the whole chain, most of which are aimed to solve other environmental problems, such as water pollution, nitrogen loss and odor[67]. For example, *Opinions on Accelerating the Resource Utilization of Livestock and Poultry Breeding Waste* aimed at improve manure management and use efficiency which also contribute to GHG emission reduction. *Technical Guidelines for Green Agricultural Development* aimed at nitrogen and phosphorus pollution and improve feed use efficiency, but also contribute to GHG

Table 2 Changes in proportion of equipment matching and the utilization of livestock manures in China from 1994 to 2022, and future goals for 2025 and 2030

Year	Operations matching proportion of manure facilities in industrial production (%)	Percentage of manure comprehensive utilization (%)	Percentage of dry collection of pig manure in industrial production (%)	Percentage of anaerobic digestion of liquid manure in industrial production (%)	Percentage of field-applied liquid manure in industrial production (%)	Percentage of liquid manure discharge in industrial production (%)
2000	< 20.0[56]					
2007			55.7[15]	2.3[15]	14.9[15]	74.0[15]
2008	63.0[14]					
2010		37.0[57]				
2015	66.0[58]	60.0[51]				
2017			81.4[15]	22.4[15]	46.5[15]	19.3[15]
2018	80.0[59]	74.0[60]				
2020	93.0[61]	75.0[51]				
2021	95.0[62]					
2025		80.0[63]				
2030		85.0[40]				

emission reduction. The lack of specific carbon emission reduction policies and the negative impact of policy measures on other environmental issues on carbon reduction result in the inefficiency of the carbon reduction effect of policy implementation. when there are no targeted incentives for GHG emission mitigation, livestock producers will not make efforts to reduce GHG emissions.

Also, China has great diversity of natural endowments and climatic conditions, and complex types of farming (from one-family farmyard operations to large-scale production with tens of thousands of animals). Existing policies, laws, regulations, and standards have not yet managed to address this diversity and complexity in a specific way. This will lead to low efficiency and even ineffectiveness of low-carbon policies and measures in the implementation process. For example, biogas projects with high cost and complex operation process can achieve carbon emission reduction effect with low energy consumption and high biogas production in the southern region with high temperature, but in the north cannot achieve sustainable emission reduction effect due to high energy consumption and high economic investment. In addition, a series of policies and regulations and economic subsidies are currently implemented for large intensive production only. These policies have had no impact on farmyard and small-scale production which still account for a significant share of production. Non-standardized construction of treatment facilities, continuing direct discharge of liquid slurries to surface waters and gas emission from opened manure treatment process make this part production becoming an important contributor to GHG emissions in China.

China lacks the operating mechanism, management regulations and operational guidelines for livestock sector to enter the carbon market. In 2022, China released the first standard of accounting method for GHG emissions from livestock production[32], but this standard method only considers GHG emissions from the production site (including CH_4 emissions from enteric fermentation, CH_4 and N_2O emissions from manure management, methane recovery and CO_2 emissions from net purchased electricity and heat). Livestock production is an industrial sector involving animal production and related feed crop production, manure treatment and utilization, product transportation and processing. With the continuous advancement of the integrated crop and livestock production, the entry of livestock sector into the carbon market for carbon trading is not limited to location of production.

5 Conclusions and outlook

The livestock sector has developed quite rapidly in China over the last three decades in animal number and scale of operations. This development has created the problem such as the decoupling of crop and livestock systems, low resource and energy use efficiency, and environmental losses of carbon and nitrogen. The main impediments to low-carbon development of livestock sector are (1) losing the links within and between livestock and crop system; (2) fragmentation and single

mitigation technologies; (3) data gaps of livestock-derived GHG emissions assessment; and (4) lack of capacity building for livestock sector to enter the carbon market.

In the context of continued growth in the consumption of livestock products of an extended period of time, improving the system production efficiency and recycling rate is the key to reduce the GHG emission intensity to achieve low-carbon transformation of livestock production. The two efficiency improvements are reflected in feed, manure and energy utilization. This requires significant improvements in feeding and manure management practices, and strengthen in government policy measures. It is necessary to reconsider the current policy.

It is imperative to develop policies, regulations and support programs to promote the low-carbon development of livestock production. This will require: (1) establish accurate assessment standards and regulations for GHG emissions from livestock sector throughout the life cycle of feed-animal production-manure treatment-manure application-product processing; (2) establish actionable mitigation technology guideline, and establishment of comprehensive region-specific and production facility type-specific low-carbon livestock production mode; (3) establish a systemwide GHG emission monitoring network, and establish a carbon emission accounting database for livestock production; (4) establish a carbon labeling system for livestock products and a production subsidy policy for supporting low-carbon products, in order to increase the enthusiasm of producers to shift from traditional production to low-carbon production; and (5) establish carbon trading systems for livestock sector to promote the integration of livestock sector into the carbon market.

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Compliance with ethics guidelines

Sha Wei, Junming Fan, Yanfeng Tian, and Hongmin Dong declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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