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Analysis of the coupling coordination of livestock production, residential consumption, and resource and environmental carrying capacity in China

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Increasing demands for livestock products have stimulated rapid increases in the number of livestock and the scale of farming, thus increasing pressure on resources and the environment. Coordinating the development of livestock production (LP) with residential consumption (RC), resources and the environmental carrying capacity (RECC) is important to ensure sustainable development. In this study, the entropy weight method and the improved-coupling coordination degree (CCD) model were used to identify the spatial–temporal coordination development characteristics of livestock production-residential consumption-resource and environmental carrying capacity (LRRE). Furthermore, the spatial autocorrelation model (SAM) and gray model (GM) were used to analyze the spatial aggregation characteristics and future development trends of the CCDs of the LRRE in China. The findings show that the CCDs of the LRRE values in 31 Chinese provinces increased from 2005 to 2020, but no provinces reached a high coordination level. Specifically, the coordinated development level of LRRE is relatively high in the central, eastern and northeastern regions and relatively low in the western region. The spatial autocorrelation analysis confirmed that the high-high (H-H) aggregation areas were mainly distributed in the northeastern, eastern, and central regions, while low-high (L-H) agglomeration was distributed in the western region. This phenomenon is mainly attributed to the continuous expansion of the scale of livestock production in western China. Regions with relatively developed economies have more funds to invest in environmental protection projects. Using GM method, we find that the CCDs of LRRE in 31 provinces in China will increase from 2021 to 2030, and all provinces will reach the basic coordination level. However, most of the western regions will barely reach the basic coordination level. This result indicates that the low level of LRRE development in western China may be difficult to change in the short term. The level of coordinated LRRE development in the relatively developed eastern region is increasing. The spatial layout of China's livestock industry should be appropriately adjusted, its expansion rate in the western region should be decreased, and the ecological environment of the areas bordering the western and central regions should be improved. These findings have practical implications for other large livestock production countries. Promoting the coordinated development of LRRE is also

an important condition for agricultural transformation in developing countries, especially for improving the environment in key areas of the livestock industry.

1 Introduction

Since its reform and opening up, China's development has led to a significant increase in the demand for livestock products (He et al., 2018; Zhao et al., 2021). Currently, China has become the largest producer of livestock products worldwide (Bai et al., 2018; Zhang C. et al., 2019). In 2020, China's meat, egg, and milk production were 899 Mt., 341 Mt., and 368 Mt., respectively (NBS, 2022); worldwide, pork accounted for 37.95% of production, and beef and chicken accounted for more than 10%, respectively (USDA, 2022). However, the expanding scale of livestock farming has placed tremendous pressure on resources and the environment (Zheng et al., 2019). Livestock production releases a large amount of greenhouse gases (GHGs) and uses limited resources, such as land (Post et al., 2020), which affects soil and water safety and poses certain hazards to human health (Rosa et al., 2020). In China alone, compared to their numbers in 2000, the number of pigs in 2022 increased by 36.22 million, theoretically increasing nitrogen and phosphorus discharges by 39.84 and 5.98 10^4 t, respectively (Zhou et al., 2024), placing enormous pressure on river and soil ecosystems. Waste emissions from ruminants in China have been estimated to cost $32.2 billion in damage to ecosystems (Du et al., 2018). Residents living near farms for a long time have also been frequently exposed to respiratory and cardiopulmonary diseases (Gerbecks et al., 2020). Coordinating the relationships among livestock breeders, resources, the environment and residents has become the key to the development of the current breeding industry.

The development of animal husbandry should be compatible with the resource environment and residents' consumption; an uncoordinated development relationship may lead to an unstable food supply and ecological disaster. Agriculture is a complex process that results from interactions between humans and nature and is intensely affected by resources, society and market price (Hatfield et al., 2020; Seguin et al., 2021). Livestock production needs to occur in spaces with substantial regional resources and environmental carrying capacity (RECC), as exceeding the RECC may permanently damage the local ecological structure (Zhang Y. et al., 2022). For example, livestock production is dependent on land and crops to absorb manure, and if resources are insufficient, the ammonia, nitrogen and phosphorus produced during livestock production can severely pollute the air, rivers and soil. With the development of the economy, the rising demand for livestock products will further stimulate growth in the livestock industry (Sun et al., 2021), which will also impose greater environmental pressure (Qian et al., 2022). Population size and residential consumption preferences drive expansion in the livestock sector. If these factors are ignored, the development of the livestock sector may fall short of realistic development goals. For example, provinces with large populations do not have sufficient meat production capacity, which may limit the food supply capacity of these areas. However, although the resource environment and residential consumption play key roles in the development of livestock systems, this relationship is not yet clear; however, an understanding of it is crucial for the layout of China's livestock industry. Therefore, focusing on in-depth analyses of the coupling coordination degree (CCD) of livestock production (LP), residential consumption (RC), and the RECC (LRRE) is important for evaluating the effect of agricultural policy and promoting the coordinated development capacity of the livestock industry.

Currently, much research considers the impacts of natural disasters on socioeconomic factors (Ekwueme, 2022; Mann and Gupta, 2022) and food security (Jabal et al., 2022) or the impacts of extreme disasters on sustainable business development (Habib and Mourad, 2023). While these studies can help readers understand climate change in depth, they neglect to consider livestock factors. Some scholars are currently focusing on the environmental pressures brought about by agricultural production, especially the environmental damage caused by the livestock industry. For example, several scholars have measured theoretical livestock manure emissions in different regions (Wang et al., 2021) and water, soil, and atmospheric pollution caused by livestock production (Han et al., 2023). Nevertheless, few scholars have studied the development of the livestock industry from a resource-environment perspective (Han et al., 2023). Other relevant studies often focus on environmental pressure (carbon emission) or a certain method of agricultural land resource utilization, but pay less attention to coupling coordination (Jia et al., 2023; Liu et al., 2023). Several scholars have begun to establish a coupling coordination degree model (CCDM) that analyzes the development-oriented relationships between different systems such as fishery systems and environmental quality (Peng et al., 2021); RECC (Chen et al., 2022; Zhang et al., 2022a); agricultural green development and food security (Zhang et al., 2022b; Zhang and Li, 2022); urbanization and the ecological environment (Ariken et al., 2021; Gao et al., 2021; Yang et al., 2022); tourism and the ecological environment (Zhang and Li, 2021; Zhang et al., 2023); and water resource use efficiency and economic development (Dai et al., 2022; Zhang and Li, 2022). However, few studies have systematically investigated the coupling coordination relationship of LRRE to analyze the effects of environmental policies and improve ecological development. The United Nation Framework Convention on Climate Change

(UNFCCC) proposes improving the capacity for coordinated development between production systems and ecosystems to better respond to climate change (Liu F. et al., 2022). The growing consumer demand for meat has stimulated further expansion of livestock production, greatly increasing pressure on resources and the environment (Liang et al., 2023). Countries impacted by this growth need an approach for achieving the coordinated development of the LRRE system. Therefore, this paper provides an effective reference for other large livestock-producing countries worldwide by analyzing the temporal and spatial changes and future trends in the coordinated development of LRRE in China.

To explore the development relationship of China's LRRE system, in this study, a coupled relationship evaluation framework for the LRRE system is constructed and an improved-CCDM is used to analyze the CCDs of the LRRE in China from 2005 to 2020. Furthermore, the spatial autocorrelation model (SAM) and the gray model (GM) are used to analyze the spatial aggregation characteristics and future development trends of the CCDs of LRRE in China. The contributions of this paper are as follows: (1) The resource environment and residential consumption play crucial roles in the development of the livestock industry. However, the coupling coordination development relationship between these variables has not yet been demanded; this information is critical for determining the layout of livestock production. Therefore, a framework for assessing the sustainable development of the livestock industry is constructed from the perspectives of LP, RC and RECC, thus providing practical assistance in guaranteeing food security, adjusting the layout of the livestock industry and alleviating environmental pressure. (2) In the construction of indicators, in contrast to existing studies, in this study, we consider GHGs to be an undesired output of livestock production systems; furthermore, we collected and utilized data on the meat consumption of residents in each region of China, thus creating a comprehensive LRRE indicator system. (3) Methodologically, we use an improved-CCDM to calculate the CCD of the RECC, increasing the accuracy of the results, and the SAM and GM to analyze the spatial aggregation characteristics and future trends of the CCD for each Chinese province from 2021 to 2030. This analysis strategy is helpful for researchers and policymakers because it more clearly explains the spatial distribution characteristics and evolutionary trends of the CCD of the LRRE in each province in China and provides a realistic basis for agricultural green development policy formulation.

2 Index selection, methods, and data sources

2.1 Index selection

2.1.1 Livestock production systems

LP systems contain social, economic, and ecological elements (Zhao et al., 2021). The social element refers mainly to the quantity of food (meat, egg, and milk) produced by livestock. The economic element consists of the total output value of the livestock industry and the value of livestock production per unit of farmland area. The ecological elements include livestock manure, nutrient supplies from livestock manure, and GHG emissions from livestock farming processes. Livestock manure, manure nutrient supply, and GHG emissions are calculated as follows:

(1) Calculation of livestock manure

The study selected pigs, sows, poultry, beef cattle, dairy cows, sheep, horses, donkeys, and mules as subjects. According to Li et al. (2022), rearing quantity was based on the slaughter of pigs and poultry; stockpiles were used to calculate the quantities of the other animals. In addition, due to the influences of rearing methods, climatic environment and other factors, the manure emission factors of various livestock in different areas are differed We referred to Zhou et al. (2014) to set the livestock manure emission factors of each livestock type (Table A.1 in Supplementary material A). The specific calculation formula (1) is as follows:

$$Q_{manure} = \sum_{i=1}^{n} P_i \times T_i \times \mu_i \qquad (1)$$

Q_{manure} is the quantity of manure excreted by livestock; P_i is the number of livestock i slaughtered or stockpiled. T_i is the rearing time of livestock i, and μ_i is the manure emission factor of livestock i.

(2) Calculation of nutrient supply from livestock manure as follows equation (2):

$$S_{manure} = \sum_{i=1}^{n} P_i \times \varphi_i \times \theta \qquad (2)$$

S_{manure} is the livestock manure nutrient supply; φ_i is the nitrogen or phosphorus emissions of livestock i; and θ is the nutrient retention rate. We referred to the recommended values given in the Technical Guide to Livestock Manure Land Carrying Capacity Measurement, which indicated that the nutrient retention rates of nitrogen and phosphorus are 65% (MARD, 2018).

(3) Calculation of greenhouse gas emissions from livestock farming as follows equation (3):

$$GHGs = \sum_{i=1}^{n} P_{Ruminants} \times \varepsilon_i + Q_{manure} \times \sigma_i + Q_{manure} \times \tau_i \quad (3)$$

$GHGs$ are the GHG emissions from livestock farming, $P_{Ruminants}$ represents the stockpile of ruminants, ε_i is the enteric fermentation methane emission factor, Q_{manure} is the quantity of livestock manure, σ_i is the livestock manure methane emission factor, and τ_i is the livestock manure nitrous oxide emission factors. We referred to Guo et al. (2017) to define enteric fermentation methane emission factors, livestock manure methane emission factors, and livestock manure nitrous oxide emission factors (Table A.2 in Supplementary material A).

2.1.2 Resource and environmental carrying capacity

The RECC subsystem consists of resource carrying capacity and environmental carrying capacity systems (Zhang F. et al., 2019). In this paper, referring to Chen et al. (2022) and Zhao et al. (2022), we selected agricultural land area, crop sown area, irrigated area, regional crop nutrient demand, regional crop manure nutrient demand, fertilizer use, total feed production, rural electricity

consumption, total water resources, and road mileage for the evaluation of the resource subsystem. To evaluate the environmental subsystem, we selected the forest coverage rate, wetland area, pollution control investment, annual average $PM_{2.5}$ concentration, and green area.

The calculations of regional crop nutrient demand and nutrient requirements for crops from livestock manure were based on the Technical Guide to the Measurement of Land Carrying Capacity of Livestock and Poultry Manure (MARD, 2018). The calculation process is as follows equation (4):

(1) Calculation of regional crop nutrient demand:

$$Q_{Nutrients} = \sum_{i=1}^{n} P_i \times \gamma_i \qquad (4)$$

$Q_{Nutrients}$ is the regional crop nutrient requirement, P_i is the yield of crop i, and γ_i is the crop i nutrient demand coefficient (Table A.3 in Supplementary material A).

(2) Calculation of the manure nutrient requirements of crops from livestock manure as follows equation (5):

$$Q_{Manure\ fertilizer} = \sum_{i=1}^{n} \left(Q_{Nutrients} \times \alpha_i \times \beta_i \right) / \delta_i \qquad (5)$$

where $Q_{Manure\ fertilizer}$ is the nutrient requirement of crops from livestock manure; α_i represents the share of chemical fertilizer nutrients in the total nutrient requirements of crops; β_i is the proportion of livestock manure nutrients to the total nutrient requirements of crops; and δ_i is the utilization rate of livestock manure nutrients. For convenience, we referred to the recommended values given in the Technical Guide to Livestock Manure Land Carrying Capacity Measurement (MARD, 2018), where β_i is 50%, the utilization rate is 30% for nitrogen and 35% for phosphorus (Zheng et al., 2019), and α_i is 45%.

2.1.3 Residential consumption

The residential consumption system consists of the livestock product consumption level and consumption potential. The main evaluation indicators of consumption potential were GDP, GDP *per capita*, urbanization level, *per capita* income, population size and Engel's coefficient (Cao et al., 2019; Roux et al., 2021). The consumption level included *per capita* meat, egg, and milk consumption demand, as well as the total meat, egg, and milk consumption of residents (Fan and Fang, 2020). Table 1 shows the LRRE indicator system.

2.2 Methods

2.2.1 Improved-CCDM

The entropy weight method can be used to comprehensively evaluate several dimensions; it is often used in comprehensive evaluation research because of its scientific basis and simplicity. In this study, the entropy weight method was adopted to calculate the total score of each subsystem; the specific calculation methods used are

described in Sahoo et al. (2017) and Zhang C. et al. (2019). The total score of each subsystem was calculated. Then, the improved-CCDM was used to calculate the CCD of the LRRE. The CCDM is mainly used to evaluate the strength and correlation between the interactions of systems and has been widely used in several fields (Cheung and Ma, 2011; Tan et al., 2022). The calculation is as follows equation (6) (Ariken et al., 2021):

$$C = \left\{ \left(\left(f(LP) \times g(RC) \times y(RECC) \right) / \left(f(L) + g(RE) + y(C) \right) / 3 \right)^3 \right\}^{1/3} \qquad (6)$$

where C represents the coupling degree between LRRE, and $f(LP), g(RC)$, and $y(RECC)$ are the evaluation indices of LP, RC, and $RECC$, respectively.

Furthermore, we can calculate the CCD of LRRE by formulas (7, 8):

$$T = \alpha f(U) + \beta f(E) + \mu y(C) \qquad (7)$$

$$D = \sqrt{CT} \qquad (8)$$

where D is the CCD for the three systems, $0 \leq D \leq 1$; when D is closer to 1, the CCD is higher. T is the comprehensive evaluation index for the coordinated development of the LRRE subsystems. α, β, and μ represent the weight values of the LRRE subsystems. We referenced Shen et al. (2018) and Jiang et al. (2022) and used the improved-CCDM to calculate α, β, and μ. The equations are as follows equation (9):

$$\alpha = \alpha / (\alpha + \beta + \mu), \beta = \beta / (\alpha + \beta + \mu), \mu = \mu / (\alpha + \beta + \mu) \qquad (9)$$

Li J. et al. (2021) and Peng et al. (2021) were referenced to construct the coupling coordination level (Table 2). In Table 2, we divide coupling coordination degree into five levels. When the degree of dissonance coordination increases to a high level, the coordination level of the LRRE system increases, and livestock production, residential consumption and resource environment match.

2.2.2 Spatial autocorrelation

Moran's I is commonly used to measure the spatial aggregation characteristics of and period changes in industry (Ping et al., 2004; Zhou et al., 2014). Therefore, we used the global Moran's I to test the spatial correlation of LRRE with equation (10):

$$Global\ Moran's\ I = \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij} \left(y_i - \bar{y} \right) \left(y_j - \bar{y} \right) / s^2 \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}$$

$$s^2 = \frac{1}{n} \sum_{i=1}^{n} \left(y_{ij} - \bar{y} \right); \bar{y} = \sum_{i=1}^{n} y_i / n \qquad (10)$$

where y_i and y_j are the levels of CCD in province i and province j, respectively; $\bar{y}$ is the average level of CCD; w_{ij} represents the elements in row i and column j of the spatial weight matrix; n is the number of provinces; and s^2 is the sample variance.

TABLE 1 Indicator system of LRRE.

System	Subsystem	Indicators	Attributes
Livestock production	Economic	Total output value of the livestock industry (10^8 CNY)	+
		Output value of livestock industry per unit farmland area (10^4 CNY/ha)	+
	Society	Yield of meat (10^4 t)	+
		Yield of eggs (10^4 t)	+
		Yield of milk (10^4 t)	+
	Ecological	Livestock manure (10^4 t)	−
		GHG emissions from livestock farming processes (10^4 t)	−
		Nutrient supply from livestock manure (10^4 t)	+
Residential consumption	Consumption potential	Gross domestic product (10^8 CNY)	+
		Gross domestic product (GDP) *per capita* (10^4 CNY per person)	+
		Per capita income (CNY per capital)	+
		Urbanization rate (%)	+
		Engel's coefficient (%)	+
		Population size (10^4 person)	+
	Consumption level	*Per capita* meat consumption (kg)	+
		Per capita egg consumption (kg)	+
		Per capita milk consumption (kg)	+
		Total meat consumption (kg)	+
		Total egg consumption (kg)	+
		Total milk consumption (kg)	+
Resource and environmental carrying capacity	Resource carrying capacity	Agricultural land area (ha)	+
		Crop sown area (ha)	+
		Irrigated area (ha)	+
		Regional crop nutrient demand (10^4 t)	+
		Regional crop manure nutrient demand (10^4 t)	+
		Fertilizer use (10^4 t)	+
		Feed production (10^4 t)	+
		Rural electricity consumption (10^4kw)	+
		Total amount of water resources (10^8 m³)	+
		Road mileage (10^4 km)	+
	Environmental carrying capacity	Forest coverage rate (%)	+
		Wetland area (ha)	+
		Pollution treatment investment (10^4 CNY)	+
		Annual average PM2.5 concentration (10^4 t)	−
		Green area (10^4 ha)	+

To adequately express the trend of regional differences, we further used the local spatial autocorrelation method to reveal the correlation of local study units in the neighborhood space (Li Q. et al., 2021). The specific expressions are as follows equation (11):

$$Local\ Moran's\ I = \left(y_i - \bar{y}\right) \sum_{j=1}^{n} w_{ij} \left(y_i - \bar{y}\right) / s^2 \qquad (11)$$

2.2.3 GM (1.1) prediction model

The GM (1.1) is the traditional prediction model and can develop and utilize explicit and implicit information from modest data to determine the mathematical relationships between factors. Typically, discrete models are used to construct a model for the period-by-period analysis of intercropping. However, discrete models can perform only short-term analysis of the development of an objective system, and cannot adapt to the requirements of long-term analysis, planning and decision-making. Therefore, the GM is more suitable for short-term forecasting analysis (Jiang et al., 2022) and is widely used for prediction studies (Qian and Wang, 2020; Geng et al., 2021; Liu H. et al., 2022). Therefore, to visualize the dynamic evolution trajectory of the CCD of the LRRE in the future, we adopted this method to forecast the CCD of the LRRE from 2021 to 2030 in 31 provinces in China. The GM (1.1) model is constructed as follows:

TABLE 2 Coupling coordination level of LRRE.

Coupling coordination type	CCD value range	Specific performance
Class V	$0 < D \leq 0.2$	Dissonance coordination level
Class IV	$0.2 < D \leq 0.4$	Low coordination
Class III	$0.4 < D \leq 0.6$	Basic coordination
Class II	$0.6 < D \leq 0.8$	Intermediate coordination
Class I	$0.8 < D \leq 1$	High coordination

First, the original sequence determined by is the following equation (12):

$$x^0(i) = \left[x^0(1), x^0(2), \cdots x^0(n) \right] \tag{12}$$

Second, the whitening differential equation is calculated as follows equation (13):

$$dx^0(t)/dt + ax^0(t) = u \tag{13}$$

where a is the development gray number and u is the endogenous control gray number.

Furthermore, the solution of equation (13) is equation (14):

$$x^0(k+1) = \left[x^0(1) - (u/a)e^{ak} + u/a \right] \tag{14}$$

2.3 Data sources

The data were obtained from the China Statistical Yearbook, China Rural Statistical Yearbook, China Animal Husbandry and Veterinary Statistics Yearbook, China Provincial Statistical Yearbooks and the website: https://data.cnki.net/. All the data are time series data from 2005 to 2020. In this study, we referred to Sun et al. (2019) for the division of China's four regions.[1]

3 Results

3.1 Comprehensive evaluation results of the LS, RC, and RECC

In this study, the entropy method was first used to calculate the comprehensive scores for LS, RC and RECC from 2005 to 2020 as a

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1 Eastern region: Beijing, Tianjin, Hebei, Shandong, Shanghai, Jiangsu, Zhejiang, Fujian, Guangdong and Hainan; central region: Shanxi, Henan, Anhui, Jiangxi, Hubei and Hunan; western region: Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, Inner Mongolia, Tibet and Xinjiang; and northeastern region: Liaoning, Jilin, and Heilongjiang.
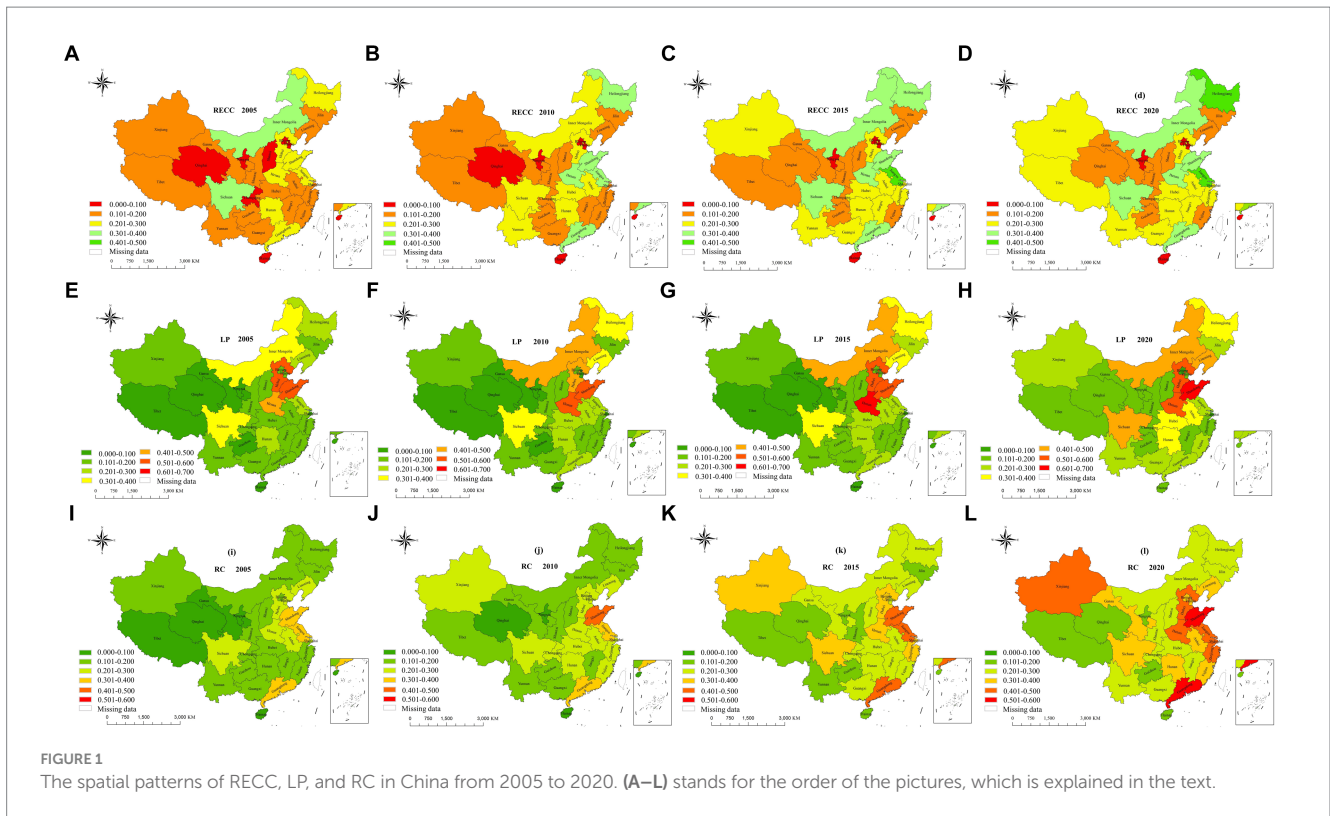
way to understand the development of each system. The scores for each system are shown in Figure 1.

Resource and environmental carrying capacity (RECC). Figures 1A–D, show that the RECC in China's provinces increased from 2005 to 2020. This result is similar to the findings of Liao et al. (2020). However, unlike Li et al. (2022), who studied the RECC at the national level, our study focused on 31 provinces in mainland China. This approach can be used to analyze the spatial and temporal trends of China's RECC more effectively. Specifically, in 2005, except for Sichuan and Inner Mongolia, the RECCs of all the provinces in China were relatively low (<0.3). With the rapid development of China's economy and policy support, the RECC levels of Chinese provinces improved comprehensively; those of Henan, Shandong, Jiangsu, Guangdong, and Heilongjiang exhibited the most obvious increase. Jiangsu and Heilongjiang reached 0.4–0.5 in 2015 and 2020, respectively, and had the highest provincial RECC levels in China. Guangdong, Jiangsu and Shandong are coastal cities and the best economically developed provinces in China. A good economy ensures that these areas have sufficient funds to improve the environment. However, Beijing, Tianjin, Ningxia, and Hainan had the weakest RECCs, with no significant improvement between 2005 and 2020. Ningxia, located in western China, is characterized by arid and semiarid regions, and its severe environment leads to a relatively weak resource carrying capacity. Moreover, although western China's RECC has improved, it was still at a low level (0.1–0.2). Beijing and Tianjin are economically developed cities in China. However, the high level of urbanization and large population consumes a large amount of resources, which is a massive challenge for RECC. Overall, improvements of in factors such as the scale of agriculture, water resources, infrastructure and pollution treatment capacity have greatly contributed to the RECC. However, some regions are weak due to differences in economic levels, resource reserves, and pollution treatment among provinces (Liao et al., 2020; Tan et al., 2022).

Livestock production (LP) (Figures 1E–H). From 2005 to 2020, the spatial and temporal characteristics of China's livestock production changed significantly. In 2005, the regions with higher-intensity livestock production were concentrated in Shandong, Henan, Hebei, Sichuan, and Inner Mongolia, all with livestock production intensities above 0.3. In 2010, livestock production intensity increased significantly in Heilongjiang, Liaoning, and Inner Mongolia, reaching 0.351, 0.353, and 0.457, respectively. In 2020, the intensity of livestock production in the western regions of Yunnan, Sichuan, and Xinjiang, central regions of Anhui, Hubei, and Hunan, and northeastern region of Liaoning further increased, especially in Sichuan and Liaoning, which had livestock production values of 0.430 and 0.442, respectively. These regions have good conditions for livestock development, such as fertile grasslands, agricultural land, and water resources; their excellent resource endowments have led livestock development policy to gradually tilt toward the western and northeastern regions. China's 14th Five-Year Plan for Agriculture also identifies the western and northeastern regions as the main livestock production areas. By producing high-resolution maps of livestock production in China, Cheng et al. (2023) found that the intensity of livestock production in China is increasing, especially in Northwest China and in rural areas, and while this growth contributes to reducing hunger and poverty, it may increase pressure on cleaner production.

Residential consumption (RC). Figures 1I–L shows the evolution characteristics of the spatial distribution of livestock product

FIGURE 1
The spatial patterns of RECC, LP, and RC in China from 2005 to 2020. **(A–L)** stands for the order of the pictures, which is explained in the text.

consumption by residents in China from 2005 to 2020. In 2005, the highest livestock product consumption levels occurred mainly in Shandong, Jiangsu and Guangdong, within a range of 0.3 to 0.4. In 2010, Shandong had the highest livestock product consumption level (0.402); furthermore, the consumption level in the central and eastern regions, such as Hubei, Hunan, Anhui, Zhejiang, and Fujian, increased to above 0.2. In 2015, the livestock product consumption levels in the eastern and central regions rose to above 0.2, with Beijing, Henan, Hebei, Zhejiang, Shandong, Jiangsu, and Guangdong reaching levels above 0.3. In 2020, the livestock product consumption level in the eastern region further increased, especially in Shandong and Guangdong, which had the highest levels in China. In the western and northeastern regions, only Xinjiang reached a livestock product consumption level of 0.4–0.5. In fact, the eastern region, as China's pioneer in opening up to the outside world, has enormous economic development advantages (Zhang Y. et al., 2022). Rapid economic development has attracted a larger population and increased residential consumption levels (Zhang Z. et al., 2022). The results of our study also reinforce this social phenomenon.

3.2 Spatial–temporal characteristics of the CCDs of the LRRE in China

As shown in Figure 2, the CCDs of the LRRE in 31 provinces of China increased from 2005 to 2020; however, only a few provinces reached an intermediate coordination level (0.6–0.8) in 2020, and most provinces exhibited basic coordination (0.4–0.6). This situation indicates that there is still potential for further coordinated development of LRRE in China. Among them, Ningxia, Xinjiang, and Gansu had the highest annual average growth rates, reaching 2.14,

2.37, and 2.46%, respectively. Shandong, Tibet, Sichuan, Shanxi, and Jilin Provinces had average annual growth rates of less than 1%. The CCDs of the LRRE reached an intermediate coordination level in major livestock production provinces such as Shandong, Henan, Hebei, Sichuan, and Heilongjiang. These provinces have relatively excellent resource endowments but still have not reached a high coordination level, primarily because although the RECCs of these regions are constantly improving, the production intensity of livestock products and the consumption level of residents are rising faster. Hainan, Tibet, Qinghai, and Ningxia have always had a low coordination level. All these provinces are situated in the western region; furthermore, Tibet, Qinghai, and Ningxia are characterized by high-quality pastoral areas in China, sparse populations, and poor resource endowments, which lead to relatively low CCDs.

As shown in Figure 3, the spatial distribution characteristics reveal relatively high CCDs in the central, eastern and northeastern regions and relatively low CCDs in the western region. Specifically, only Hebei and Shandong reached an intermediate coordination level in 2005, and the surrounding areas were mostly between the basic coordination and low coordination level. No province was at the dissonance coordination levels. In 2010, Henan Province increased from a basic coordination level to an intermediate coordination level, and coastal regions essentially reached a basic coordinate level. Jiangsu reached the intermediate coordination level in 2015, as did Heilongjiang, Sichuan, and Guangdong in 2020. From 2005 to 2020, except for Tibet, Qinghai, Ningxia, and Hainan in the western region, all the provinces achieved a basic coordination level. This shows that the development of China's livestock industry has not been at the expense of the environment in relation to increases in the consumption levels of residents; rather, the relationships among production, consumption, and resources and the environment has continued to shift toward

FIGURE 2
CCDs of the LRRE in China from 2005 to 2020.
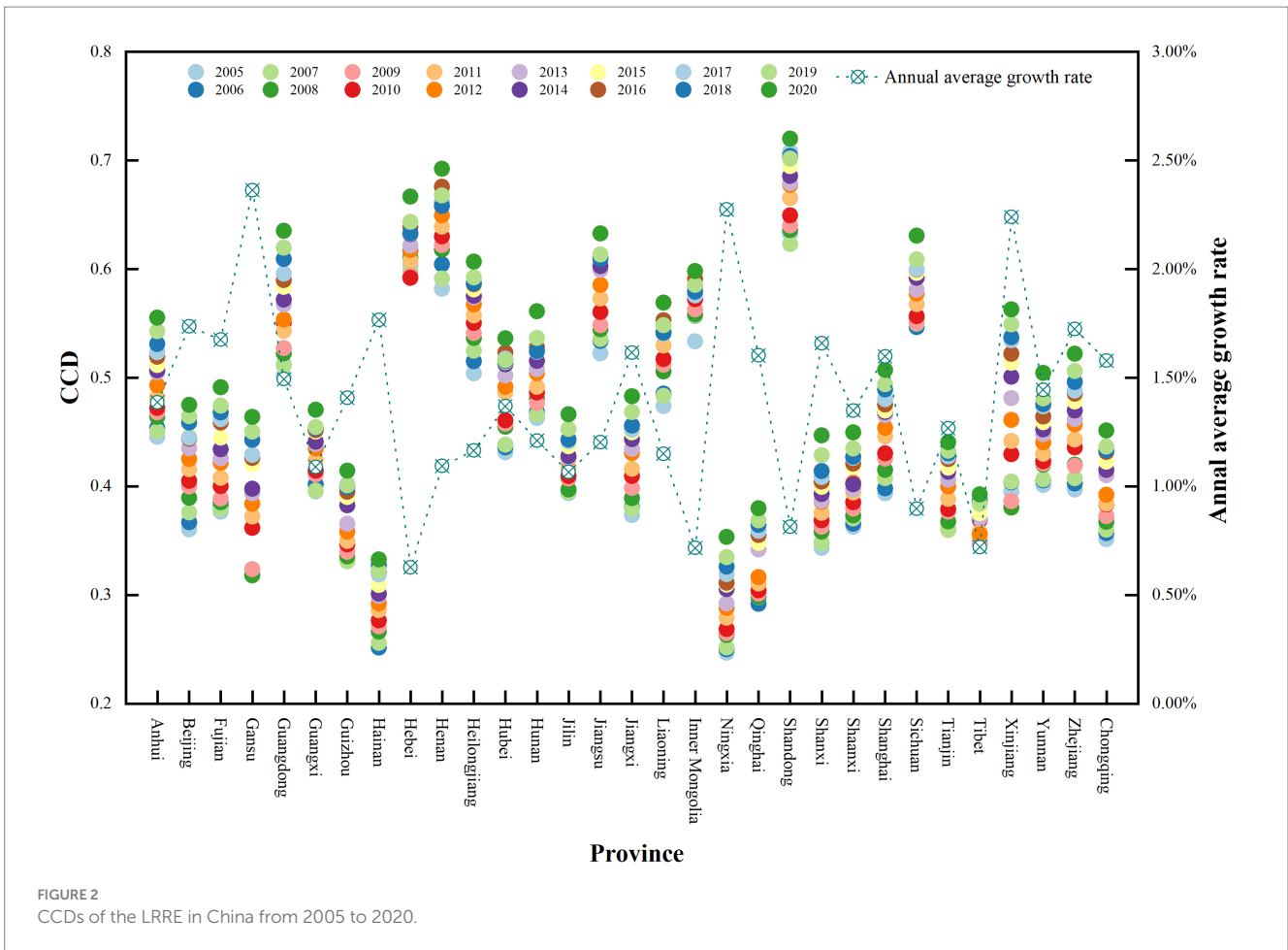
coordinated development (Fan et al., 2020). However, at the same time, the coordinated development level of LRRE in some provinces in China, such as Beijing, Tianjin, Ningxia, Qinghai, and Tibet, remains at a low coordinated level. These areas should pay attention to matching multidimensional systems such as livestock production, resources and the environment, and residential consumption. Any system that develops more slowly than others may negatively impact residents' welfare and social economy.

3.3 Spatial autocorrelation analysis of the CCDs

Table 3 presents the global spatial autocorrelation results for the CCD of the LRRE. The results showed that the global Moran's I was positive and significant ($p < 0.1$), indicating that the spatial distribution of the CCDs of the LRRE in China was positively correlated and significantly clustered. Furthermore, Figure 4 shows the local spatial clustering characteristics of the LRRE in 2005, 2010, 2015, and 2020 in 31 Chinese provinces, with a significance level less than 10%. The main aggregation regions were located in the eastern, central, northeastern, and some western regions of China. Specifically, the high-high (H-H) aggregation areas were mainly distributed in the northeastern, eastern, and central regions. In particular, Hunan, Jiangxi, and Fujian changed from low-high (L-H) aggregation to H-H aggregation, indicating that the influence of these three provinces on

the surrounding areas became positive. The L-H aggregation regions were mainly concentrated in the junction regions of the central and western provinces, such as Shanxi, Shaanxi, Ningxia, Gansu, Chongqing and Guizhou Provinces, indicating that the CCDs in these provinces were lower than that in the surrounding areas. These regions are on the Loess Plateau and have a relatively harsh ecological environment (Li J. et al., 2021; Li Q. et al., 2021), which should be noted by the Chinese government. Moreover, we found that the H-H aggregation in Jilin shifted to L-H aggregation from 2005 to 2010, indicating that the CCD in Jilin decreased compared to that in the surrounding areas. The possible reasons for this phenomenon were that the intensity of livestock production and consumption level in Jilin Province increased; however, the RECC did not simultaneously increase.

3.4 CCD prediction results

Predicting the coordinated development trend of LRRE in different regions of China can provide a valuable reference for policy makers. Figure 5 shows that the CCDs of all 31 Chinese provinces will increase from 2021 to 2030, and all provinces will be at a level of basic coordination. From 2021 to 2030, Gansu, Anhui, Hubei, Hunan, Liaoning, Xinjiang, and Zhejiang will transition from a basic coordination level to an intermediate coordination level. In 2030, Fujian (0.592) and Shanghai (0.597) will reach an intermediate
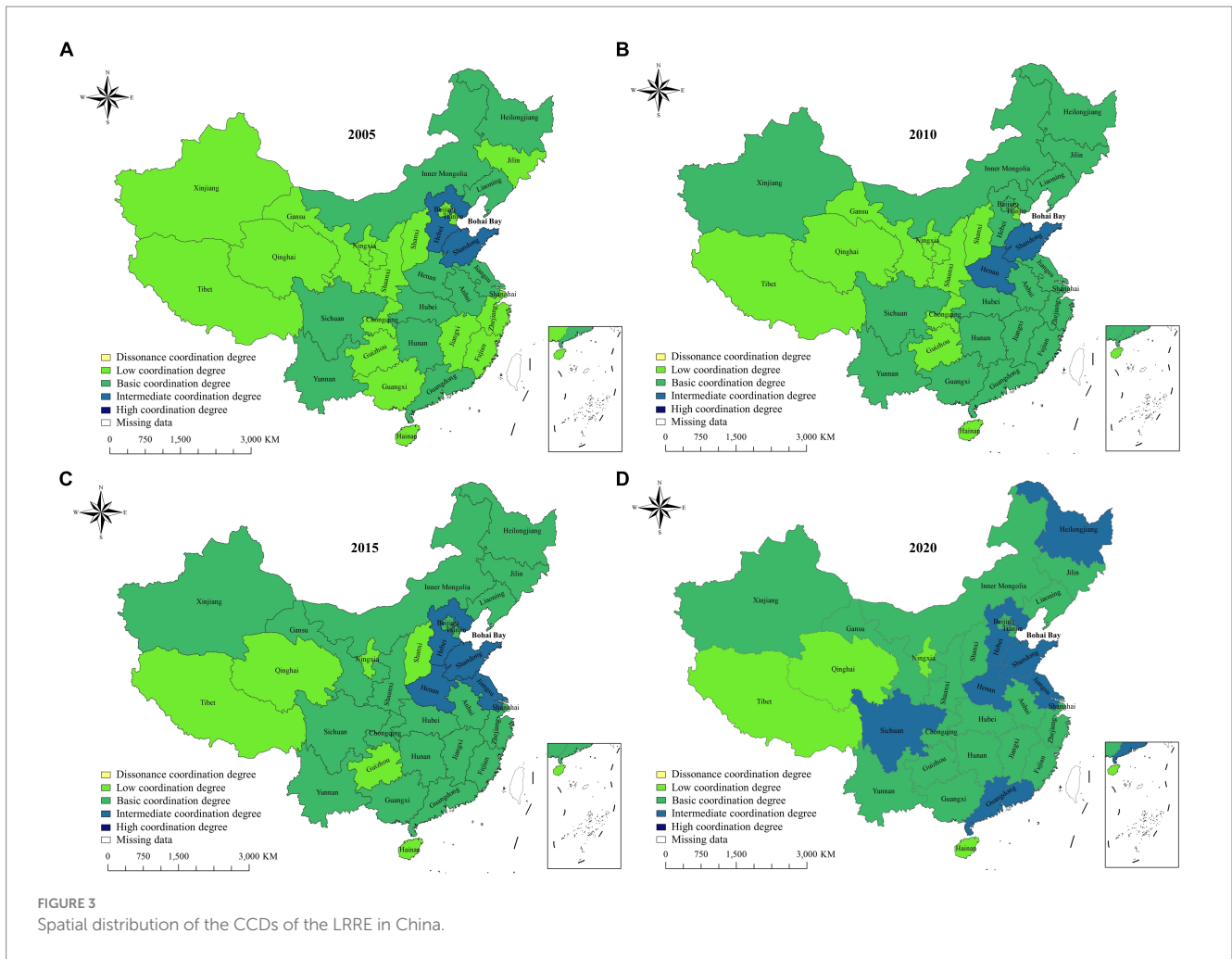
FIGURE 3
Spatial distribution of the CCDs of the LRRE in China.

coordination level, and Henan (0.752), Xinjiang (0.766), and Shandong (0.799) will reach a high coordination level. Although Ningxia, Qinghai, Tibet, and Guizhou Provinces will reach a basic coordination level in 2030, the CCD levels in these regions will still be lower (less than 0.5), suggesting more potential for improvement. These prediction results indicate that the low level of coordinated development of LRRE in western China may struggle to change in the short term. The level of coordinated LRRE development in the developed eastern region is increasing. Therefore, in the future, China's livestock industry should appropriately adjust its spatial layout, reduce the expansion rate of the livestock industry in the western region, and improve the ecological environment in the areas bordering the western and central regions (arid and semiarid regions).

4 Discussion

A scientific evaluation of the status of sustainable development in the livestock sector has importance for most developing countries, as it relates to stable food supplies and ecological environment improvements. Several researchers have endeavored to explore the environmental catastrophes caused by livestock farming, but additional research is needed to determine how livestock farming can be sustainable. The development of the livestock industry is strongly

related to resources, the environment and resident consumption levels, and we have made efforts to analyze the development of these factors via scientific methods and comprehensive data. A modeling assessment of the sustainable development of China's livestock sector is necessary because China is the largest producer and consumer of meat worldwide, and subject to pollution caused by the livestock industry. Therefore, we selected China as an example to explore the relationships among LP, RC, and the RECC; these relationships can provide useful information for the sustainable development of the livestock industry in China and other major agricultural countries.

The spatial and temporal characteristics of each subsystem of the LRRE in China are obviously different. In particular, there are significant spatial differences between the production and consumption of livestock products. Livestock production is concentrated mainly in the central region and Shandong; however, the intensity of livestock production is increasing in the western and northeastern regions. The consumption of livestock products occurs mainly in economically developed and densely populated areas (eastern and part of central China). This finding is similar to the findings of Yang et al. (2022), who reported that large quantities of meat are consumed in the central and eastern regions of China, where the population is concentrated, though livestock farming in the western pastoral areas is also expanding due to the rising demand for meat. As the economy grows, the demand for meat will continue to

TABLE 3 Global Moran's index of CCD in China from 2005 to 2020.

Variables	Moran's I	Z	p-value*
2005	0.059	1.528	0.065
2006	0.060	1.610	0.054
2007	0.061	1.663	0.048
2008	0.067	1.982	0.024
2009	0.072	2.309	0.010
2010	0.064	1.818	0.034
2011	0.070	2.150	0.016
2012	0.071	2.214	0.013
2013	0.066	1.946	0.026
2014	0.063	1.756	0.040
2015	0.062	1.672	0.047
2016	0.061	1.617	0.053
2017	0.058	1.442	0.075
2018	0.058	1.470	0.071
2019	0.061	1.637	0.051
2020	0.059	1.546	0.061

rise, placing more environmental pressure on the areas with concentrated livestock production (Sun et al., 2021). Fortunately, the overall RECC level in China is increasing providing a high level of ecological security for livestock production. However, the Chinese government should also focus on some western regions (Qinghai, Ningxia, and Gansu) where the RECC level is still low and not conducive to the green development of the livestock industry.

Overall, the CCDs of the LRRE in China's provinces increased from 2005 to 2020, indicating that China's livestock industry is transforming to green development. However, notably, whether the western region can continue to sustain the continuous growth of consumption demand for livestock products is a key issue. The CCDs of Qinghai, Tibet, and Ningxia have not significantly improved over the past decade. The results of the spatial autocorrelation test and prediction also reveal that the western provinces exhibit obvious L-H aggregation characteristics; Tibet, Gansu, Ningxia and Guizhou will have the lowest CCDs in China in 2030. These findings indicate that the ability of western China to sustain expansions in the scale of the livestock industry is both a present and future concern. In fact, the Chinese government proposed ecological civilization construction as early as 2012; this concept requires improving the ecological environment by adjusting the industrial layout and investment in environmental management (He et al., 2023). Furthermore, the pattern of China's livestock production has changed. The scale of livestock production in the eastern and southern water network areas has been continuously reduced, and the ecological environment has improved (Zheng et al., 2021). However, despite the decrease in the scale of livestock in the eastern and southern regions, the increase in consumer demand has led to the need to expand livestock production in other regions of China. In addition, western China has a large amount of pasture and land, which is conducive to expanding livestock production (Klotzbucher, 2009). However, this scenario has exacerbated ecological degradation in western China (Briske et al., 2015). Several studies have shown that the soil and pastures in western

China have been severely damaged by the continued expansion of grazing (Dong et al., 2020; He et al., 2023). In fact, the Chinese government has advocated using the production method of "grazing prohibition, resting grazing and rotational grazing" to reduce the ecological impact of grazing, but this method is not conducive to the livelihoods of herders and does not support the growing consumer demand for meat (Harris, 2010). Currently, the Chinese government urgently needs to re-examine the pattern of livestock production and implement measures to improve the RECC in western China (Shang et al., 2014).

As population size and affability continue to increase, the global demand for meat consumption continues to rise, resulting in more serious environmental problems. Livestock production requires large amounts of water, grassland, and forage crops; meat production is also a major source of GHG emissions. In some developed countries, the demand for meat consumption is high. However, the layout of the livestock industry is coordinated with residents' dietary habits and resource endowments, so the livestock industry has not caused severe damage to the environment, as in the United States (Tonsor and Lusk, 2022). The sustainable development of the livestock sector is also strongly related to national economic transformation policy. Australia has one of the highest rates of meat consumption worldwide' (Ford et al., 2023). To avoid the adverse impact of the large-scale livestock industry on the environment, the Australian government requested residents to reduce excessive meat consumption and improve the agricultural production environment, which ultimately reduced the environmental pressure caused by the livestock industry (Sievert et al., 2022). Developing countries are experiencing rapid population and economic growth; thus, the consumption of meat and the scale of animal rearing are expanding, which creates challenges for environmental sustainability (Alobo Loison and Hillbom, 2020; Ronaghi and Ronaghi, 2021). Therefore, promoting the coordinated development of LRRE is an essential condition for agricultural transformation in developing countries (Benson and Mugarura, 2013).

5 Conclusion and policy implications

5.1 Research conclusion

With the growth of the economy, residential demand for meat is increasing, which in turn stimulates the expansion of the livestock industry; however, overfarming can harm the environment. Therefore, promoting the coordinated development of LRRE systems has become the key to sustainable development. This study established an analytical framework for the coupling coordination development of the LRRE. The SAM and GM (1.1) were used to analyze the spatial correlation and future trends of the CCD of the LRRE systems. This analysis strategy can help policy makers understand the development pattern of China's LRRE system while providing effective evidence for optimizing the layout of China's livestock sector. The main conclusions of this study are as follows.

(1) From 2005 to 2020, the levels of China's LP, RC, and RECC increased. However, there were great differences in the spatial distributions of LP, RC, and RECC in China. The highest intensities of livestock production were concentrated in Shandong, Henan, Hebei, Inner Mongolia, and Sichuan and then shifted to the central, western and northeastern regions. The consumption of livestock products

FIGURE 4
Local spatial autocorrelation results of the CCDs of the LRRE in China from 2005 to 2020.
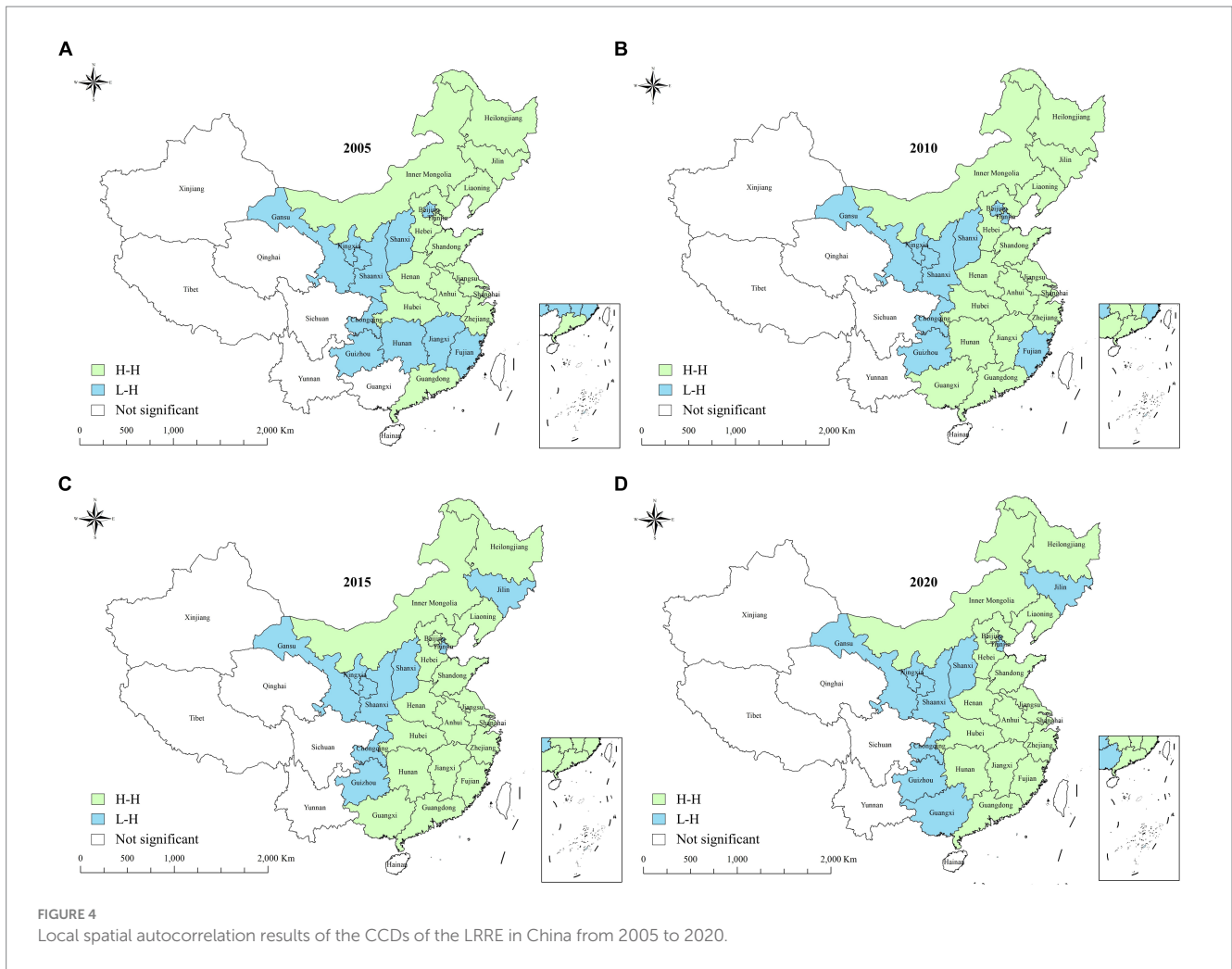
occurred mainly in the eastern coastal areas of China. In comparison to the other provinces, Jiangsu, Heilongjiang, Shandong, Guangdong, Sichuan, and Inner Mongolia had higher RECCs. (2) The CCDs of the LRRE continued to increase in 31 Chinese provinces from 2005 to 2020, with relatively high levels in the central, eastern and northeastern regions and relatively low levels in the western region. (3) The spatial autocorrelation analysis confirmed that the high-high (H-H) aggregation areas were mainly distributed in the northeastern, eastern, and central regions, while low-high (L-H) agglomeration was distributed in the western region. (4) According to the prediction results, the CCDs of the LRRE in 31 Chinese provinces will increase to different degrees from 2021 to 2030, and all provinces will reach the basic coordination level. However, most of the western regions will barely reach the basic coordination level. This result indicates that the low level of LRRE development in western China may be difficult to change in the short term.

5.2 Policy implications

Based on these conclusions, we propose the following policy recommendations.

(1) The Chinese government needs to consider and address the trend of expanding livestock farming in the western and northeastern

regions, as well as the still high-intensity livestock production levels in some southern water network areas, such as Anhui, Hunan, and Hubei. The government should adjust its environmental protection policy to reduce ecological and environmental pressure in southern water network areas. Moreover, because Beijing, Tianjin, Ningxia, and Hainan had the weakest RECCs, these areas should reduce the intensity of their livestock production and increase their areas of forests and vegetation. (2) The consumption of livestock products occurs in China's coastal areas, so large and standardized farms should be appropriately built in these areas to supply residents with primary meat foods to alleviate ecological pressure in other areas. Sustainably guiding people's food consumption and encouraging them to eat poultry and eggs instead of beef or mutton will help reduce the consumption of water and food and reduce the risk of soil degradation. The proportion of meat food imports can be appropriately increased to meet the residential demand for meat food consumption. (3) The CCDs of the LRRE are low in the central and western junction regions, such as Shanxi, Shaanxi, Ningxia, Chongqing, and Guizhou. The Chinese government needs to focus on these areas and provide support. In addition, these areas need to develop cleaner production techniques, protect pastures and vegetation, and improve their RECCs. (4) The eastern and central regions have higher overall CCDs and are in the H-H aggregation area. These regions should take full advantage and of their situation
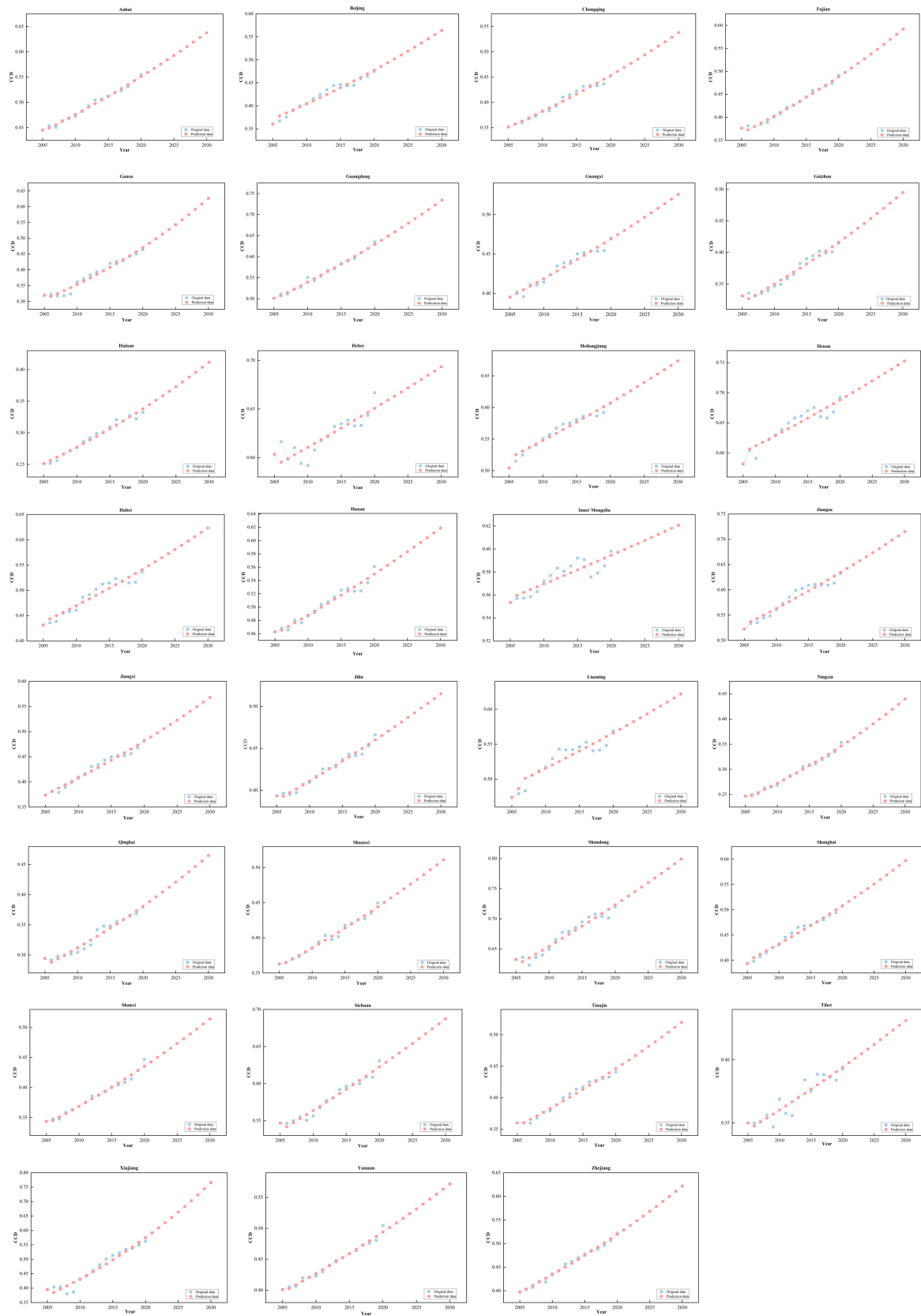
FIGURE 5
CCDs prediction results in China from 2021 to 2030.

while providing technology and capital to the western region to improve the green development capacity of their livestock industry. The western region is the main production area for beef, mutton, and milk in China. According to the 14th Five-Year Plan for China's livestock development (MARD, 2021), the western region is likely to further expand its farming scale in the future. However, to protect the environment, the green development capacity of its livestock industry needs to be improved in the western region, large-scale biogas engineering and power generation technology needs to be developed in the highland cold region, and a complete resource recycling system needs to be established to cope with the expanding trend of the livestock industry in the future.

6 Study limitations

The analytical results of this study can guide developing countries in the coupling coordination development of LP, RC and RECC, and help with developing effective measures for adjusting the spatial distribution of the livestock industry. However, this study has several limitations. First, due to the limitation of data availability, the evaluation index system of this study lacks relevant livestock production technology, such as information on the mechanization rate of the livestock industry, the level of digitalization, and the education level of workers; thus, the level of livestock development in some regions may be underestimated. In future research, technical evaluation systems for livestock production can be added, along with relevant technical standards. Second, although this study was based on 31 provinces in mainland China, many of China's provinces have vast land areas, and the distribution of industrial development, population, climate, and resource conditions within each province varies greatly; therefore, examining the development of the LRRE in terms of provincial-level data may lead to rough generalizations. Therefore, in the future, if higher resolution maps or data can be accessed to analyze the development of LRRE, the layout of China's livestock industry can be optimized. Finally, although this paper used an improved-CCDM, SAD, and GM, the rapid development of technology may permit future research to use a combination of multidisciplinary techniques such as management science and ecology to assess the environmental impacts and optimize the layout of the livestock industry more accurately.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found at: https://data.cnki.net/.

Author contributions

KZ: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Writing – original draft, Writing – review & editing. JW: Conceptualization, Formal analysis, Funding acquisition, Software, Writing – original draft. HL: Conceptualization, Data curation, Investigation, Methodology, Software, Writing – original draft. ZZ: Methodology, Formal analysis, Writing – original draft. HW: Supervision, Formal analysis, Project administration, Funding acquisition, Writing – review & editing. JL: Funding acquisition, Resources, Supervision, Writing – review & editing.

Conflict of interest

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

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1365076/full#supplementary-material

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