Environmental Science and Pollution Research (2024) 31:5881–5895
https://doi.org/10.1007/s11356-023-31316-8

RESEARCH ARTICLE

Resilience of agricultural development in China's major grain-producing areas under the double security goals of "grain ecology"

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Received: 6 September 2023 / Accepted: 28 November 2023 / Published online: 22 December 2023

Abstract
The development of agriculture faces uncertainties due to global climate variability and the scarcity of agricultural resources. Enhancing agricultural development resilience is essential for improving agriculture's adaptability to the external environment and ensuring food security. It is imperative to prevent and control agricultural pollution as it worsens. Thus, enhancing the resilience of agricultural development requires balancing food security and ecological security. The present study constructs an evaluation system for agricultural development resilience in China with three levels: resistance, resilience, and reengineering ability. The agricultural development resilience of China's main grain-producing areas is evaluated using the entropy method, and regional differences are analyzed using kernel density estimation and the Theil index. The obstacle model was used to identify and analyze the obstacles that affect agricultural development's resilience to propose countermeasures. The results showed that (1) agricultural development resilience in China's main grain-producing areas has steadily increased from 0.317 to 0.427. The resilience of agrarian development in Heilongjiang, Shandong, and Henan provinces ranges from 0.473 to 0.575, which is far higher than the mean development level; (2) Regional differences in the main grain-producing areas are narrowing from 0.077 to 0.023; (3) The main grain-producing areas share common obstacle factors, emphasizing the critical role of technological innovation, investment, and machine-cultivated land resources in enhancing agricultural resilience against external risks. Paying attention to the amount of fertilizer usage is crucial to achieving ecological security goals.

Keywords Ecological security · Resilience in agricultural development · Main grain-producing areas · Food security

Introduction

According to the research report "Nature Food", the world food system accounts for over one-third of global anthropogenic greenhouse gas emissions. The emissions from the land sector account for two-thirds of the entire food system's emissions, which is even higher in developing countries. The emissions generated in the grain production process account for 39% of the total emissions of the entire grain system. On the other hand, in agricultural development, using fertilizers, pesticides, etc. can cause varying environmental pollution. Therefore, how to reduce carbon emissions in the food system, especially in agricultural production, is a global ecological issue that requires attention. Food security is fundamental to national economies, people's livelihoods, and social stability. It serves as the cornerstone of economic development and the maintenance of social well-being. Therefore, the solution to agricultural carbon emissions also needs to consider the bottom line of food security. However, the global supply of agricultural products has faced increasing instability in recent years. Some countries have started imposing restrictions on food exports. Additionally, extreme climate events influenced by the natural environment can significantly impact annual grain yields. The "World Food Security and Nutrition Report" released in July 2021 by the Food and Agriculture Organization of

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the United Nations (FAO) highlights that climate change, conflicts, and economic recessions worsen food insecurity. Global crop yields are further affected by climate change, pests, diseases, and various other factors (Arumugam et al. 2023; Agwu et al. 2018; Liu et al. 2020; Mao et al. 2022). Furthermore, dependence on food imports can also impact food security (Abedrabboh et al. 2023). These uncertain factors have intensified global food security challenges.

The sustainable development goals set by the United Nations include eradicating hunger, achieving food security, and taking urgent action to address climate change and its adverse impacts. The development of agriculture is closely related to climate. "The State of Food Security and Nutrition in the World 2023" indicates approximately 735 million hungry people worldwide. Many regions are still in the deepening food crisis, so it is necessary to strengthen the resilience of food to cope with the food crisis caused by climate and conflict and strive to eliminate the root causes of food insecurity. Thus, addressing the mitigation of uncertain risks in agricultural development, enhancing agriculture's resilience to threats, promoting pollution control measures, and achieving a balance between food security and ecological security are critical focal points in global agricultural development. This becomes particularly urgent in developing countries, where ensuring food production and agricultural economic security while minimizing environmental damage caused by external instability represents a pressing challenge that needs to be addressed (Wang et al. 2019; Li et al. 2021).

China has recognized the significance of agriculture in addressing climate change by making it a key focus for adaptation efforts in 2021. China has reiterated the importance of the "dual carbon goals" in 2022, emphasizing the need for agricultural emission reduction and carbon sequestration to combat climate change. China has issued multiple documents to emphasize the importance of food security. The no. 1 central document of the Central Committee in 2022 highlights the primary task of "agriculture, rural areas, and farmers" as ensuring food production and supply of critical agricultural products. The 14th 5-Year Plan of China underscores the importance of national food security as a bottom line and emphasizes the continuous improvement of the ecological environment for sustainable agricultural development. Enviromental security and ecological security concern everyone (Qin et al. 2023; Huang et al. 2023; Wang et al. 2021; Zhang et al. 2018). Therefore, improving the resilience of agricultural development is a necessary choice to respond to the national policy orientation and solve the practical problems faced in agricultural development. The ecological and food security of agriculture in China are critical global concerns and the central focus of attention in the country's agricultural development. With China being a major agricultural nation, it accounts for a significant proportion of the global grain output. The stable development of agriculture in major grain-producing regions holds vital importance in maintaining national food security. These regions are representative examples of promoting the resilience of agricultural development.

In this study, an indicator system, including three primary, nine secondary, and 17 tertiary indicators, was proposed to assess agricultural development resilience thoroughly in balancing food security and ecological security. By employing relevant models, regional differences and obstacles to agricultural development in different areas can be identified for proposing corresponding measures. The present study aims to (1) integrate the resilience theory and build a set of agricultural development resilience index systems based on considering food security and ecological security; (2) evaluate the agricultural development resilience and regional differences in 13 major grain-producing areas of China and analyze the obstacle factors; (3) analyze carbon emissions in agricultural development and decompose influencing factors; and (4) propose measurement for improving the resilience of agricultural development.

Literature review

Food security and its influencing factors have been the research focus on ensuring global sustainable development. The Food and Agriculture Organization of the United Nations (FAO) defined food security as "the ability to restructure the supply of basic food at any time and worldwide to support stable expansion of food consumption and offset fluctuations in production and prices," as stated in the "Rome Declaration on the Elimination of Hunger and Malnutrition" adopted during the First World Food Summit. Initially, the global emphasis was increasing food production to provide adequate food and clothing. Over time, with the development of agriculture, food production has increased. Local governments have recognized the significance of food security in the context of global sustainable development.

Food security is evaluated through three key indicators: food production, protein supply, and dietary energy supply adequacy (Saboori et al. 2023). Climate change, availability of arable land and water resources, and agricultural productivity are important factors that impact food security (Tiwari and Joshi 2012; Lv et al. 2022; Premanandh 2011). The issue of agricultural carbon emissions is a crucial factor that affects regional ecological security. Currently, the use of agricultural land can increase carbon emissions primarily through fertilizers, pesticides, agricultural films, and diesel usage (Woomer et al. 2004). Previous works have examined the correlation between food security and ecological security, with ecological agriculture emerging as a primary solution to address agricultural and environmental challenges, deserving attention in future agricultural development (Yang et al. 2022a, b). Achieving green development in agriculture requires ensuring both food production safety and environmental safety. Therefore, the goals of food security and agricultural ecological security are complementary and should be considered comprehensively to achieve sustainable outcomes rather than focusing solely on individual aspects (Lu 2012).

Agricultural carbon emissions are closely linked to the ecological environment. Six primary sources of carbon emissions in agriculture are identified: agricultural fertilizers, pesticides, agricultural diesel, agricultural plastic films, crop planting area, and agricultural irrigation area. To calculate the total agricultural carbon emissions, the emission coefficient of each carbon source is multiplied by the corresponding emissions. The emission coefficients used in this study are as follows: 0.8956 kg/kg for agricultural fertilizers, 4.9341 kg/kg for pesticides, 0.5927 kg/kg for agricultural diesel, 5.1800 kg/kg for agricultural plastic films, 312.6000 kg/hm^2 for crop-planting area, and 25.0000 kg/hm^2 for agricultural irrigation area (Woomer et al. 2004; West and Marland 2002; Dubey and Lal 2009).

The research on agricultural resilience primarily revolves around defining the concept, developing evaluation methods, and proposing improvement pathways. The concept of resilience was introduced into ecology by Holling (1973), who defined it as the ability of a system to rapidly recover to its original state and maintain its structure and function. In the economic context, resilience refers to an economy's ability to recover and adapt, enabling it to bounce back from disruptions quickly and continue to grow (Martin et al. 2015). Scholars argue that economic resilience pertains to the stability and development of the financial system within which it operates (Hassink 2010; Edwards and Mercer 2012). Within agriculture, resilience is understood as the ability of the agricultural system to withstand external disturbances and maintain stability (Foster 2007). The evaluation of agricultural resilience employs various methods in the academic community. These include the use of indicator systems (Sandoval-Solis et al. 2011; Cellini and Torrisi 2014; Oxborrow and Brindley 2012; Quendler and Morkūnas 2020), artificial intelligence–based measurements (Karanth et al. 2022), spatial measurements from the perspective of economic geography (Huang and Ling 2018), and case analysis (Alessa et al. 2008; Ashkenazy et al. 2018; Berry et al. 2022). Efforts to enhance agricultural resilience have been proposed from different angles. Hasnain et al. (2023) and Li et al. (2022) suggest strategies for improving agricultural resilience through biochar utilization, talent cultivation, and financial investment. Wei et al. (2021) emphasizes enhancing farmers' capacity to respond and adapt to unpredictable economic events by strengthening the foundations of the agricultural economy and improving agricultural production efficiency. Jung et al. (2021) leverage advanced technologies like remote sensing and artificial intelligence to bolster the resilience of agricultural systems. Measures to improve agricultural resilience encompass actions such as enhancing water storage to mitigate drought risks, optimizing the efficiency of agricultural land use and irrigation methods, and bolstering support for technological innovation and financial resources. (Smith and Edwards 2021; Li et al. 2022; Yoosefdoost et al. 2022; Gao and Song 2020).

Research method and indicator design

Figure 1 shows the framework of this study.

Entropy method

The entropy method can determine the weight of a particular factor, ensuring that the data is more objective and reasonable. To compare the resilience level of agricultural development in major grain-producing areas in different years, the article incorporates time variables into the entropy method to ensure that the resilience level of agricultural development in different periods is comparable.

(1) Dimensionless treatment of indicators. The article uses the extreme value method to perform dimensionless processing on the data of each indicator, converting the indicator values to 0–1, which can avoid the impact of different indicator dimensions. The evaluation index system has two types of indicators: positive and negative. Positive indicators refer to the more significant the value of the indicator, the better the condition of the indicator. Negative indicators refer to the more significant the value of the indicator, the worse the condition of the indicator. The standardized treatment formulas for the two types of indicators are different, as shown in Eqs. (1) and (2).

$$\text{Positive indexes, } X'_{\text{tij}} = \frac{X_{\text{tij}} - X_{\text{jmin}}}{X_{\text{jmax}} - X_{\text{jmin}}} \tag{1}$$

$$\text{Negative indexes, } X'_{\text{tij}} = \frac{X_{\text{jmax}} - X_{\text{tij}}}{X_{\text{jmax}} - X_{\text{jmin}}} \tag{2}$$

where X_{tij} denotes the jth indicator values of province i in year t; X_{jmax} and X_{jmin} denote the maximum and minimum values of the jth indicator, respectively; X'_{tij} denotes the jth indicator value of province i in year t after processing.

(2) Standardized processing of raw indicators.

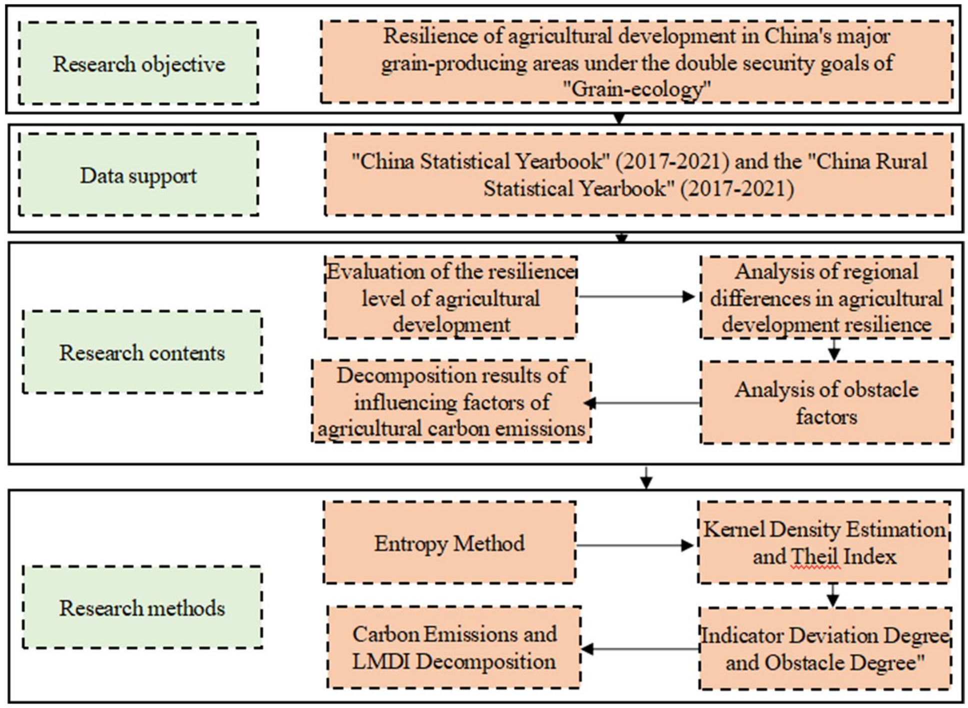

Fig. 1 Framework for the methodology process

To ensure the effectiveness of the data, the dimensionless processed indicators are standardized and translated to obtain the standardized indicator values:

$$X''_{\text{tij}} = 0.99 \times X'_{\text{tij}} + 0.01 \tag{3}$$

(3) Calculate the proportion of each sample indicator value

$$P_{\text{tij}} = \frac{X''_{\text{tij}}}{\sum_t \sum_i X''_{\text{tij}}} \tag{4}$$

(4) Calculate the entropy value of the *j*th indicator

$$S_{\text{j}} = -\ln(\text{kn})^{-1} \sum_{\text{t}} \sum_{\text{i}} P_{\text{tij}} \ln\left(P_{\text{tij}}\right) \tag{5}$$

where k denotes the number of provinces and n denotes the number of years.

(5) Calculate the differentiation coefficient of the *j*th indicator

$$G_{\text{j}} = 1 - S_{\text{j}} \tag{6}$$

(6) Calculate the weight of the *j*th indicator

$$W_{\text{j}} = \frac{G_{\text{j}}}{\sum_{\text{j}} G_{\text{j}}} \tag{7}$$

(7) Calculate the comprehensive evaluation value of the resilience level of agricultural development in each province

$$H_{\text{ti}} = \sum_{\text{j}} \left(W_{\text{j}} \times X''_{\text{tij}}\right) \tag{8}$$

Kernel density estimation

Kernel density estimation (KDE) is a nonparametric estimation method that was proposed by Gibson et al. (1955) and Parzen (1962). It carries out function-fitting distribution from the characteristics of the data itself, avoids the error that may be caused by setting the function form artificially, and has incomparable advantages over traditional estimation.

$$f(x) = \frac{1}{\text{kh}} \sum_{\text{i}=1}^{\text{k}} k\left(\frac{h_{\text{ti}} - h_{\text{t}}}{h}\right) \tag{9}$$

where h_{ti} denotes the resilience value of province i in year t; h_{t} denotes the mean resilience value of k provinces in year t; $k\left(\frac{h_{\text{ti}}-h_{\text{t}}}{h}\right)$ denotes a Gaussian kernel function, representing the number of samples; h denotes the bandwidth, determined using the Silverman thumb rule.

Theil index

The Theil index was proposed by Theil in 1967 to measure the relative differences in regional development. It can reflect inter-regional and intra-regional differences and quantify the contribution of the two to the overall contrast. The range of values for the Theil index is [0, 1], and the larger the value, the more significant the difference. There are 13 major grain-producing regions in China, with substantial regional differences. The 13 provinces are divided into five areas: North China, Northeast China, East China, Central China, and Southwest. This article uses the Theil index method to analyze the differences within and between major grain-producing regions.

$$T = \sum_{i=1}^{k}[\left(\frac{1}{k}\right) * \left(\frac{h_{ti}}{h_t}\right) * \ln(h_{ti}/h_t)] \tag{10}$$

where T denotes the Theil index, n denotes the number of provinces, h_t denotes the average resilience of agricultural development in the region, and h_{ti} denotes the agricultural development resilience value of province i. The larger the T, the more significant the overall regional differences in agricultural development resilience, which can be divided into intra-regional differences (T_{wr}) and inter-regional differences (T_{br}).

$$T = T_{wr} + T_{br} \tag{11}$$

According to the rules of geographical location, the article divides 13 main grain-producing areas into 5 groups, using g_m ($m = 1, 2, 3, 4, 5$) representing the mth group gm. The number of individuals in g_m is n_m. Then there is $\sum_{m=1}^{M} n_m = k$. Using T_m represents the intra-regional gap of agricultural development resilience in group m, and the formula for the intra-regional gap is as follows:

$$T_m = \sum_{i \in gm} \frac{y_i}{y_m} * \ln\left(\frac{y_i}{y_m} * n_k\right), i \in g_m \tag{12}$$

where y_i denotes the share of agricultural development resilience in province i in the overall regional agricultural development resilience, using y_m denotes the share of agricultural development resilience in group m in the overall level of agricultural development resilience in the region. The equation for the internal disparities in the five regions of North China, Northeast China, East China, Central China, and Southwest China is as follows:

$$T_{wr} = \sum_{m=1}^{M} y_m * \left[\sum_{i \in gm} \frac{y_i}{y_m} * \ln\left(\frac{y_i}{y_m} * n_m\right)\right] \tag{13}$$

Further, calculating the contribution rate D_m of internal differences in the m_{th} group of regions contribution rate D_b of regional differences.

$$D_m = y_m * \frac{T_m}{T}, m = 1, 2, 3, 4, 5 D_b = \frac{T_b}{T} \tag{14}$$

Analysis of obstacle factors

The present study introduces research on obstacle factors to analyze further the main factors that hinder the resilience of agricultural development in major grain-producing areas. The calculation method for obstacle factor research uses "indicator deviation degree" and "obstacle degree" to diagnose the research object, and the formula follows Huang et al. (2019).

(1) Calculate the deviation degree A_{tij}

$$A_{tij} = 1 - X''_{tij} \tag{15}$$

(2) Calculate factor barriers B_{tij}

$$B_{tij} = W_j \times A_{tij} / \sum_{j=1}^{17} \left(W_j \times A_{tij}\right) \times 100\% \tag{16}$$

Carbon emissions and LMDI decomposition

The calculation formula for the total amount of agricultural carbon emissions is

$$E = \sum_i E_i = \sum_i T_i \delta_i \tag{17}$$

where E is the agricultural carbon emissions; E_i is the carbon emissions of various carbon sources ($i = 1, 2, ..., 6$); T_i is the amount of various carbon emissions sources; and δ is the carbon emission coefficient of various carbon emissions sources. This work uses the LMDI decomposition method to analyze the influencing factors of China's agricultural carbon emissions. The decomposition of agricultural carbon emissions is

$$E = \sum_i E_i = \sum_i \frac{T_i \delta_i}{M} \cdot \frac{M}{P} \cdot P = \sum_i S_i \cdot I \cdot P \tag{18}$$

where P is the total grain output; M is the total power of agricultural machinery; $S_i = \frac{T_i \delta_i}{M}$ representing the carbon emission intensity of the ith carbon source converted to unit agricultural machinery power; the I carbon source is converted to the carbon emission intensity per unit of agricultural machinery power; $I = M/P$ denotes the utilization rate of agricultural machinery.

Based on the decomposition idea of LMDI, the difference in agricultural carbon emissions in the T-Year (reporting period) and the 0-year (base period) can be decomposed into the change values brought by three influencing factors, the residual value of 0.

$$\Delta E = E^T - E^0 = \Delta E_S + \Delta E_I + \Delta E_P \tag{19}$$

$$D = \frac{E^{T}}{E^{0}} = D_{S} \times D_{I} \times D_{P} \quad (20)$$

where ΔE is the growth of agricultural carbon emissions. D is the growth rate of agricultural carbon emissions. $E^{T} and E^{0}$ are agricultural carbon emissions in year t and year 0. $\Delta E_{S}, \Delta E_{I}, \Delta E_{P}$ are the contribution values of carbon emission intensity, utilization rate of agricultural machinery, and total grain output to the growth of agricultural carbon emission in turn. D_{S}, D_{I}, D_{P} are the contribution rates of carbon emission intensity, utilization rate of agricultural machinery, and total grain output to the growth rate of agricultural carbon emission.

Indicator design and data sources

The indicator system method is the primary measurement method for resilience in the academic community. Martin (2010) and Davies (2011) have conducted research that comprehensively measures the economic resilience of a region from resilience, recovery, reconstruction, and renewal capabilities. The present study draws inspiration from relevant research on resilience and combines the characteristics of agriculture itself. It is believed that agricultural development resilience refers to the resistance and resilience of agriculture to external shocks during the development process and can have good creativity in the future to achieve sustainable development. The specific indicator design is as follows in Table 1.

Resistance is a crucial attribute of an agricultural system that enables it to mitigate the impact of uncertain events and withstand external risks. It encompasses three sub-dimensions: production capacity, ecological capacity, and economic capacity. Production capacity primarily refers to the agricultural system's ability to resist risks by making essential investments. These investments

Table 1 Agricultural development resilience index system

Primary index	Secondary index	Thirdly index	Index attribute	Index weight	Number
Resistance ability	Production capacity	Proportion of rural population to the total population (%)	Positive direction	0.024	D1
		Irrigation area of cultivated land (1000 ha)	Positive direction	0.060	D2
		Crop planting area (1000 ha)	Positive direction	0.051	D3
		Total power of agricultural machinery (10,000 kW)	Positive direction	0.068	D4
		Machine cultivated area (1000 ha)	Positive direction	0.079	D5
		Disaster area (1000 ha)	Negative direction	0.074	D6
	Ecological capacity	Application amount of agricultural fertilizers (converted to pure) (10,000 tons)	Negative direction	0.073	D7
		Application of pesticides (ton)	Negative direction	0.031	D8
		Application of agricultural plastic film (ton)	Negative direction	0.071	D9
		Application of agricultural diesel (10,000 tons)	Negative direction	0.052	D10
	Economic capacity	Total output value of agriculture, forestry, animal husbandry, and fishery (100 million yuan)	Positive direction	0.044	D11
Resilience ability	Proportion of primary industry	The proportion of added value of the primary industry to regional GDP (%)	Positive direction	0.044	H1
	Income	Per capita disposable income in rural areas (yuan/person)	Positive direction	0.053	H2
	Consumption	Consumption expenditure amount (yuan/person)	Positive direction	0.039	H3
Reengineering ability	Asset investment	Fixed assets investment in agriculture, forestry, animal husbandry and fishery (100 million yuan)	Positive direction	0.074	Z1
	Technological innovation investment	Expenditure for Science and Technology (100 million yuan)	Positive direction	0.098	Z2
	Ecological governance	Soil erosion control area (1000 ha)	Positive direction	0.065	Z3

include human resources, water and soil resources, and agricultural mechanization, which play a pivotal role in agricultural development. The total power of agricultural machinery serves as a vital driving force in increasing grain production, ensuring the reliability of agriculture and serving as a fundamental guarantee for food security. However, it is essential to consider the coordination of agricultural development with the environment because agricultural fertilizers, pesticides, diesel oil, and film will have specific impacts on the ecological environment. These factors are considered to be negative indicators of the agricultural ecosystem due to their potential for pollution. On the other hand, economic capacity is measured by the economic benefits derived from agriculture, forestry, animal husbandry, and fishery. It is best represented by the total output value of these sectors, reflecting the financial health of agricultural activities. Resilience, as mentioned earlier, also relates to the ability of the agricultural system to recover losses and maintain stable development after facing adversity. Mainly measured by the proportion of added value in the primary industry and the income and consumption situation of rural people. The reengineering ability is demonstrated through the agricultural system's capacity to self-adjust and revitalize after disruptions. Fixed asset investment, technological innovation, and ecological governance contribute to this resilience. Local governments' financial support for agricultural development is reflected in the investments made in the fixed assets of agriculture, forestry, animal husbandry, and fishery. Meanwhile, scientific and technological expenditures exemplify the agricultural system's capacity for technological innovation. Furthermore, the area of soil erosion control showcases the agricultural system's capabilities for ecological governance.

The data presented in this study is primarily sourced from the "China Statistical Yearbook" (2017–2021) and the "China Rural Statistical Yearbook" (2017–2021), which ensures the credibility and reliability of the information provided.

Results

Evaluation of the resilience level of agricultural development

The present study employs the entropy method to assess the agricultural development resilience of China's main grain-producing areas from 2016 to 2020. By calculating the agricultural development resilience values and 5-year averages of the 13 provinces, the study presents the results in Fig. 2. Overall, the resilience of agricultural development in the main grain-producing areas exhibited a stable upward trend during the 13th 5-Year Plan period. Provinces such as Heilongjiang, Shandong, Henan, Jiangsu, and Anhui consistently demonstrated agricultural development resilience values above the regional average. These provinces showcased robust agricultural performance and ranked among the top in total grain production, further underscoring their agricultural prowess. Conversely, provinces like Liaoning, Jilin, and Jiangxi displayed lower agricultural development resilience values than the regional average. Identifying the factors limiting agricultural development in these regions is crucial to developing targeted strategies for enhancing rural development resilience. The agricultural development resilience values fell in an intermediate range for other areas, indicating the potential for further improvement and strengthening of their farming systems.

Figure 3 visually illustrates the dynamic evolution of agricultural development resilience over the 5 years from 2016 to 2020. In the initial years from 2016 to 2018, the curve exhibited relatively minor fluctuations, reflecting ongoing efforts to improve agricultural development resilience. However, significant changes were observed from 2019 to 2020, as evidenced by the rightward movement of the waveform in the kernel density curve. The increasing steepness of the peak and reduced horizontal width suggest a trend towards numerical growth, indicating a narrowing

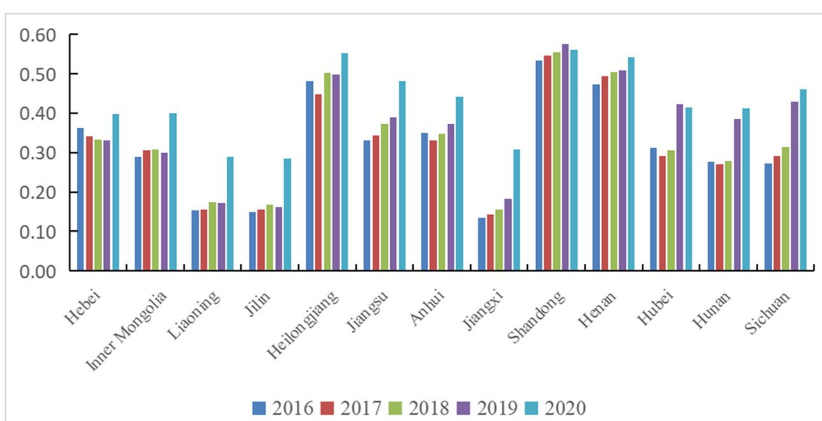

Fig. 2 Resilience of agricultural development in major grain-producing areas (2016–2020)

agricultural resilience gap and a dynamic convergence feature among the regions. These fluctuations can be attributed to the time lag in policy implementation and the effectiveness of testing measures introduced to promote agricultural modernization. The "13th 5-Year Plan" played a crucial role in this regard, as it introduced binding indicators for agricultural modernization, explicitly focusing on enhancing grain production capacity, resource protection, and allocation. The plan also emphasized the quantity and quality of China's arable land resources, proposing key protection initiatives to ensure national food security. Due to the time required for policies to take effect, the substantial results observed from 2019 to 2020 signify the culmination of dedicated implementation efforts. The analysis underscores the importance of formulating and implementing long-term policies to enhance agricultural resilience effectively. The narrowing resilience gap among the main grain-producing areas indicates substantial progress toward achieving a more balanced and robust rural development landscape in China.

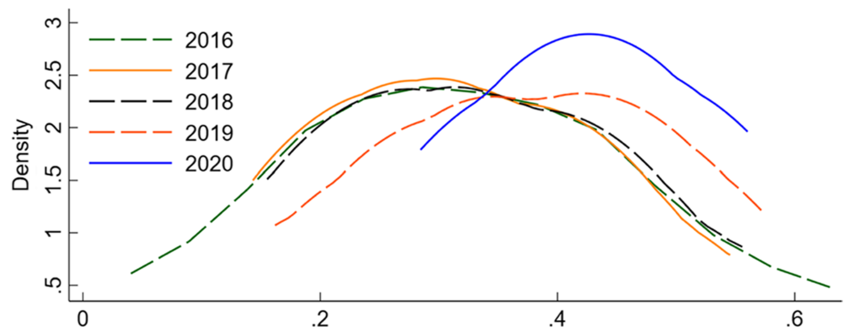

Fig. 3 Distribution of tenacity core density of agricultural development in major grain-producing areas

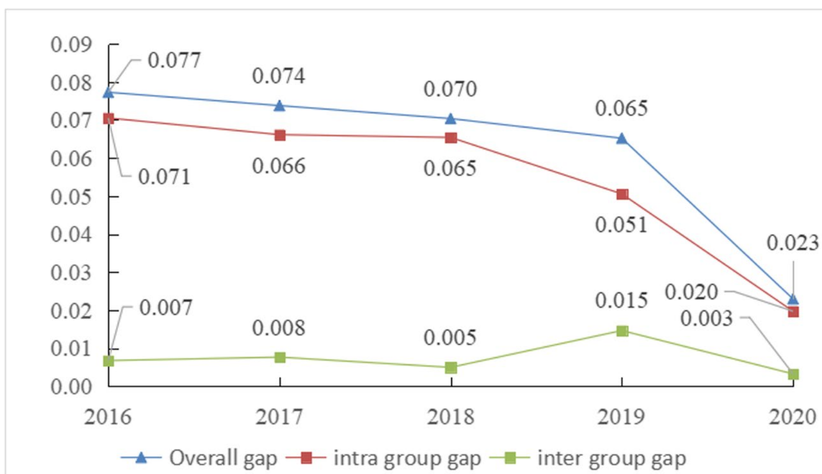

Fig. 4 Results of the Theil index of agricultural development resilience in major grain-producing areas (2016–2020)

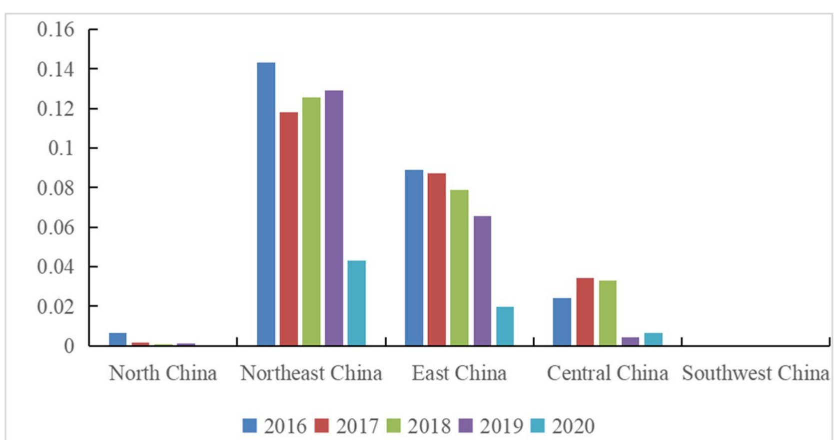

Fig. 5 Results of the Theil index of agricultural development resilience in different regions of major grain-producing areas (2016–2020)

Analysis of regional differences in agricultural development resilience

Figure 4 shows a gradual narrowing of the gap in agricultural resilience among China's main grain-producing areas from 2016 to 2020. The primary focus has been reducing the intra-group gap, which pertains to regional differences. Notably, the contribution rate of the intra-group gap signifies substantial efforts to address regional disparities and promote more balanced agricultural development. Figure 5 indicates the reasons for the large gap within the intra-group. One notable intra-group difference lies in Northeast China, specifically in Heilongjiang, Jilin, and Liaoning provinces. Heilongjiang stands out as a leader in grain production, while Jilin and Liaoning provinces have room for improvement, particularly concerning disparities in irrigated and machine-cultivated farmland areas compared to Heilongjiang. Nevertheless, the gap within Northeast China has notably narrowed over the years, highlighting the crucial role of agricultural development in this region for overall agricultural progress in China. The resilience gap in East China, which includes Jiangxi Province, has also been steadily narrowing, primarily attributed to the concerted efforts of Jiangxi Province in recent years. The focus on soil erosion control and the successful implementation of the "Gannan Model" for landslide control have significantly contributed to improvements in agricultural resilience. These developments in Jiangxi Province serve as a valuable learning experience for enhancing agricultural development resilience. The narrowing gaps in agricultural resilience among regions signify notable progress in promoting balanced and sustainable agricultural development across China's main grain-producing areas. Continued efforts to address disparities within and between regions can further enhance agricultural resilience and contribute to the overall stability and productivity of the farming sector.

Analysis of obstacle factors

Table 2 presents an analysis of obstacle factors affecting agricultural development resilience in China's major grain-producing areas, focusing on data from 2016 and 2020. The study identifies critical influencing factors in different regions to provide a reference for improving the resilience of future agricultural development. The common obstacles faced by North China, Northeast China, and Southwest China include Z2 science and technology expenditure, D7 fertilizer usage, and D5 machine-cultivated area. Meanwhile, Heilongjiang Province in Northeast China has unique challenges with the Z3 soil erosion control area. These are critical issues that Heilongjiang needs to face in the later stages of agricultural development, which are also the same question in East China. The soil and water management

Table 2 Obstacle factors for agricultural development resilience in major grain-producing areas

Year		Hebei	Inner Mongolia	Liaoning	Jilin	Heilongjiang	Jiangsu	Anhui	Jiangxi	Shandong	Henan	Hubei	Hunan	Sichuan
2016	First	Z2	Z2	Z2	Z2	Z2	D6	Z3	Z2	Z2	Z2	Z2	Z2	Z2
	Second	D5	Z1	D5	D5	D9	Z1	D9	D5	D6	D6	D9	D9	D5
	Third	Z1	D5	D7	D9	D7	Z3	Z2	Z1	D5	Z1	Z1	D5	D6
2020	First	Z2	Z2	Z2	Z2	Z2	Z1	Z1	Z1	D7	D7	D7	D7	Z2
	Second	Z1	D7	D5	D5	D7	D7	D7	D5	D5	Z2	D5	Z2	D7
	Third	D5	D5	D7	D7	Z3	Z3	Z3	Z2	Z2	Z1	Z1	Z1	D5
Region		North China		Northeast China			East China				Central China			Southwest China

area reflects the ability to rebuild and maintain competitiveness in the later stages of agricultural development. As non-renewable resources, soil and water resources are vital in sustaining agricultural growth. Furthermore, Shandong Province in East China and Central China face obstacles related to D7 fertilizer usage. So technological innovation, financial investment, and machine-cultivated land resources are crucial factors in enhancing the resilience of agricultural development. Proper use of fertilizers is also essential when implementing green development.

Agricultural carbon emissions

Agricultural development in 13 major grain-producing areas was assessed to calculate the carbon emissions using the total agricultural carbon emissions formula, and the findings are presented in Fig. 6. The results indicate a substantial reduction in total carbon emissions from agriculture in these regions. In 2016, the recorded total carbon emissions were 94.0851 million tons, significantly dropping to 86.6372 million tons in 2020. This reduction demonstrates the successful implementation of measures to effectively control carbon emissions from agricultural activities in these grain-producing areas. Moreover, the carbon emissions per grain production unit have also declined. In 2016, the carbon emissions per unit of grain production were 0.2011 tons, and by 2020, they decreased to 0.1647 tons. This decrease highlights the efforts made to enhance the efficiency of agricultural practices and reduce carbon emissions while maintaining grain production levels. The National Agricultural Modernization Plan (2016–2020), issued by the State Council in October 2016, played a crucial role in promoting green agriculture, emphasizing environmentally sustainable development, and ensuring food security. The measures implemented during the 13th 5-Year Plan, such as reducing the use of pesticides and fertilizers in agricultural production and the comprehensive work plan for energy conservation and emission reduction, have significantly contributed to successfully controlling carbon emissions in these significant grain-producing areas. These achievements demonstrate remarkable progress in aligning agricultural practices with environmental sustainability goals, reflecting a strong commitment to green and sustainable development in the farming sector.

Table 3 Carbon emission intensity (unit, tons/kW)

Year	2016	2017	2018	2019	2020
S1	0.051	0.049	0.046	0.043	0.041
S2	0.008	0.008	0.007	0.006	0.006
S3	0.011	0.011	0.010	0.010	0.009
S4	0.010	0.010	0.010	0.009	0.008
S5	0.002	0.002	0.002	0.002	0.002
S6	0.052	0.051	0.049	0.048	0.047
Total	0.135	0.130	0.124	0.117	0.112

Decomposition results of influencing factors of agricultural carbon emissions

Table 3 presents the carbon emission intensity per unit of agricultural machinery power for six carbon sources: agricultural fertilizers (S1), pesticides (S2), agricultural diesel (S3), agricultural plastic films (S4), crop planting area (S5), and agricultural irrigation area (S6).

Throughout the entire 13th 5-Year Plan period, China's main grain-producing areas have experienced a continuous reduction in agricultural carbon emissions, with the intensity of such emissions decreasing from 0.135 tons/kW in 2016 to 0.112 tons/kW in 2020. These positive trends indicate the successful implementation of national agricultural green development policies. Among the six types of carbon sources, the adoption of scientific and technological methods for fertilization and optimization of the "water–energy" relationship in irrigation practices can be pursued to reduce carbon emission intensity further. Table 4 depicts the carbon emission growth as well as the impact of agricultural carbon emissions from 2017 to 2020. Based on the trend of carbon emissions growth in 2016, the overall carbon emissions

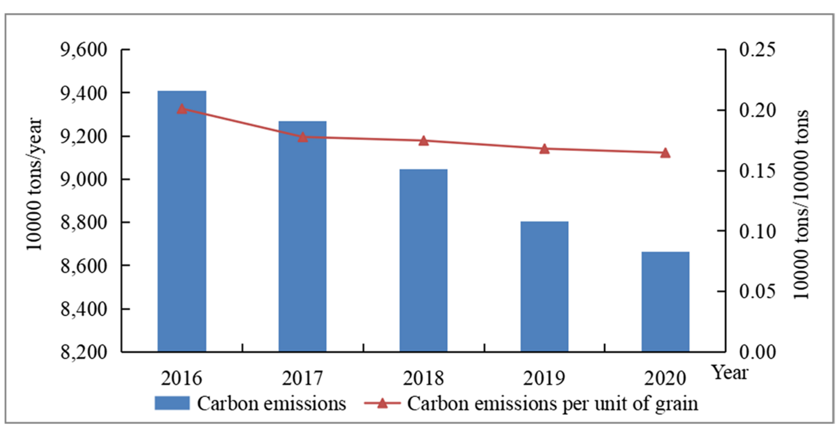

Fig. 6 Trends in agricultural carbon emissions and carbon emissions per unit of major grain-producing areas(2016–2020)

Table 4 Impact of agricultural carbon emissions from 2017 to 2020 (based on 2016)

Year	Carbon emission growth		Carbon intensity		Utilization rate of agricultural machinery		Total grain output	
	ΔE(10,000 tons)	D	ΔE_S(10,000 tons)	D_S	ΔE_I(10,000 tons)	D_I	ΔE_P(10,000 tons)	D_P
2017	−140.19	0.99	−320.60	0.97	−482.77	0.95	663.19	1.07
2018	−360.72	0.96	−783.32	0.92	−180.69	0.98	603.29	1.07
2019	−605.70	0.94	−1257.14	0.87	−25.55	1.00	676.99	1.08
2020	−744.79	0.92	−1647.71	0.83	154.90	1.02	748.02	1.09

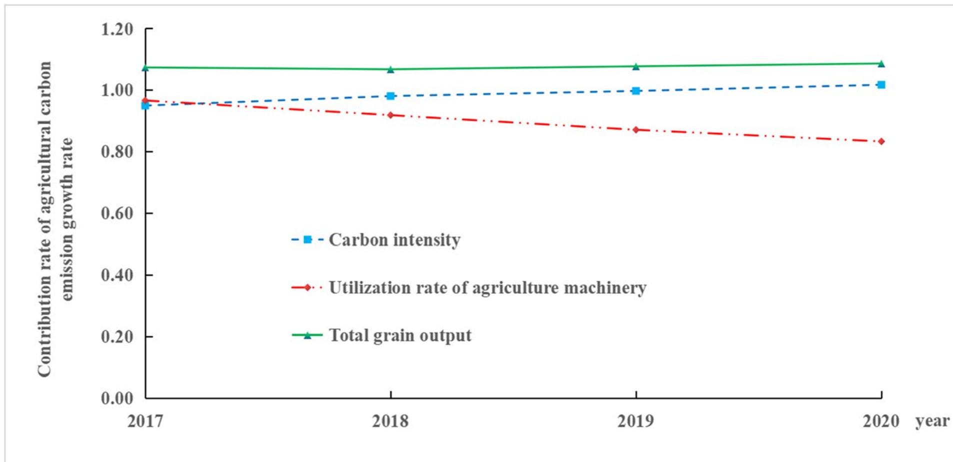

Fig. 7 Contribution rate of influencing factors of agricultural carbon emissions from 2017 to 2020

growth of agriculture in China's major grain-producing areas has gradually decreased, and carbon emissions have been well controlled. This is inseparable from the "weight loss and drug reduction" policy implemented in China in 2015. Figure 7 shows the contribution rate of influencing factors of agricultural carbon emissions. Decompose the influencing factors and analyze the contribution rate of carbon emission intensity, agricultural machinery utilization rate, and total grain yield to carbon emission growth. The reduction of carbon emission intensity is beneficial for promoting the reduction of the growth of agricultural carbon emissions. But the increase in the utilization rate of agricultural machinery and grain production will accelerate the growth of carbon emissions. Firstly, the extensive use of agricultural machinery increases fuel consumption, leading to an increase in total carbon emissions. Secondly, an increase in grain production will inevitably require necessary inputs from factors such as pesticides, fertilizers, and plastic films, which are also important sources of carbon emissions in agricultural production. The main grain-producing areas bear the heavy responsibility of maintaining national food security, and the promotion of agricultural machinery can expand the scale and production of agriculture and increase the production capacity of the main grain-producing areas with the purpose of enhancing the resistance of China's grain to the outside world. Therefore, the key is how to coordinate the relationship between food security, agricultural machinery promotion, and ecological environmental protection while improving food resistance.

Discussion

This study provides an idea that has good reference significance for developing countries on balancing food security and ecological security to improve agricultural development resilience and better adapt to external environmental changes. Diversifying 13 major grain-producing areas can provide a reference for multiple scenarios. The efforts to enhance agricultural resilience presented in this study hold practical value and can benefit developing countries in various regions. The ultimate goal is for countries to work together to strengthen the resilience of agriculture to the outside world, achieve food security, and retard environmental pollution caused by agricultural development.

The development of agriculture is conducive to alleviating the food crisis, but agricultural carbon emissions are a problem that must be faced in food production. The previous works only consider agricultural carbon emissions or food security separately. For example, reducing carbon emissions through agricultural productive services, farmland spatial transition, or technological progress (Bai et al. 2023; Ke et al. 2023; He and Ding 2023). Improve food security by optimizing the agricultural industry chain or mechanization (Tisorn et al. 2023; Yamauchi 2016). Food and ecological security are significant global concerns and research areas for scholars worldwide. Environmental security is a prerequisite for food security, meaning that increasing food production at the expense of environmental pollution is not a viable solution. The scientific use of fertilizers and mechanization are closely related to carbon dioxide emissions (Yang et al. 2022a, b). Ensuring food security requires carefully considering factors influencing grain production, carbon dioxide emissions, and the uncertainties of the external environment. Few studies integrate resilience theory into agricultural development. Therefore, enhancing agricultural development resilience should involve thoroughly assessing multiple indicators rather than focusing on one aspect. Existing research about resilience mainly analyzes a specific region, such as developing agriculture resilience in sub-Saharan Africa and Germany. Both of them emphasized the importance of technology (Muhan 2023; Kuntke et al. 2022). The comparative analysis between different areas is short. For parts with strong correlations, exploring the gaps between them and learning from each other's good experiences is necessary. Regional differences in agricultural resilience can be substantial due to variations in agricultural infrastructure, and the obstacles hindering resilience improvement can also differ. Most research focuses on specific countries or provinces, necessitating targeted measures to address regional disparities. The indicators used to measure agricultural development resilience need to be more comprehensive, going beyond economic or production resilience alone.

Increase the popularization of agricultural mechanization and promote the modernization of agriculture

The popularization of agricultural mechanization plays a crucial role in increasing grain production. China has recognized this and implemented the "13th 5-Year Plan for National Agricultural Mechanization Safety Production" to promote agricultural mechanization. In recent years, the Inner Mongolia Autonomous Region has made significant progress in agricultural development. This can be attributed to the continuous deepening of the supply-side structural reform in agriculture and the optimization of energy institutions and agricultural mechanization in the region. Looking ahead, Jiangxi Province can further enhance the efficient use of agricultural machinery. This can be achieved by promoting agricultural industrialization and developing the farm equipment industry. Implementing subsidy policies for purchasing agricultural machinery can encourage farmers to adopt mechanization. Technological integration is another aspect to focus on. Dynamic monitoring of agricultural mechanization production status can be enhanced by integrating technologies such as big data with agricultural machinery. This enables precise operations and improves the efficiency of agricultural machinery use. Furthermore, it is essential to strengthen the cultivation of farming talents and ensure the availability of agricultural technology. This includes providing adequate training and support to farmers, enabling them to effectively utilize agricultural machinery and avoiding the increase in carbon emissions caused by ineffective use of mechanization. By doing so, farmers can fully benefit from the convenience and advantages of agricultural mechanization. The ultimate goal is to improve food production capacity and ensure the ability to cope with external resistance.

Strengthen the protection and governance of water and soil resources to ensure the basic resources for agricultural development

The decrease in water resources in Henan Province from 33.98 billion cubic meters in 2018 to 16.86 billion cubic meters in 2019 directly impacted the province's grain production that year. Despite being located in the lower reaches of the Yellow River Basin, Henan Province experiences a large area of severe drought. The long-term over-exploitation of water resources has increased their scarcity as a non-renewable resource. The development and utilization of water resources from the Yellow River have yet to be fully realized, which poses a constraint on the further development of agriculture in Henan Province. Addressing this issue is crucial for the future agricultural development of the province. Efforts should be made to accelerate the construction of farmland water conservancy infrastructure, strengthen barriers, and take preventive measures to prepare for safe flood control. In the case of Heilongjiang Province, attention should also be given to soil and water management issues. It is essential to focus on accelerating measures such as soil erosion control, increasing the size of soil and water management, and ensuring the availability of soil and water resources. Soil and water resources are fundamental for agricultural development, and their proper management is necessary for sustaining agricultural productivity. Both Henan and Heilongjiang provinces can address their respective water and soil management challenges by strengthening early warning systems, reducing the affected areas, and implementing timely soil erosion control measures, ensuring the stability and sustainable development of agriculture in these regions. The guarantee of soil and water resources is the fundamental resource for agricultural development and ensuring food production, which is also a measure of ecological governance capacity.

Strengthen the investment of agricultural special funds and improve the level of scientific and technological innovation

The Central Government's no. 1 document provided specific arrangements for 5 consecutive years and increased investment in agricultural infrastructure construction. However, there are significant differences in agricultural capital investment among the 13 major grain-producing regions. Capital investment plays a crucial role in technological innovation and upgrading. Firstly, optimizing the efficiency of resource allocation is essential to maximize the utilization of research and development funds and researchers. By directing funds towards technological weak points, scientific and technological innovation can be effectively improved. Secondly, adhering to the strategy of "storing grain in the land and technology" is essential. This involves ensuring the construction of high-standard farmland with high and stable yields and providing necessary agricultural development resources. For example, Jiangxi Province promotes the protection of arable land by building high-standard farmland. In Sichuan Province, promoting agriculture through technology can increase grain yield per unit sown area, maximizing the utilization of scarce arable land. However, large-scale mechanization still needs to be improved in hilly and mountainous regions due to scattered planting areas and uneven terrain. To address this, it is necessary to diversify the planting structure in hilly and mountainous areas. Additionally, innovation in diversified agricultural machinery can greatly improve the efficiency of homework. For example, precision machinery technology can improve yield per unit area. In addition, optimizing resource allocation, promoting high-standard farmland construction, and addressing mechanization challenges in hilly and mountainous regions, the major grain-producing areas can enhance agricultural development and technological innovation with the aim of ultimately improving productivity and sustainability in the farming sector. The improvement of technological innovation level can better ensure the improvement of agricultural reengineering ability.

Scientific fertilization, emphasizing the development of green and low-carbon agriculture

The National Green Agriculture Development Plan of the 14th 5-Year Plan sets forth goals to comprehensively promote green agricultural development in China by 2025. The plan aims to significantly enhance the capacity to reduce and mitigate carbon emissions, reduce the intensity of greenhouse gas emissions from primary agricultural products, strengthen the ability to sequester and fix carbon in agriculture, and enhance resilience to climate change. It also emphasizes the need to improve the efficiency of agricultural energy use. Promoting low-carbon development in agriculture is crucial to achieving these objectives while ensuring food security and safety. One approach is to encourage the reduction of fertilization and promote the efficient utilization of livestock and poultry manure and straw. For instance, scientific fertilization based on models like the GTAP (Global Trade Analysis Project) can help reduce agricultural carbon emissions (Golub et al. 2009). Since farmers are the primary users of fertilizers, raising their awareness of the importance of scientific fertilization is essential. Balancing ecological and economic benefits is critical to strengthening agriculture's green and low-carbon development. By implementing these measures, China can make significant progress in reducing greenhouse gas emissions, enhancing carbon sequestration, and promoting sustainable and environmentally friendly practices in the agricultural sector. This has a good promoting effect on improving the ecological capacity in agricultural development.

In this paper, quantitative and qualitative methods are used to construct an evaluation system of agricultural development resilience and to evaluate the agricultural development resilience of major grain-producing areas in China. The integration of qualitative and quantitative analysis in this study provides a comprehensive understanding of the obstacles to agricultural development resilience in China's 13 major grain-producing regions. By combining these analytical approaches, the study offers valuable insights and development suggestions that address each region's specific challenges. This approach recognizes the study areas' diverse geographical and terrain characteristics, allowing for targeted and context-specific recommendations. The suggested development measures, such as increasing agricultural mechanization, strengthening soil and water resource protection, promoting technological innovation, and advocating scientific fertilization are tailored to each region's unique needs and constraints. This targeted approach is crucial for ensuring effective and sustainable agricultural development, as it considers each area's specific conditions and requirements. The findings and recommendations of this study have broader implications beyond the regions examined. Developing countries facing similar challenges in agricultural development and ecological security protection can benefit from the research's suitable routes and valuable insights. The study's reference significance lies in its potential to guide agricultural development and foster ecological security protection in diverse contexts, helping countries make informed decisions and achieve sustainable farming practices.

Conclusions

In this work, the entropy method is used to evaluate the resilience level of agricultural development. Balancing food security and ecological security when constructing resilience indicators for rural development is beneficial for implementing sustainable development. Farm machinery and fertilizers should pay attention to scientific and improved efficiency rather than just increasing quantity to avoid one-sidedness caused by a single consideration of certain products—kernel density estimation and the Theil index test the regional differences. The study further analyzed the barrier impact factors that affect the resilience of agricultural development using the barrier degree model.

Total and per capita grain production in these regions has steadily increased, with a higher share of the national grain production. However, regional differences still exist. The total carbon emissions from agriculture in the prominent grain-producing areas declined, and the carbon emissions per unit of grain production were well controlled, indicating the success of promoting green agriculture during this period. The analysis of obstacle factors revealed commonalities across the significant grain-producing regions. Technological innovation, investment in fixed assets, and machine-cultivated land availability were critical factors for agricultural resilience. Additionally, the study emphasized the importance of addressing fertilizer usage to promote green and low-carbon development in agriculture.

Based on these findings, future measures to enhance the resilience of agricultural development should prioritize these aspects, including technological innovation, investment in fixed assets, machine-cultivated land resources, and the proper use of fertilizers. The agricultural sector can better resist external risks and improve its resilience by addressing these factors. These findings and suggestions provide a reference for developing countries to strengthen their agricultural response to the uncertainty of the external environment. Improving the resilience of agricultural development can enhance the stability of agriculture, ensure food security, eliminate hunger, and protect the environment.

Due to the limited research on agricultural development resilience and the lack of practical experience for reference, the existing research mainly focuses on theoretical and empirical analysis and combines Chinese practices experience. In the later stage, with the promotion of the United Nations Sustainable Development Goals and the increasing emphasis on agricultural development resilience in various countries, there will be some practical measures. In the future, we will summarize and extract the experience of more regions abroad in improving agricultural development resilience.

Acknowledgements The authors thank the institutions that provided funding.

Author contribution WL drafted the initial manuscript, analyzed the data, and conceptualized and designed the study. PZ analyzed the data and reviewed the manuscript, and WL carried out the initial analyses and reviewed and revised the manuscript. JG and YT provided guidance on the paper. All authors approved the final manuscript.

Funding This study was supported by the Shandong Province Social Science Planning and Research Project (22CSDJ60).

Data availability All data generated or analyzed during this study are included in the paper.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent to publish Not applicable.

Competing interests The authors declare no competing interests.

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