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RESEARCH ARTICLE

An index system for evaluation of agriculture green development at county level in China

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KEYWORDS

Agriculture green development, index system, quantitative evaluation, Spearman correlation analysis

HIGHLIGHTS

- Objective based county-level AGD evaluation index system was established.
- A typical agricultural county of Quzhou County in the North China Plain was use as a representative study.
- Unbalanced development was revealed as well as large gaps relative to targets.
- Spearman rank correlation analysis revealed more synergistic effect than trade-off effect.
- Trade-off existed between eco-environment and both food production and socioeconomic dimensions.

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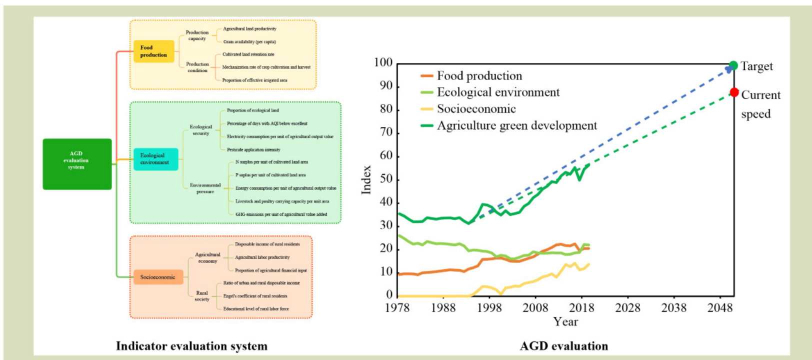
GRAPHICAL ABSTRACT



ABSTRACT

Agriculture green development (AGD) has become an unavoidable choice to address the unique national circumstances of China. This study established a county-level AGD evaluation index system, comprised three dimensions, food production, ecological environment and socioeconomic development, using 20 indicators. The assessment delved into historical trend and current situation, utilizing Spearman rank correlation analysis to analyze trade-off and synergy relationships, using Quzhou County, Hebei Province as a case study. The main findings were in four areas. Firstly, the index for AGD in Quzhou County increased by 58.9% from 1978 to 2019. The major contribution were the social economy (65.8%) and food production (53.5%), whereas the ecological environment was found to have had a negative impact. Secondly, in 2019, the AGD index was only 56.4, indicating substantial potential for improvement relative to the target value. A notable difference in scores existed between the three dimensions, with the order being ecological environment (66.3) > food production (61.7) > socioeconomic (41.3). Also, 90% of the indicators did not reach the target value. Thirdly, relationship analysis of the indicators revealed that the synergistic effect exceeded the trade-off effect. Specifically, 46.3% of the indicators had no significant relationship, 35.3% had a synergistic relationship, and 18.4% had a trade-off relationship. Finally, interdimensional indicator relationships exhibited a trade-off effect between the ecological environment and both food production and socioeconomic dimensions. However, a positive trend of synergy between production and ecology has emerged since 2015. In conclusion, the quantitative evaluation index system exposed the unbalanced development and significant potential relative to the target value of AGD in Quzhou County, despite notable progress.

1 Introduction

Agriculture green development (AGD) underscores the harmonious integration of green practices with overall development. Its primary objective is to transform the current production mode, characterized by high resource input and high environmental costs, toward a sustainable model that promotes high productivity, efficient resource utilization and low environmental impacts[1]. County is the smallest administrative unit with a complete administrative structure and is considered the most practical unit for policy implementation in China. Constructing a comprehensive evaluation index system and analysis methodology at county level is crucial to explore the historical transformation of AGD and identify the key limiting factors that determine priority action directions, which also meaningful for the overall agriculture transformation in China.

Evaluation index system has been widely used in sustainable agriculture assessment and research. For example, Zhang et al.[2] established a comprehensive framework and an index system, which including three dimensions and 18 detailed indicators to assess the progress and the balance of development. Kanter et al.[3] took a complete-cycle approach to analyze the interaction of agriculture to the Sustainable Development Goals (SDGs), including indicators of human well-being beyond income or direct health concerns (e.g., related to gender, equality and nutrition), as well as diverse environmental indicators ranging from soil health to biodiversity to climate forcing. Some scholars viewed sustainable agriculture as a set of management strategies whereas others considered it as a specific goal[4,5]. However, there is a consensus within the academic community that the framework of sustainable agricultural development revolves around environmental, economic and social dimensions[2]. The World Resources Institute developed an agricultural sustainable development index system to assess the environmental implications of agricultural production[6], which has become integral to the SDG index framework[7]. Béné et al.[8] assessed the sustainability of the global food system using 25 sustainability indicators across 12 SDGs. Springmaan et al.[9] revised the planetary boundary values related to food system, discovering that the emission might surpass planetary boundaries by 2050. They emphasized the need for coordinated measures to mitigate the increasing environmental stress. Christophe et al.[10] designed a sustainability indicator for the global food system and examined the influence of missing data on the trade-off between indicator comprehensiveness and sample size.

The AGD initiative, proposed in 2016, presents a promising avenue for achieving sustainable development in China[11]. AGD aims to the synergy realization among food security with environmental carrying capacity and social socioeconomic development[12]. A series of studies have been conducted since 2018 focusing on the evaluation of AGD[11,13]. Many scholars agree that resource conservation, environmental friendliness and high use efficiency are common components of AGD[14–16]. In terms of index-weighting methods, researchers have employed subjective-weighting methods, objective-weighting methods and a combination of the two. The subjective-weighting method is mainly analytic hierarchy process[17,18], whereas objective-weighting methods include the principal component analysis[19] and the entropy-weighting method[13,15,16]. The principle for combining subjective- and objective-weighting includes the combination-weighting method[20], the entropy method, the equal-weighting method, and the analytic hierarchy process [14,21]. For index evaluation, there have been two main methods, index grading and assigning. The index grading method involves expert consultation and literature review to assign grades to the original indices based on corresponding numerical intervals. The process is relatively simple, but highly subjective due to the classification of index grades. The index assigning method encompasses grade assigning, standardized coefficient method, and extreme value standardization method. The grade assigning method establishes a percentage score for each grade after the index is assigned, but the subjectivity of the grading process significantly affects the final result[17]. The standardized coefficient method compares the current value with the base year value to assess regional inter annual changes but cannot assess development levels across diverse regions[18,20]. The extreme value standardization method facilitates the comparison of development levels between areas and years. It employs the maximum sample value to standardize the original data into a value between 0 and 1, but it primarily applies to studies with larger sample sizes[14,15,22]. Many researchers adopt the comprehensive evaluation function approach[13,18] and the TOPSIS method to generate the index after giving each indicator a score[21,22]. The achievements to data have already significantly aided in advancing AGD. Nonetheless, research constraints persist. Firstly, there is a lack of a quantitive index system at county level, which is the fundamental unit of national administrative regulation has full political and economic functions, being the optimum unit for implementing AGD[23]. However, available research on the AGD index system is mainly at the national, provincial and municipal levels, resulting in an insufficiency of research and evaluation at county level. Consequently, no standardized evaluation standards and measurement tools for AGD exist at county level. Secondly, there are ambiguities in the research on the intended value of AGD. Most current AGD evaluation studies focus on the differences among objectives, but few on the target-based evaluation. This makes it challenging to ascertain the actual gap between objects and goals for AGD; it also lacks a quantitative basis for analysis of correlation between indicators.

This study used Quzhou County, Hebei Province as a case study, being a typical agricultural production area of the North China Plain. It established an AGD evaluation index system and defined target values for each indicator based on theoretical optimal value, SDGs and national development planning. This study proposes a quantitative tool to evaluate the current progress for other counties in China and provide guidance for the future actions aimed at accelerating AGD.

2 Materials and methods

2.1 Agriculture green development (AGD) index system

The essence of AGD lies in harmonizing the production, environmental, and socioeconomic benefits of agricultural development, and pursuing maximum food productivity within environmental threshold. Thus, food production, ecological environment and socioeconomic development were selected as the three dimensions of AGD, with food production divided into production capacity and production condition, ecological environment into ecological security and environmental pressure, and socioeconomic development into the agricultural economy and rural society. The whole index system encompasses three dimensions, six primary level indicators and 20 secondary level indicators (Fig. 1).

2.2 Target values of agriculture green development (AGD) indicators

The methodologies from the SDGs (2021 SDG Index and Dashboard) were used to determine the upper and lower bounds in the index system[7]. A four-step decision method was employed to ascertain the upper bound for indicators; if the prerequisites for the previous step were met, subsequent steps were bypassed. The details were: (1) relevant planning targets for countries and counties defined for 2030 or later; (2) theoretical optimal value exists for the upper bound; (3) data exists for internationally advanced countries, such as the EU, Japan, South Korea and the USA; and (4) highest development level of observed values designated by the SDG principle that no one must be left behind.

The lower limit of the index was defined as the lowest 2.5% value of the 164 counties in Hebei Province for 2018. The bounds and attributes of each indicator are presented in Table 1 and Table S1.

2.3 Source for obtaining indicator data

The county-level index system covered 20 secondary indicators, encompassing 110 basic metrics for 1978 to 2019. The data primarily originated from “Quzhou County Statistical Yearbook” “Quzhou County Statistical Bulletin of National Economic and Social Development” “Handan City Statistical Yearbook” and “Handan City Environmental Quality Bulletin”. Additionally, parameters such as livestock and poultry bearing capacity per unit of cultivated land area, nitrogen and phosphorus surplus per unit of cultivated land area, and GHG emission per unit of agricultural added value were derived from the well-established parameters used in the NUFER model.

2.4 Methodology for measuring the agriculture green development (AGD) index

2.4.1 Data standardization processing

Variables were linear converted to yield dimensionless values between 0 and 1 by the extreme value standardization method. This ensured that each index was of the same order of magnitude and was an ascending variable. The upper and

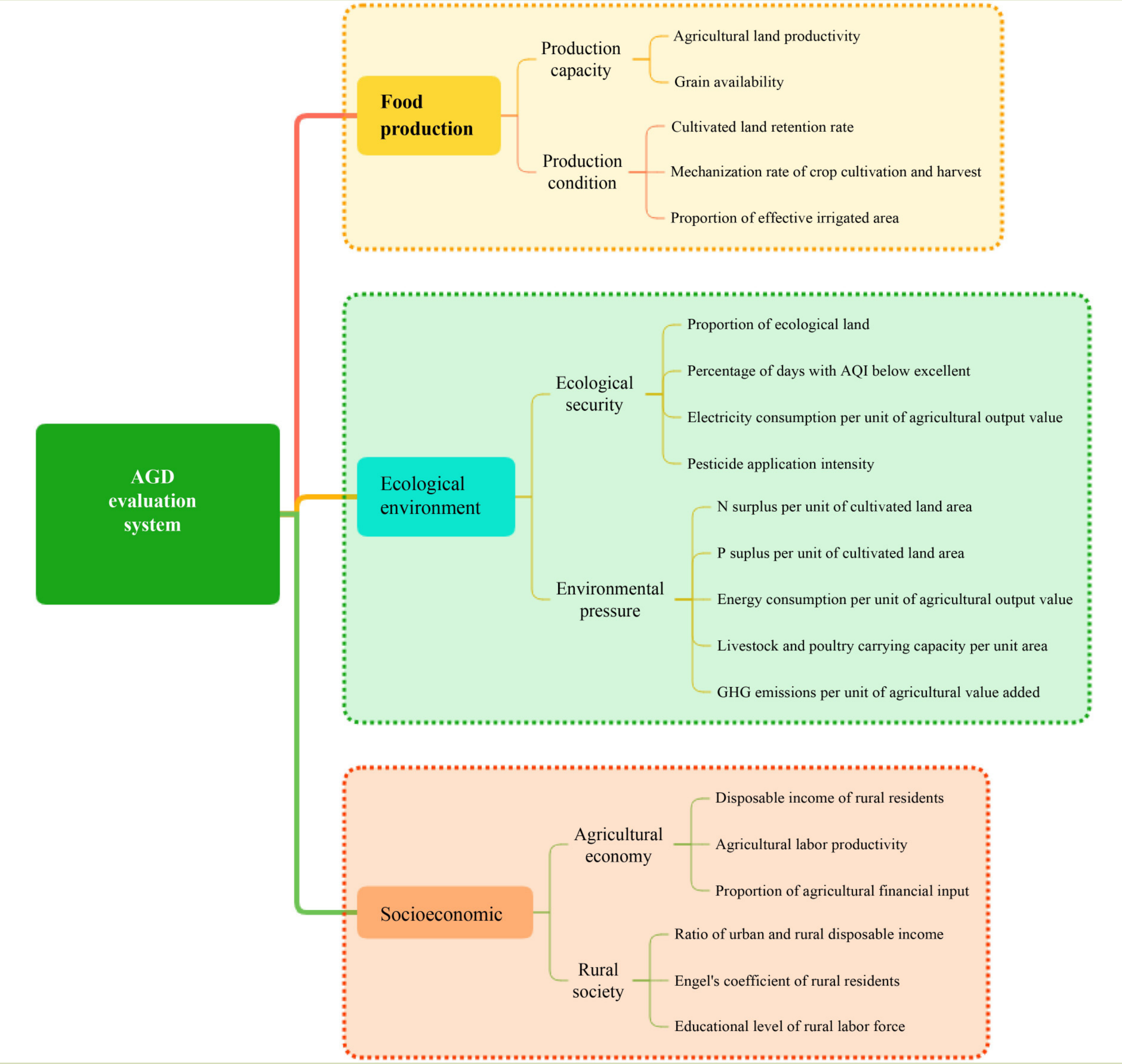


Fig. 1 County-level agriculture green development (AGD) evaluation index system.

lower bounds determined were applied to standardize indicators through modifying the direction of indicators.

Standardization formula for positive and negative indicators were:

$$x' = \frac{x - \min(x)}{\max(x) - \min(x)} \quad (1)$$

$$x' = \frac{\max(x) - x}{\max(x) - \min(x)} \quad (2)$$

where, x' is the adjusted standardized value, x is the original data value, and max(x) and min(x) are the target value and minimum value of the indicator, respectively.

2.4.2 Indicator weighting determination

This study suggested that all AGD dimensions should be coordinated but the importance of secondary indicators varied. Consequently, the three dimensions and six first-level indicators were weighted using the equal-weighting method. In contrast, the secondary level indicators were weighted by the expert-consultation method[24]. The weightings of indicators at each level are given in Table 1.

2.4.3 Index calculation

The AGD index was determined using the comprehensive evaluation function method, summarizing the indictor score

Table 1 Indicator for county-level agriculture green development (AGD) evaluation system

Dimension	Primary indicator	Secondary indicator	Weighting	Upper bound	Lower bound	Unit for upper and lower bounds	Direction
Food production	Production capacity	Agricultural land productivity	9.3	79,995	11,790	$CNY \cdot ha^{-1}$	Positive
		Grain availability per person	7.3	1345	125	kg	Positive
	Production condition	Cultivated land retention rate	6.0	100	88.8	%	Positive
		Proportion of effective irrigated area	5.2	100	15	%	Positive
		Mechanization rate of crop cultivation and harvest	5.5	90	37.6	%	Positive
Ecological environment	Ecological security	Proportion of ecological land	3.3	75	1.2	%	Positive
		Percentage of days with AQI below excellent level	4.5	12.5	100	%	Negative
		Electricity consumption per ten-thousand yuan of agricultural output value	3.8	54.7	3739	kWh	Negative
		Pesticide application intensity	5.0	2.6	32.0	$kg \cdot ha^{-1}$	Negative
	Environmental pressure	N surplus per unit of cultivated land area	3.5	80	633	$kg \cdot ha^{-1}$	negative
		P surplus per unit of cultivated land area	3.4	20	296	$kg \cdot ha^{-1}$	Negative
		Energy consumption per ten-thousand yuan of agricultural output value	3.0	417	25,105	MJ	Negative
		Livestock and poultry carrying capacity per unit of cultivated land area	3.4	2.7	10.8	$LU \cdot ha^{-1}$	Negative
		GHG emissions per million yuan of agricultural value added	3.4	104.7	471.7	t	Negative
Socioeconomic	Agricultural economy	Disposable income of rural residents per person	6.1	44,000	8001	CNY	Positive
		Agricultural labor productivity per person	5.5	6.50	0.23	10^4 CNY	Positive
		Proportion of agricultural financial input	5.1	20.0	3.2	%	Positive
	Rural society	Ratio of urban and rural disposable income	5.9	1.0	3.3	None	Negative
		Engel's coefficient of rural residents	5.2	20.0	33.6	%	Negative
		Educational level of rural labor force	5.6	90.0	13.8	%	Positive

with weightings as:

$$F(x) = \sum_{i=1}^{n} w_i f_{i(x)} \quad (3)$$

where, $F(x)$ is the comprehensive evaluation index of AGD, w_i is the weighting corresponding to the ith evaluation indicator, $f_i(x)$ is the score of the i indicator and n represents the number of evaluation indicators. The comprehensive evaluation index ranged from 0 (lowest) to 100 (highest). A higher score indicated a better AGD level.

2.5 Correlation analysis of indicators

Spearman correlation analysis has no requirements on data type and distribution, and is not sensitive to outliers[25]. Spearman correlation coefficient can measure the correlation strength between variables[26]. Therefore, it was used to evaluate the monotonic relationship between indicator pairs. The steps were as follows.

2.5.1 Adjustment of data direction

Each indicator was divided into positive and negative directions, indicating that larger values resulted in better performance and vice versa. Therefore, it was necessary to adjust the direction of the original value of the indicator into ascending variables. This facilitated the synergic and trade-off analysis between indicators from the perspective of performance instead of value.

2.5.2 Determination of the rank

For a pair of indicators (X_i,Y_i) $(i = 1,2,...,n)$ with sample size n, the n observed values of indicators X and Y were sorted from small to large to obtain the descending position rank of the two indicators in each sample, that is, the rank. The list rank is shown in Table 2.

Table 2 Variable ranking

Variable X	Ranking
4	n
7	n–1
8	n–2
…	…
15	2
19	1

2.5.3 Calculation of rank correlation coefficient

Rank correlation coefficient (r) was calculated to test the rank correlation degree, with the rank of X_i and Y_i being R_i and Q_i, respectively. Then the Spearman's correlation coefficient between indicators X and Y was defined as:

$$r = 1 - \frac{6}{n(n^2-1)}\sum_{i=1}^{n}(R_i - Q_i)^2 \tag{4}$$

where, r falls between −1 and 1, with $r > 0$ when the index is positively correlated and $r < 0$ when the index is negatively correlated. The larger the $|r|$, the higher the correlation between the indicators.

2.5.4 Determination of synergy and trade-off relationships between indicators

The results of correlation analysis were used to describe the synergistic and trade-off effects. Synergy between indicators implies that progress in one aspect benefited another whereas a trade-off implies that progress in one aspect disadvantaged another. The interactions between paired indicators were categorized into three groups: synergistic effect, trade-off effect ($P < 0.05$ was statistically significant), and no relationship. When r was greater than 0.6, the effect was deemed to be a synergistic, when r was less than −0.6, the effect was deemed to be a trade-off, and when r was between −0.6 and 0.6, there was deemed to be no relationship between indicators[27].

3 Results

3.1 Historical change in agriculture green development (AGD)

As shown in Fig. 2(a), the AGD of Quzhou County was broadly categorized into two stages. The first stage spanned from 1978 to 2003, during which the index of AGD fluctuated and but did not improve. In the second stage, from 2003 to 2019, there was a rapid rise of 53.2% in the index over 16 years. Over the whole period, the index rising from 35.5 to 56.4, an increase of 58.9%. This increase was because of an increase in the socioeconomic index, which contribution to the total growth by 65.8% (Fig. 2(b)). Notably, another dimension that contributed significantly to the increase was food production, with an exponential contribution of 53.5%. In contrast, the overall ecological environment level had a worsening trend with an overall negative effect.

The socioeconomic index of Quzhou County from 1978 to 2019 increased by 13.8 points (Fig. 2(b)). The contribution rates of agricultural financial input and urban-rural disposable income ratio to the index growth were 20.6% and 18.0%, respectively. In contrast, the contribution of other indicators to this dimension were all less than 9% (Fig. 3). In 2019, the food

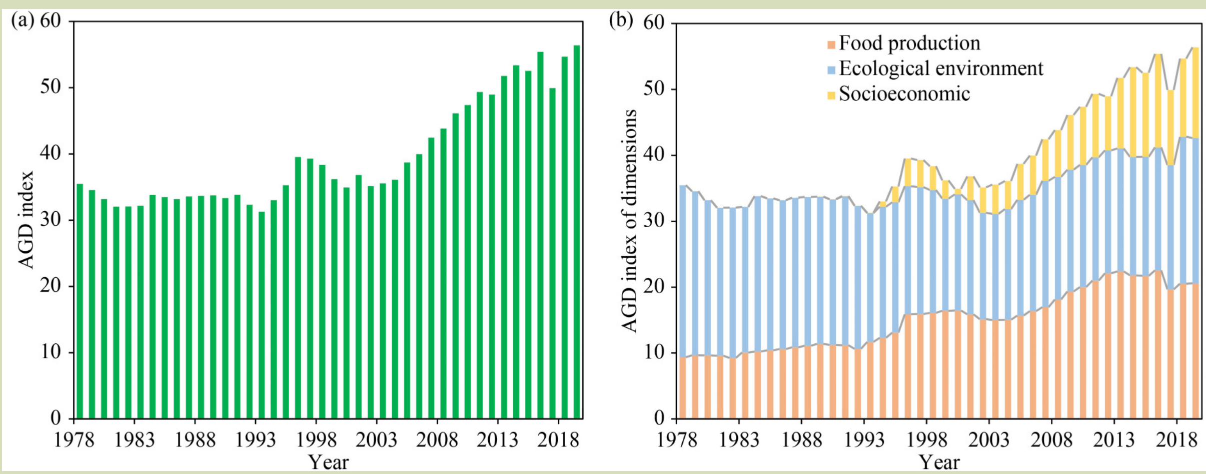
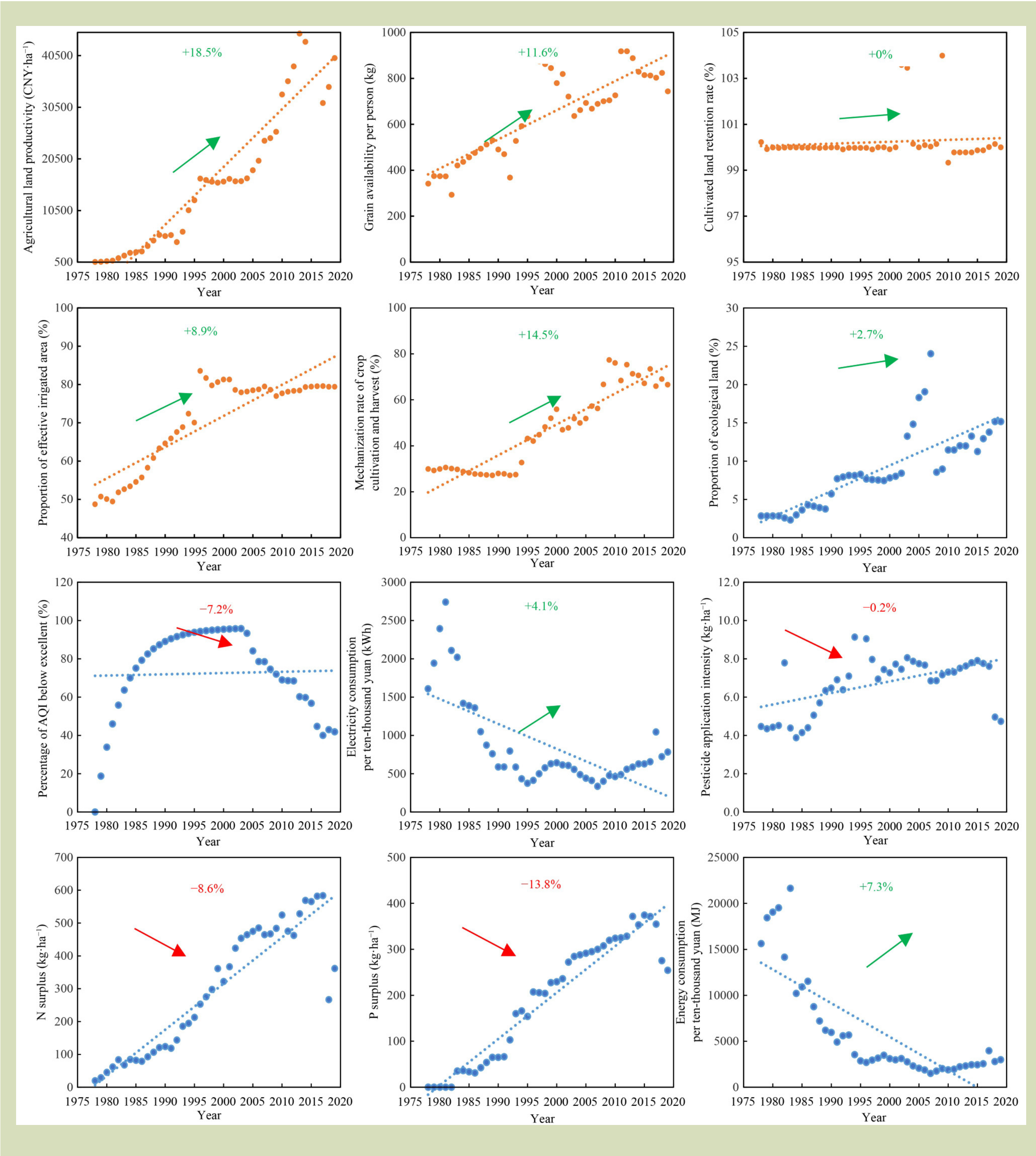


Fig. 2 Changes in agriculture green development (AGD) index (a) and three dimensions (b) in Quzhou County from 1978 to 2019.

production index (20.6 points) was 1.2 times higher than in 1978 (9.4 points). For the dimensions of food production, agricultural land productivity and crop mechanization rate contributed the most, with contributions of 18.5% and 14.5%, respectively. Other indicators in this dimension contributed less than 10% to the growth of the AGD index. The ecological environment index dropped from 26.1 points in 1978 to 13.8 points in 2019, a drop of 47.3%. Within this dimension, the scores of nitrogen and phosphorus surplus per unit cultivated land area, the proportion of days below air quality index (AQI) level of excellent, and the carrying capacity of livestock and poultry per unit cultivated land area all had a downward trend. However, other indicators had a slow upward trend.



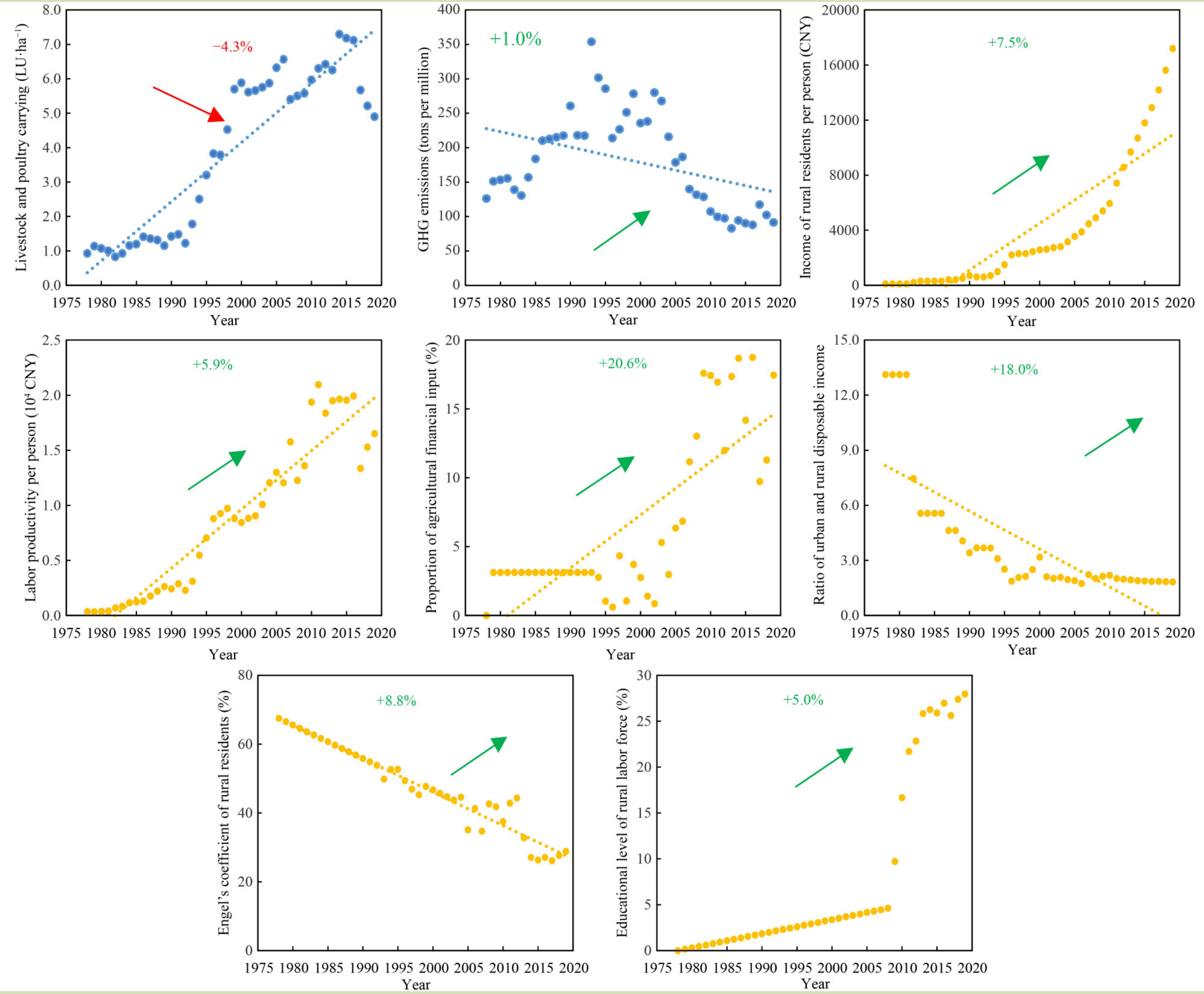


Fig. 3 Historical trend of secondary indicators and their contribution to the agriculture green development (AGD) index.

3.2 Current status of agriculture green development (AGD)

The AGD index was 56.4 points, leaving a gap of 43.6 points from the target performance of 100 (Fig. 2(a)) and with a lack of balance between the three dimensions (Fig. 2(b)). The scores for each dimension were: ecological environment (66.3 points) > food production (61.7 points) > socioeconomic (41.2 points). Considering the secondary indicators, the per capita disposable income of rural residents was only 17,202 yuan per person, and the agricultural labor productivity was 17,000 yuan per person. These values represented only 39.1% and 25.0% of the target value, respectively. Also, only 28.0% of the agricultural workforce had high school education or above, which was only 31.0% of the target value. The food production dimension scored 61.7 points, which was 38.3 points lower than the target value. A deeper analysis (Fig. 2(b)) revealed that the contribution rate of production capacity (primary index) to the food production index was only 36.9%. This mostly reflected the low land productivity and low per capita grain consumption. The land productivity of Quzhou County in 2019 was only 40,035 CNY·ha^{-1}, amounting to just 50.0% of the target. The ecological environment index achieved 66.3% of the target. Considering secondary indicators, this was mostly because the electricity consumption per unit of agricultural output was extremely high and the phosphorus surplus per unit of arable land area far exceeded the threshold. Specifically, the electricity consumption per ten-thousand yuan of agricultural output was 784 kWh, which was 14.3 times that of target values; farmland phosphorus surplus of cultivated land as high as 254.3 kg·ha^{-1}, which was 12.7 times higher than the threshold of 20.0 kg·ha^{-1}.

From the perspective of secondary indicators, the average of all 10 positive indicators was only 56.2% of the target value, which was substantially below the standard. Conversely, the average of the 10 negative indicators was only 42.8% of the target value (Fig. 4). Of the 20 indicators, only cultivated land retention rate and GHG emissions per unit of agricultural added value reached the target value. Notably, both electricity consumption per unit of agricultural output and the phosphorus surplus per unit of cultivated land area did not even achieve 10% of the full score, being the indicators with the largest gap. The energy consumption per unit of agricultural output was below 15% of the target. The indicators such as the nitrogen surplus per unit of cultivated land area, proportion of ecological land area and agricultural labor productivity did not reach 30% of the target value.

3.3 Index correlation relationship analysis

The analysis revealed that the synergistic effect of indicators in each dimension of AGD in Quzhou County surpassed the trade-off effect (Fig. 5). The proportion of correlations between indicators was: synergistic relationship (49.2%) > insignificant relationship (36.1%) > trade-off relationship (14.8%). The food production dimension displayed a pronounced synergistic effect, with 60% of the indicator pairs reflecting synergistic relationships and the remaining 40% indicating insignificant correlations. This suggested that food production capacity and production conditions often simultaneously improved or declined. Examining the interactions of indicators within each dimension, the trade-off effect dominated the relationships between ecological environment, food production and socioeconomic indicators, with the proportion of trade-off relationships being 24.1% and 28.9%, respectively. More than 50% of the indicator pairs between food production and socioeconomic dimensions revealed a synergistic effect, causing the overall synergistic effect to outweigh the trade-off effect across all indicators of agricultural green development dimensions. The trade-off relationship presented by the

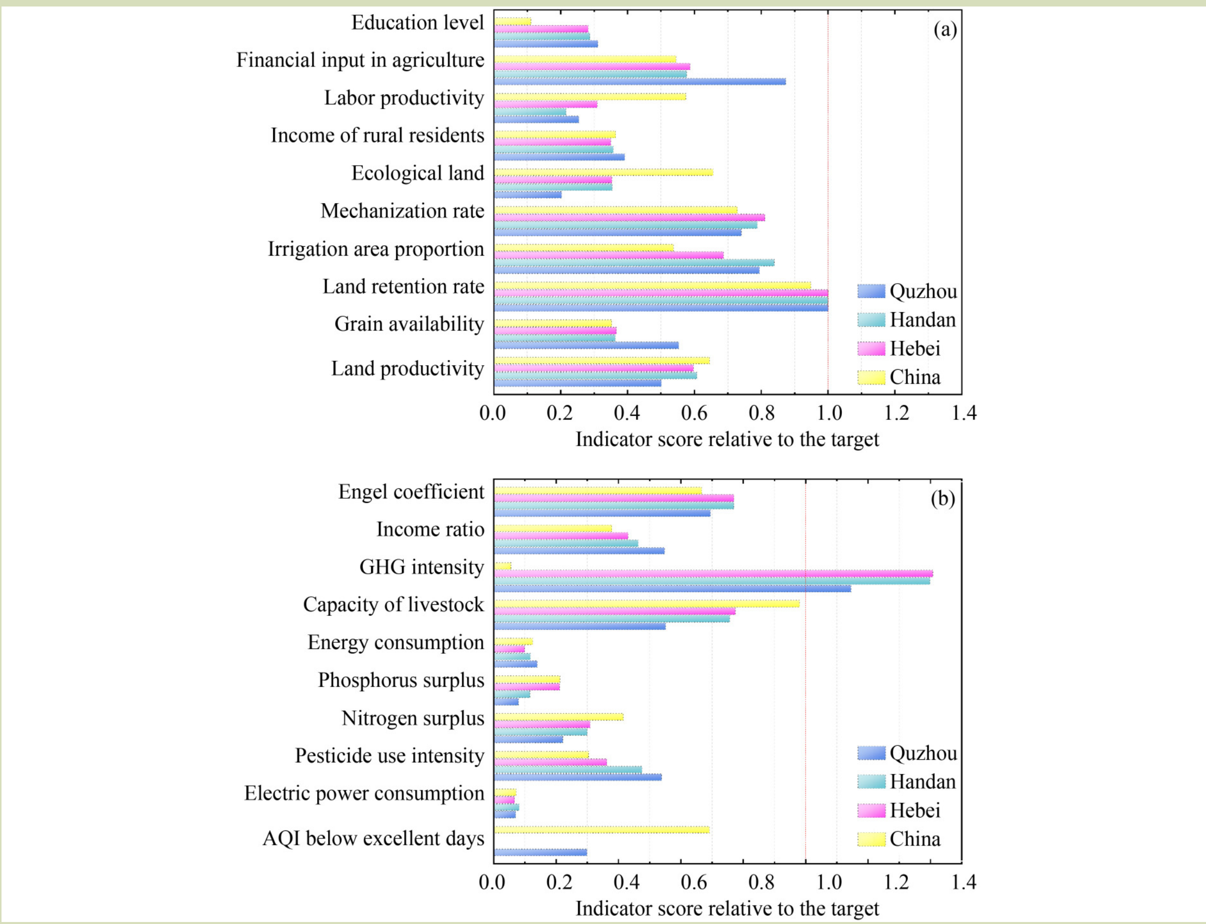


Fig. 4 Gap between agriculture green development (AGD) positive (a) and negative (b) indicators, and target values for Quzhou County, Hebei Province, China.

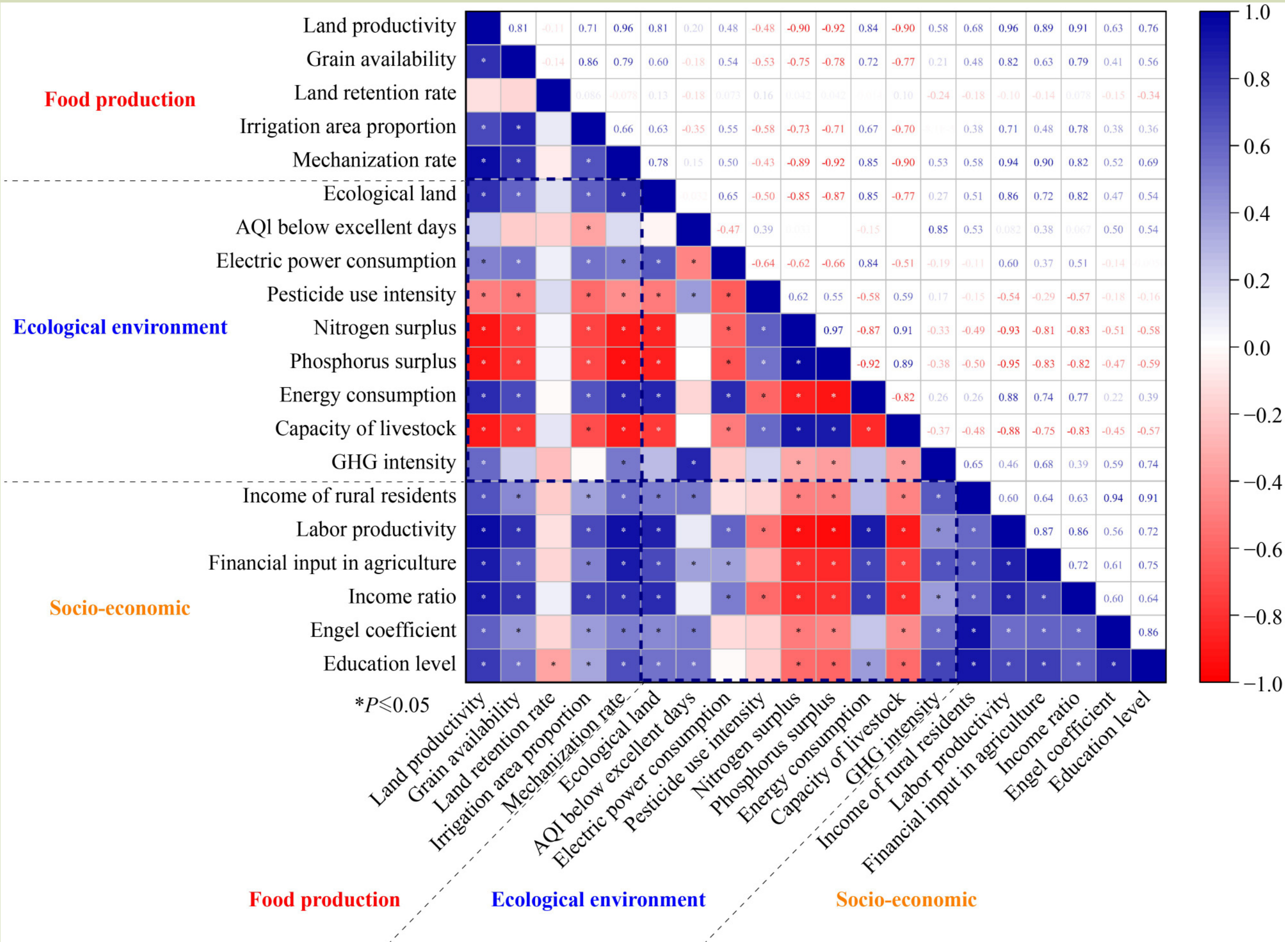


Fig. 5 Trade-off and synergy relationship between agriculture green development (AGD) indicators in Quzhou County, Hebei Province, China.

interdimensional indicators aligned with the traditional model, that is, economic development caused environmental costs.

From a holistic evaluation system standpoint, the synergistic relationship between AGD indicators outweighed the trade-off relationship. This suggested that Quzhou County has had a good start toward achieving the goals of AGD. Of the indicators, agricultural land productivity and agricultural labor productivity revealed a higher proportion of synergy. Therefore, prioritizing the improvement in agricultural land productivity and labor productivity indicators promoted the realization of the remaining indicators. In addition, the indexes with the greatest trade-off effect were the nitrogen and phosphorus surplus per unit of cultivated land area and the livestock and poultry carrying capacity per unit of cultivated land area. Hence, significant attention should be given to this trade-off effect, and the realization of regional AGD should be promoted.

4 Discussion

4.1 Research uncertainties analysis

The comprehensive analysis results indicated that the level of AGD in Quzhou County fluctuated from 1978 to 2001, but had a rapid rise after 2002. Nevertheless, it remained at a relative low level compared to the target value. Currently, only the cultivated land retention rate and GHG emissions per unit of agricultural added value attained the target value. This was mainly due to the actual agricultural development, but also partly due to the definition of the target. We acknowledge there are uncertainties in our research, but it does make some contribution to the understanding of the AGD despite the limitations of data availability and comprehensive evaluation.

For instance, taking the per capita grain occupancy in the USA as a reference, this study established the target value for this indicator at 1345 kg per person. Nonetheless, the present per capita grain consumption in Quzhou County stands at 744 kg per person. This is 57% higher than the national average (474 kg per person), 86% above the UN Food and Agriculture Organization food security line (400 kg per person)[28,29] and 2.1 times to the global per capita food consumption (~350 kg)[30]. Despite this, the indicator showed a steady growth trend, doubling in 2019 (744 kg) compared with 1978 (342 kg), the results still reflect the county-level progress in AGD goals, with substantive credibility.

Besides, this study used the subjective expert-consultation method to inform the weighting of the indicators for AGD. The advantage of this approach is that the weighting is derived from experts in relevant fields who assess the significance of indicators according to their professional knowledge, ensuring high authority and professionalism[31]. While objective-weighting methods, such as entropy-weighting, principal component analysis, and multi-objective programming, have a strong objectivity and mathematical theoretical basis[32], they are also affected by data variability. As a result, the weighting value assigned may be inconsistent with the actual attribute of the index[33]. An objective method was thus adopted to clarify the influence of different methods on the AGD index. When the expert-consultation method assigned weights to indicators, the change range of the AGD index was 35.5 to 56.4 (Fig. 6). Using the entropy-weighting method gave index variation from 33.9 to 49.9. Although the index calculated using the entropy-weighting method was slightly lower than that calculated using the expert-consultation method, the historical change trend of was consistent. In short, the AGD index is trustworthy, despite the uncertainties from defined target value and indicator weighting.

4.2 Experience and suggestions for promoting agriculture green development (AGD)

This study categorized the AGD of Quzhou County into two stages. From 1978 to 2003, the first stage saw a steady increase in food productivity. However, a significant deterioration in the ecological environment occurred, causing the comprehensive AGD index to stagnate. In 1978, China introduced the household contract responsibility system, altering production relationships. This system motivated farmers and enhanced agricultural productivity[34]. In 1983, the per capita food occupation reached 421 kg per person, surpassing the international food security standard line (400 kg per person) for the first time[35]. Concurrently, the food production index increased by 24.7%. However, during this period, a significant increase in fertilizer and pesticide use contributed to the observed increase in crop yields[36]. The average annual growth in nitrogen and phosphate fertilizer input was 43.6% and 240%, respectively, and pesticide application increased by 56.7%. Simultaneously, livestock and poultry production increased by 90%. Such agricultural activities led to a significant rise in nitrogen and phosphate surplus per unit of cultivated land to 186 and 160 $kg \cdot ha^{-1}$, respectively. GHG emissions per unit of agricultural added value also increased from 12.6 kt per billion yuan in 1978 to 35.4 kt per billion yuan in 1993, an increase of about 180%.

The second phase was from 2003 to 2019. During this period,

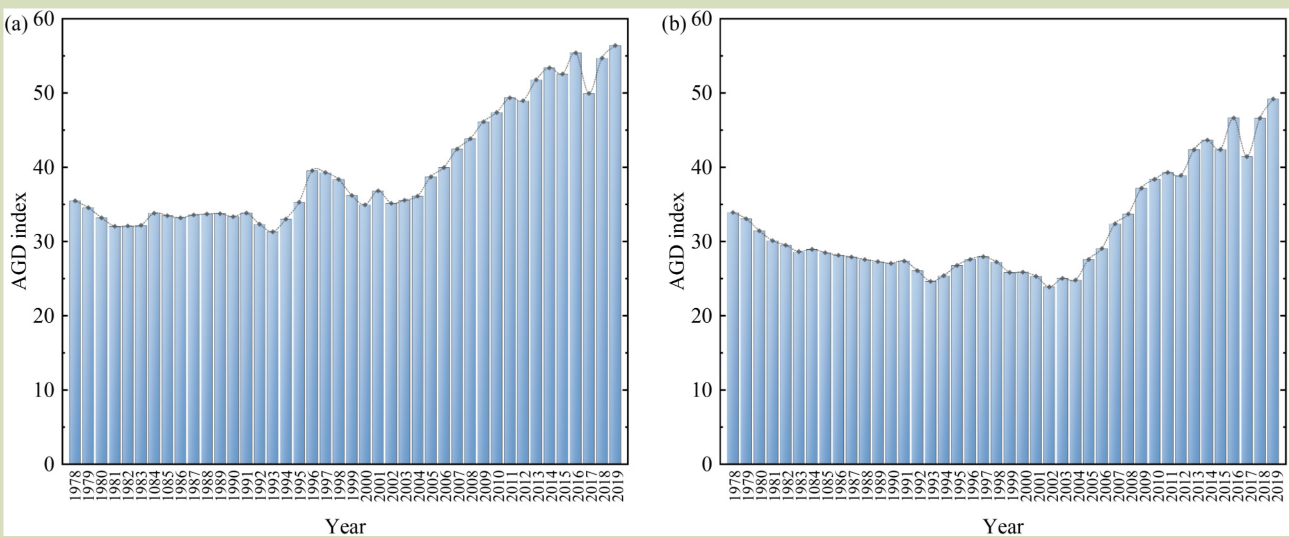


Fig. 6 Agriculture green development (AGD) index of expert-consultation method (a) and entropy-weighting method (b).

the AGD index increased significantly. The contribution of all dimensions increased positively. The development of agricultural production and ecological environment gradually tended to coordinate, although the contribution rate of the socioeconomic dimension (60.2%) was still markedly higher than those of the ecological environment (20.7%) and food production dimension (19.2%). During this period, the implementation of essential engineering actions represented by the reduction of fertilizer and pesticide, improvement in cultivated land quality, construction of high-standard farmland and water-saving irrigation significantly promoted the synergy between agricultural production and ecology, and facilitated AGD by reducing the resource input and improving resource use efficiency[1]. Technology innovation cooperated with multistakeholders have great contribution to the transformation. For example, to manage the surplus of nitrogen and reduce the NH_3 emissions, the government cooperated with universities to develop scientific fertilization actions, formulated fertilization guidelines for major crop systems, customized new nitrogen fertilizers containing urease inhibitors with fertilizer enterprises, and provided special subsidies at the same time, strengthened science popularization and publicity, and effectively improved nutrient use efficiency[37]. Also, the experience of participatory scientific and technological innovation and the integrated landing mode of government, enterprises, universities and markets have provided important references and support for the green transformation of agriculture on the North China Plain and even the whole country.

However, it is necessary to realize that its current development trend indicates that the anticipated goals by 2050 might not be met. According to the exponential growth trend observed from 2015 to 2019, the actual growth rate of Quzhou County was only 70.6% of the target development speed. The government should focus more on reducing the key limiting indicators, especially the agricultural land productivity, reducing phosphorus surplus per unit of cultivated land area, and further improving the agricultural scientific and technological innovation, accelerate the technology extension and adoption by farmers, effectively overcoming the imbalance between agricultural food production and ecological environment, and achieving multi-objective and coordinated growth.

5 Conclusions

This study constructed a target-oriented quantitative evaluation index system based on the connotation of AGD, which provided a research tool for assessing county-level agricultural transformation. Overall, the agricultural development in Quzhou County was gradually transforming from the intensive agriculture with high input and high output to the green mode with low input and high output. The AGD index of Quzhou County increased from 35.5 in 1978 to 56.4 in 2019, which was an increase of 58.9%. The contribution analysis revealed that the socioeconomic and food production indexes were the primary drivers behind the increase in the total index increase, whereas the ecological environment index contributed negatively. Although the synergistic relationship between AGD indicators has exceeded the trade-off relationship in recent years, there are still problems to overcome, such as inadequate development and seriously exceeding environmental thresholds, in order to improve the synergistic relationship between indicators that is crucial to accelerate AGD.

Supplementary materials

The online version of this article at https://doi.org/10.15302/J-FASE-2024536 contains supplementary material (Table S1).

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Compliance with ethics guidelines

Xiao Xu, Yanxiang Jia, Yuan Feng, Haixing Zhang, Wen Xu, and Qichao Zhu declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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