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RESEARCH ARTICLE

China's agriculture green development: from concept to actions

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KEYWORDS

Agricultural transformation, agriculture green development, historical trend, indicator system, theoretical conception

HIGHLIGHTS

- A target-threshold indicator evaluation system is proposed to measure China's agriculture transformation.
- Evaluation based on a development score showed China is currently at a medium level in the Agriculture Green Development initiative.
- There was a trend for increasing development scores for 2010–2020 compared to 1997–2010.
- Trade-offs between eco-environmental factors and socioeconomic/food production factors were found to be the major barriers to the transformation.
- More effort is needed to address the insufficient and uneven development to provide coordinated improvement.

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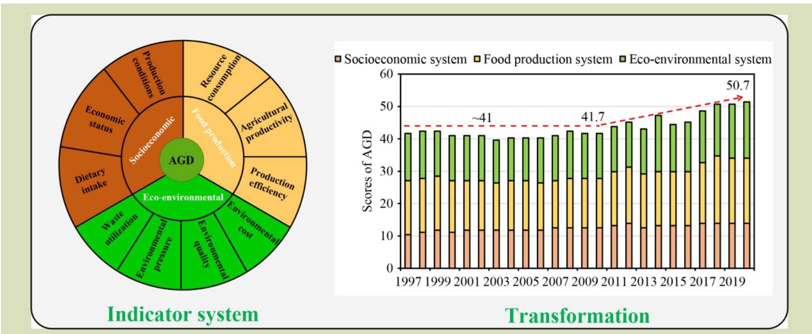
GRAPHICAL ABSTRACT



ABSTRACT

China has initiated a green transformation plan in 2015, which was soon applied to agriculture, known as the agriculture green development (AGD) initiative, with the goals of achieving food security, high resource use efficiency, and an ecofriendly environment. To assess the agricultural transformation from 1997 to 2020, this paper proposes a national-scale indicator system consisting three dimensions (socioeconomic, food production and eco-environmental) and ten sub-dimensions to quantify the AGD score. This study showed that AGD score in China was at a moderate level during 1997–2010, scoring 40 out of 100. During this stage, decreased scores in the sub-dimensions of resource consumption, environmental quality, and environmental cost have offset the improvement in the socioeconomic dimension, resulting in fluctuated scores around 40. In the second stage (2011–2020), China's AGD score improved but still at moderate level, scoring an average of 46.3, with each dimension increasing by 5.3%–25.0%. These results indicate that China has made progress in the agricultural transformation, transitioning from conceptualization to actions through the implementation of various policies and projects. However, the study emphasizes the need for more effort to address the insufficient and unbalanced development, along with the growing eco-environmental challenges, especially the trade-offs among dimensions.

1 Introduction

Agriculture has undergone a transformation from extensive to intensive practices globally, with a current focus on pursuing sustainability. In the late 1950s, the Green Revolution, led by Norman Borlaug, gained worldwide influence as farmers adopted high-yielding cereal cultivars such as dwarf wheat and rice[1]. With an enormous increase in crop yield, the Green Revolution made significant contributions to global population growth, poverty reduction, child mortality reduction, and the prevention of hunger for millions of people[2]. However, the Green Revolution has also received criticism for its heavy reliance on agricultural inputs such as machinery, nutrients, plastic materials and pesticides, which have resulted in negative impacts on biodiversity, depletion of non-renewable resources, increased energy consumption, and environmental pollution[3].

China faces unique challenges from limited resources, fragmented croplands, insufficient irrigation water and large population, and for continued economic development. After undergoing its own Green Revolution, China has managed to feed 18% of global population with only 8% of the arable land through intensive irrigation, fertilizer and pesticide application, even as its population has grown from 1 billion to 1.4 billion since 1980[4–6]. However, the rapid development has come at a cost. In the last four decades, the use of nitrogen and phosphorus fertilizers has increased threefold and 11-fold since 1978, respectively, and pesticides use has increased by 97% since 1991. The high level of agricultural input has led to soil degradation, increased greenhouse gas emissions, intensified eutrophication and reduced agricultural biodiversity[7–9]. While China had eradicated extreme poverty by 2020, the income gap between urban and rural areas, land ownership issues, low levels of agricultural modernization, and regional development imbalances severely limit farmer income[10]. Meanwhile, over 21% of population suffers from hidden hunger, 11.6% of adults have diabetes and half of the adults are currently overweight or obese[11–13]. With a growing population and a predicted increase in food consumption, particularly nutritious and healthy food, it is crucial for China to find a pathway to balance agricultural development and environmental protection and transform its agriculture toward greater sustainability[14]. This new pathway would need to prioritize socioeconomic development while limiting the negative environmental impacts of food production.

The agriculture green development (AGD) initiative, proposed in 2016, presents a potential pathway for achieving sustainable development in China[15]. Previous studies have suggested several approaches to promote the transformation, aiming to balance agricultural production within the environmental carrying capacity, such as optimizing input, enhancing system coupling, and promoting recycling. These approaches aim to improve resource efficiency, reduce emissions, enhance high-quality, safe and sufficient food supply, promote human health, and foster thriving agricultural industries and an ecologically sustainable society[16,17]. Such studies also suggest the need to focus on problem-solving from a developmental perspective, such as increasing agricultural productivity through a more effective agricultural emission control to meet ecosystem resilience, rather than just reducing pollution by lowering the inputs[18,19]. The AGD, although an emerging concept, presents a guiding principle for evolving agriculture from a production-oriented to a quality-oriented model[20]. However, previous studies have primarily focused on specific aspects, such as resource utilization or environmental protection, without establishing a quantifiable, comprehensive and target-oriented evaluation tool, which is clearly a crucial step for pinpointing areas requiring future development[21,22]. In response to this gap, our study aimed to quantitatively measure the progress of China's agricultural green transformation by developing an indicator evaluation system, emphasizing an interdisciplinary approach to tackle systemic issues[21]. We have undertaken a systematic analysis from socioeconomic, food production and eco-environmental perspectives to evaluate both development and green (i.e., the eco-environmental) facets of agriculture. The specific objectives were: (1) to propose a methodology for evaluating AGD progress; (2) to analyze historical trend and its key supporting policies and actions; and (3) to summarize China's experience in pursuing agricultural green transformation.

2 Materials and methods

2.1 Construction of the indicator evaluation system

To quantitatively evaluate China's agricultural transformation, we have developed a systematic and quantifiable evaluation system to assess the historical trend. We followed the FAO method[23] and proposed a national indicator system using five steps: (1) determine the objective of the indicator system, which is to comprehensive evaluate of the historical trend of AGD; (2) define the research boundary, which in this case is a national-scale evaluation focused on the agricultural system; (3) define the dimensions based on the connotation of AGD, viz., food production, socioeconomic and eco-environmental dimensions; (4) select ten sub-dimensions, viz., production conditions, economic status, food consumption, resource consumption, agricultural productivity, production efficiency, waste utilization, environmental pressure, environmental quality and environmental cost; and (5) establish detailed indicators to support these sub-dimensions. In the end, the indicator system consisted of 3 dimensions, 10 sub-dimensions, and 36 indicators (Table 1).

We have conceptualized an evaluation framework (Fig. 1) to guide the selection of indicators for measuring the development status. This framework is based on three interconnected systems: food production, socioeconomic and eco-environmental systems. The food production system comprises animal and crop production, which serves as the source of food for the socioeconomic system and impacts the eco-environmental system. The socioeconomic system comprises rural economy and human health, which depends on the food production system for food and eco-environmental system for a livable environment. The eco-environmental system comprises water, soil and air, and it provides services the two other systems. For example, emissions and waste from food production can be recycled back to the food production system. These three systems are interconnected and collectively constitute the agriculture system. We have selected indicators from each system to capture the development status.

2.2 AGD score calculation

To quantitatively assess China's AGD, we applied a graded scoring method to each indicator. The status of each indicator was divided into four levels (I–IV), representing low, moderate, good, and excellent from insufficient to optimal. In an ideal scenario, all 36 indicators would be of a Level IV standard, scoring a perfect 100 points, with each indicator receiving a score of 2.78 points. For indicators that do not meet the Level IV standards, a four-point method was employed to assign scores. Specifically, a score of 25%, 50%, 75% and 100% of the full score (2.78) are assigned to indicators that meet the Levels I–IV standards, respectively.

The dimensions, indicators, calculation and grading standards are shown in Table 2, and a detailed grading guideline and methodology for setting target values are shown in Table S1 in the Appendix. In cases where data were missing, we assigned the indicator as Level I, and it would obtain 25% (0.69) points. Table S1 shows the detailed indicator explanation and grading guidelines. The final score is the summation from all indicators, representing the AGD levels.

2.3 Data sources

We sourced data relevant to China's agricultural development from 1997 to 2020 from the National Bureau of Statistics and the China Rural Statistical Yearbook. Environmental data, such as air quality and water quality, were obtained from China's Ecological Environment Bulletin, China's Environmental Status Bulletin and China's Water Resources Bulletin. Soil pollution and soil erosion data were obtained from the National Soil Pollution Survey Bulletin and China's Soil and Water Conservation Bulletin.

3 Results

3.1 Historical trends in China's agricultural transformation

China's agricultural transformation from 1997 to 2020 can be roughly divided into two development stages based on evaluations made in this study. This is demonstrated in Fig. 2, with the first stage from 1997 to 2010, and the second stage from 2010 to 2020. During the first stage, the overall AGD score fluctuated by about 40 points, with Levels I and II indicators accounting for 45.9% and 16.8%, respectively. In the second stage, the proportion of Level I indicators gradually decreased from 51.5% to 23.5%, with Level III indicators increasing from 11.8% to 26.5%, making the major contribution to the overall increment from 41.7 to 50.7. Despite the continuous increase since 1997, the current overall AGD level is still classified as Moderate (with in the 25–50 score range), with a high proportion of indicators located in Levels I (23.5%), II (35.3%), and III (26.5%) but a low proportion in IV (8.8%).

Dimensions were unevenly developed from 1997 to 2020. The socioeconomic, food production, and eco-environmental scores increased by 33.3%, 20.8% and 19.1%, respectively (Fig. 3(a)), indicating insufficient synergetic development among the three dimensions. Among the ten sub-dimensions (Fig. 3(b)), agricultural productivity showed the highest increase (150%) from 1997, followed by production conditions (100%) and food consumption (25.0%). In contrast, economic status and production efficiency stagnated, while environmental quality worsened by 14.3%. The results suggest

Table 1 The AGD indicators and grading standards

Dimension	Sub-dimension	Number	Indicator	Calculation	Unit	Classification criteria			
						I	II	III	IV
Food production	Resource consumption	1.1.1	Veterinary input	Veterinary drug input / standard animal number	yuan·LU^{-1}*	>244	122–244	61–122	<61
		1.1.2	Pesticide input	Pesticide input usage (pure volume) / total planting farmland	kg·ha^{-1}	>10	5–10	2.5–5	<2.5
		1.1.3	Exogenous N input in animal feed	(N demand of animal husbandry-N supply of planting industry) / number of standard animals	kg·LU^{-1} N*	>120	60–120	0–60	⩽0
		1.1.4	Agricultural water footprint	(Main food consumption × agricultural water footprint per person) / population	t·person^{-1}·yr^{-1}	>760	620–760	480–620	<480
	Agricultural productivity	1.2.1	Cropland protein productivity	Total protein of various crops / cultivated land area	kg·ha^{-1}	<313	313–372	372–431	>431
		1.2.2	Cropland calorie productivity	(Variety of crop products calories + animal product calories) / cultivated land area	10,000 kcal·ha^{-1}	<1960	1960–2180	2180–2400	>2400
		1.2.3	Cropland economic productivity	Gross agricultural output value / cultivated land area	10,000 yuan·ha^{-1}	<6.73	6.73–8.4	8.4–10.5	>10.5
		1.2.4	Irrigation efficiency	Statistical data	–	<0.5	0.5–0.55	0.55–0.6	>0.6
	Production efficiency	1.3.1	Energy efficiency	Σ(Agricultural production primary energy consumption × per unit of energy) / gross agricultural production value	MJ·(million yuan)$^{-1}$	>7291	6197–7291	5650–6197	<5650
		1.3.2	Cropland N use efficiency	(N uptake at the harvest site + N uptake in straw) / total nitrogen input in farmland × 100	%	0-35	35–50	50–65	>65
		1.3.3	Animal N use efficiency	(N absorption of main products of livestock and poultry + N absorption of animal byproducts) /total input of nitrogen of livestock and poultry × 100	%	<10	10–20	20–30	>30
		1.3.4	Cropland P use efficiency	(P uptake at harvest site + P uptake from straw) / total P input to farmland × 100	%	0–20	20–30	30–40	>40
Socioeconomic	Production conditions	2.1.1	Agricultural investment	Investment in agriculture and forestry water affairs / rural population	yuan·person^{-1}	<3259	3259–4786	4786–6140	>6150
		2.1.2	Mechanization	Total power of agricultural machinery / cultivated land area	kW·ha^{-1}	<6.2	6.2–8.4	8.4–11.5	>11.5
		2.1.3	Rural education	Survey population of farmers with high school degree or above / total survey number of farmers × 100	%	0–22.5	22.5–45	45–90	>90
		2.1.4	Irrigation coverage	Effective irrigation area / cultivated land area × 100	%	<50	50–60	60–70	>70
		2.1.5	Land transfer	Land transfer area / regional cultivated land area × 100	%	<20	20–40	40–60	>60
	Economic status	2.2.1	Income equality	Urban resident disposable income/rural resident disposable income	–	>2.0	1.6–2.0	1.2–1.6	<1.2
		2.2.2	Farmer income	Statistical data	10,000 yuan	<0.72	0.72–2.80	2.80–8.66	>8.66
		2.2.3	Agricultural income	Rural resident agricultural income / total income of farmers	%	0–10	10–20	20–40	>40

(*Continued*)

Dimension	Sub-dimension	Number	Indicator	Calculation	Unit	Classification criteria			
						I	II	III	IV
	Dietary intake	2.3.1	Animal-derived food consumption	Animal protein production / (animal protein production + plant protein production)	%	<20	20–40	40–55	>55
		2.3.2	Protein intake	Σ (Main food consumption of residents × protein content)	$kg\cdot person^{-1}\cdot yr^{-1}$	<14.6 or >34.7	14.6–18.3 or 29.2–34.7	23.7–29.2	18.3–23.7
Eco- environment	Waste utilization	3.1.1	Animal waste recycling	Resource utilization of manure / manure production of livestock and poultry × 100	%	<35	35–55	55–75	>75
		3.1.2	Crop residues recycling	(Amount of straw returning to the field + amount of straw feeding + Amount of straw for electricity generation) / amount of straw produced × 100	%	<45	45–65	65–85	>85
		3.1.3	Plastic film recycling	Recycling agricultural plastic film / Agriculture plastic film usage × 100	%	<40	40–60	60–80	>80
	Environmental pressure	3.2.1	Crop-livestock system N surplus	(Total N input in farmland – N absorption in straw – N absorption in harvesting area) / cultivated land area	$kg\cdot ha^{-1}$	>270	180–270	90–180	<90
		3.2.2	Soil erosion[#]	Soil erosion modulus = soil erosion amount / unit area / unit time	$t\cdot km^{-2}\cdot yr^{-1}$	>5000	2500–5000	500–2500	<500
		3.2.3	Soil erosion[#]	Proportion of soil erosion area = soil erosion area / total area × 100	%	>30	20–30	10–20	<10
		3.2.4	Animal carrying capacity	Regional livestock and poultry breeding standard number of animals / cultivated land area	$LU\cdot ha^{-1}$	>2.7	1.9–2.7	1.1–1.9	<1.1
	Environmental quality	3.3.1	Surface water quality	Percentage of surface water above Level-IV (National Standard)	%	<50	50–70	70–90	>90
		3.3.2	Groundwater quality	(Sample points with water quality of IV, V and inferior V) / total measurement sample points × 100	%	>50	30–50	10–30	<10
		3.3.3	Soil pesticide pollution	Statistical data	%	>10	5–10	2–5	<2
		3.3.4	Soil heavy metal pollution	Exceeded points / total monitoring points × 100	%	>10	5–10	2–5	<2
		3.3.5	Air quality	Statistical data	day	>30	20–30	10–20	<10
	Environmental cost	3.4.1	Ammonia emission	(Fertilizer + NH_3 emissions from humans and animals) / cultivated land area × 100	$kg\cdot ha^{-1}$	>140	120–140	100–120	<100
		3.4.2	N use efficiency in food system	(Planting N input + animal husbandry N input – food N content) / food N content	$kg\cdot kg^{-1}$	>5	4–5	3–4	<3
		3.4.3	GHG emissions	(GHG emissions from animal husbandry + GHG emissions from crop farming) / cultivated land area	$kg\cdot ha^{-1}$ CO_2-eq	>6500	5000–6500	3500–5000	<3500

Note: [*]LU denotes the standard livestock numbers, i.e., dairy cow; [#]proportion of soil erosion area and soil erosion modulus are alternatives. If there was a conflict between the two, soil erosion modulus was used. National Standard for Levels I–IV surface water (3.3.1) was used in general industrial water areas and for recreational water not directly contacted by human.

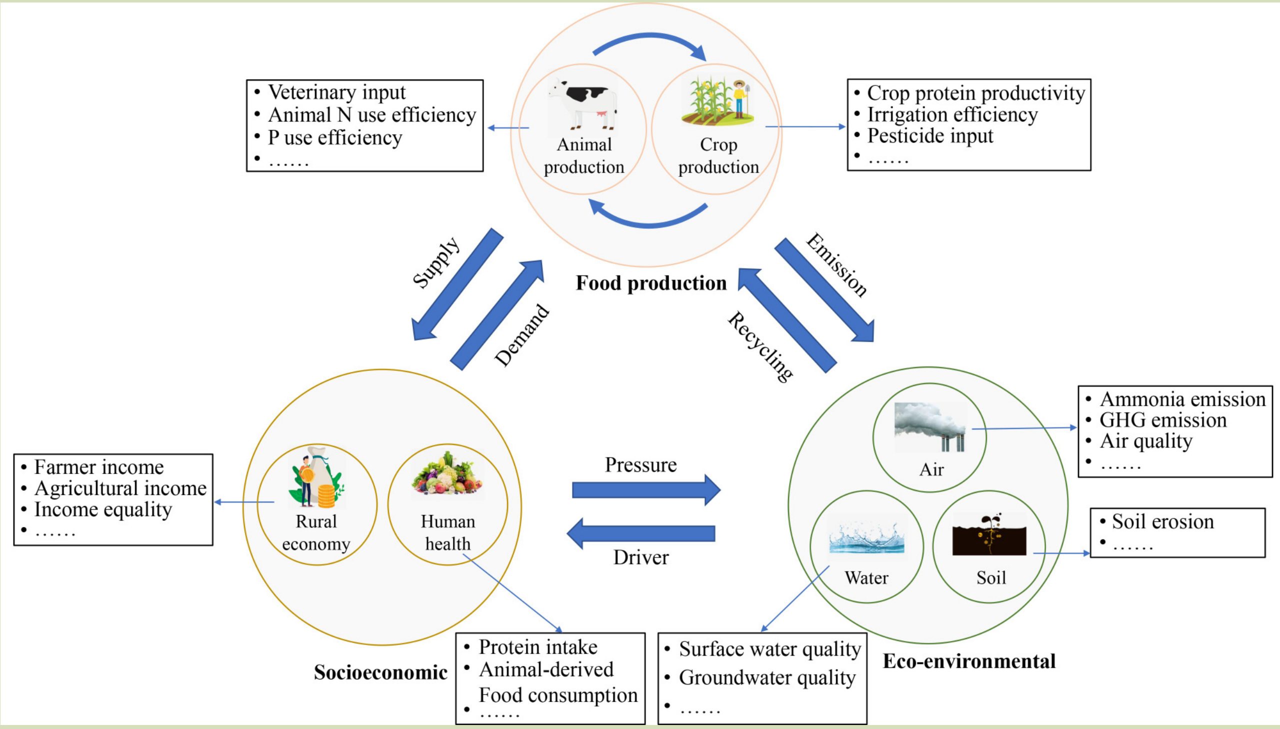


Fig. 1 Schematic representation of evaluation framework.

Table 2 AGD level grading standards

Overall score	AGD levels
0–25	Low
25–50	Moderate
50–75	Good
75–100	Excellent

an imbalance in the development of agricultural productivity and environmental quality, leading to stagnated overall score growth before 2010 and a relatively slow increase during 2010–2020.

3.2 AGD score and insights into sub-dimensions and specific indicators

This evaluation shows that the AGD score had increased significantly from 1997 to 2020, although each dimension experienced a different pattern of change in different phases. The major increase in the AGD score came from the socioeconomic dimension (Fig. 4(a)), where the proportion of Level I indicators decreased from 70% to 20% during 1997–2020. This improvement led to a 3.5-point increase in the overall score. In contrast, the food production dimension (Fig. 4(b)) remained steady from 1997 to 2005, decreasing from 2005 to 2016, then increasing again. The score of this dimension decreased from 16.7 to 14.6 in 1996–2007, and then rapidly increased to 20.1 in 2020. However, the food production dimension still fell within the moderate level, characterized by high resource consumption and low resource use efficiency. The eco-environmental dimension (Fig. 4(c)) performed least favorably, with only 3.2% of the indicators falling in Level IV, indicating severe environmental challenge faced by China. This dimension follows a similar trend to the food production dimension, deteriorating from 2003 to 2013 but subsequently improving due to the decreasing use of mineral fertilizer and pesticides.

In 2020, the AGD scored 50.7, with seven indicators at Level I, 15 at Level II and 13 at Levels III or IV. Among the total of 36 indicators, there are 20 positive direction indicators and 16 negative direction indicators (Fig. 5). The positive direction indicators achieved 52.2% of the target (Level IV standard) and the negative direction indicators (except for pesticide input due to data limitation) exceeded the threshold (Level IV standard) by 3.4 times on average. Protein intake, phosphorus use efficiency, animal waste recycling and energy use efficiency achieved the excellent level. In contrast, groundwater quality and soil heavy metal pollution exceed the threshold by more than 7.5 times. These findings suggest that while intensive

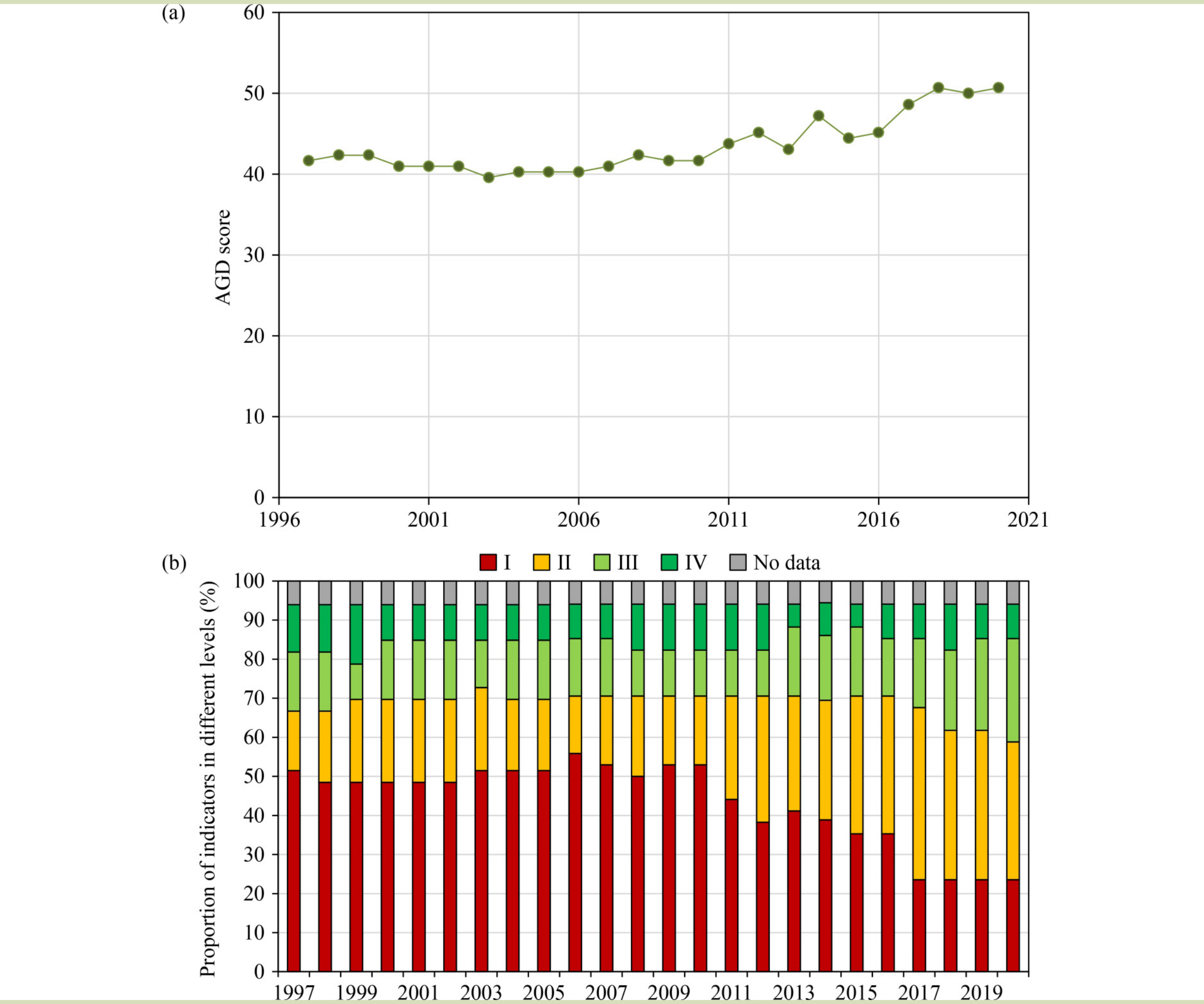


Fig. 2 Trend in AGD score (a) and distribution of indicator levels (b). Levels I–IV represent low, moderate, good, excellent levels of AGD.

agricultural production in China has boosted productivity and related farmer income, it has also accelerated resource consumption and negatively impacted the environment.

3.3 Trade-offs and synergy analysis among indicators

To gain a better understanding of the interrelationships among the indicators, a Spearman-correlation matrix (Fig. 6) was used to examine the 2020 data. At the dimensional level, we found a synergistic relationship between socioeconomic and food production. In contrast, eco-environmental and the other two dimensions demonstrate a trade-off relationship, indicating a competitive situation between development and environmental protection. Similar trade-off relationships were observed at the indicator level, where agricultural income (2.2.3) showed a significant negative correlation with most indicators from food production ($P \leqslant 0.01$). Within the eco-environmental dimension, air quality (3.3.5), GHG emissions (3.4.3), and ammonia emissions (3.4.1) are significantly negatively correlated with most of the socioeconomic indicators ($P \leqslant 0.01$). These findings show that future agricultural development should decouple from emitting atmospheric pollutants. Consequently, future development strategies need to address the trade-offs among indicators and promote coordinated development among dimensions.

4 Discussion

4.1 Agriculture developmental pathways and progress in China

In this study, we developed an indicator evaluation system to

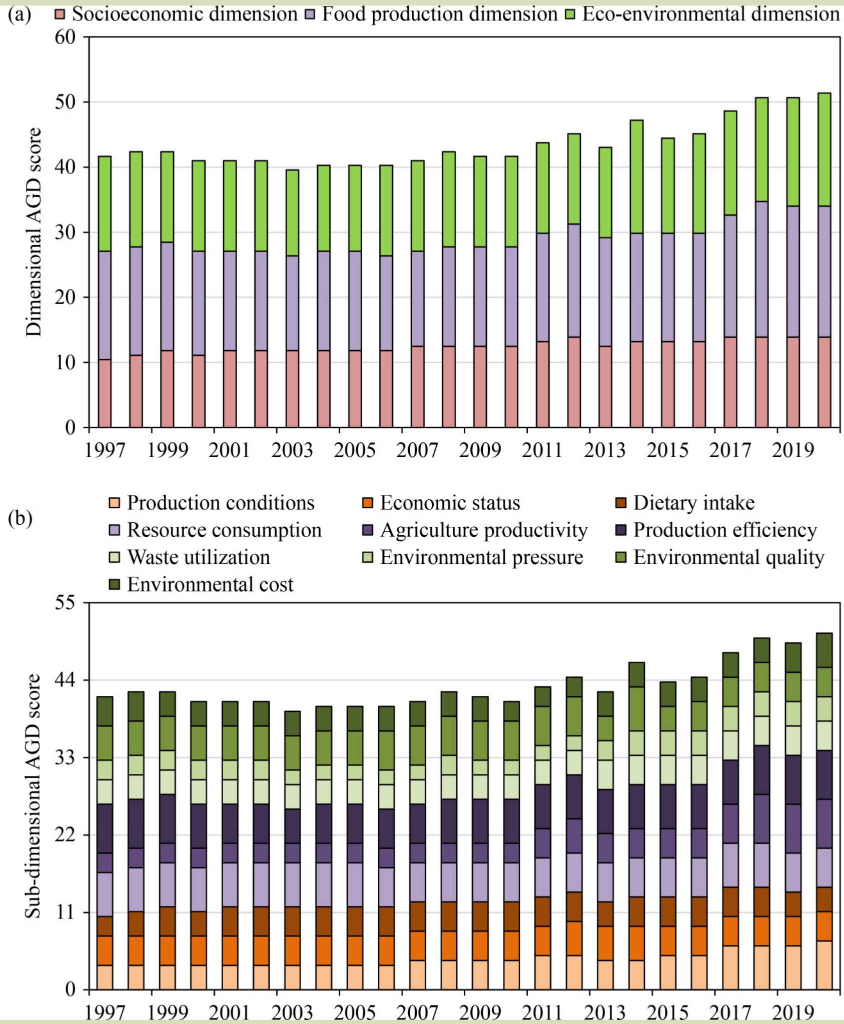


Fig. 3 Dimensional AGD (a) and sub-dimensional AGD (b) scores of China.

quantitatively evaluate agricultural transformation in China. AGD is a pathway that balances development and environmental sustainability through technological progress. Several assessments of agriculture sustainability or the food system have been conducted previously[24,25]; however, the concept of AGD largely remained theoretical rather than quantified[18]. Broadly speaking, AGD is essentially a form of sustainable agriculture model that aims to promote environmental justice. However, there are significant differences between AGD and sustainable agriculture in terms of their guiding principle, challenges and pathways. For example, European nations like Italy, Sweden and Finland have been leaders in organic agriculture, with roughly 15% of land are used for organic production[26]. Although organic farming reduces yield in theory[27], these developed regions prioritize environmental sustainability over high yields. North America has advantages in arable land resource with an arable land area per person of 0.7 ha, consequently, through technology intensification and mechanization, domestic demand for agricultural products can be relatively easily met. Similarly, developed regions with less pressure from population could pursue sustainability through conservation practices such as fallowing and reduce input intensity[28]. In contrast, China, due to its vast rural population, limited and fragmented land, and high population pressure, must prioritize high yields to ensure national food security without sacrificing the income of its rural population. Therefore, AGD represents a unique pathway that, ideally through technological progress, promotes environmental sustainability while ensuring that farm income is not compromised. Further research, however, is necessary to fully comprehend and quantify the theoretical concept of AGD.

Our study aims to evaluate China's agricultural transformation using the methodology for selecting indicators based on Kussul

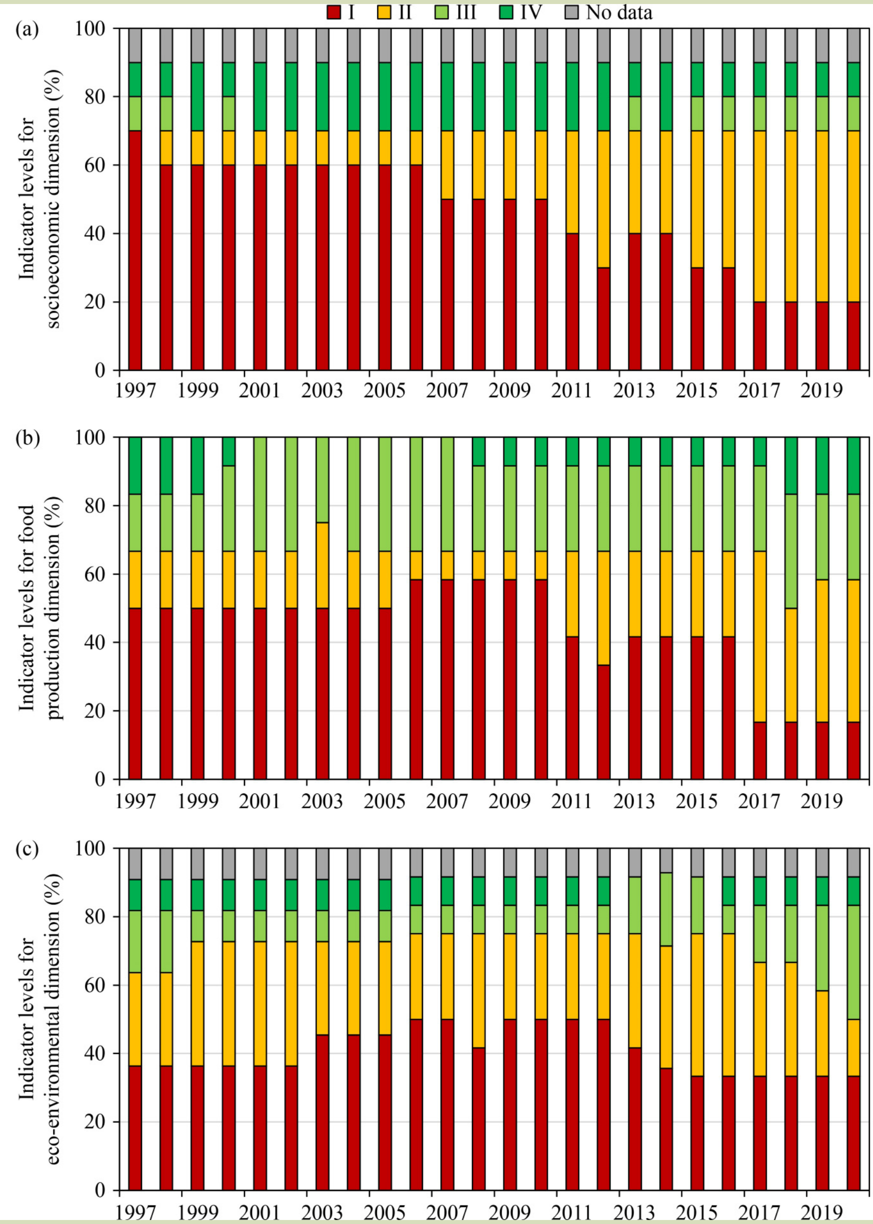


Fig. 4 Historical trends in explicit indicator levels for socioeconomic (a), food production (b) and eco-environmental (c) dimensions of China's AGD from 1997 to 2020. Levels I–IV represent low, moderate, good, excellent levels of AGD.

et al.[23]. While we recognize their limitations, we believe that the indicators we have chosen adequately reflect progress within each dimension. Rather than creating a flawless indicator system, our goal was to develop a national-scale grading system tailored to China's specific context that can accurately reveal trends in agricultural transformation. To make this evaluation better fit China's situation, we have optimized the target values for setting indicators based on China's circumstances. For example, we consider the present state of high-performing provinces as the goal for future development, and this approach makes the goal tangible rather than elusive. Additionally, the evaluation is well-suited to our needs, as it allows us to explore key questions, such as overall trends, which dimensions are most and least developed, and which indicators are being achieved or falling short of their goals. Nevertheless, high food security, low environmental impact and rural prosperity would certainly lead to a high AGD score. A relatively low score is attributable to underdevelopment but also the high standard set for AGD[29]. For example, we have adopted ambitious standards:

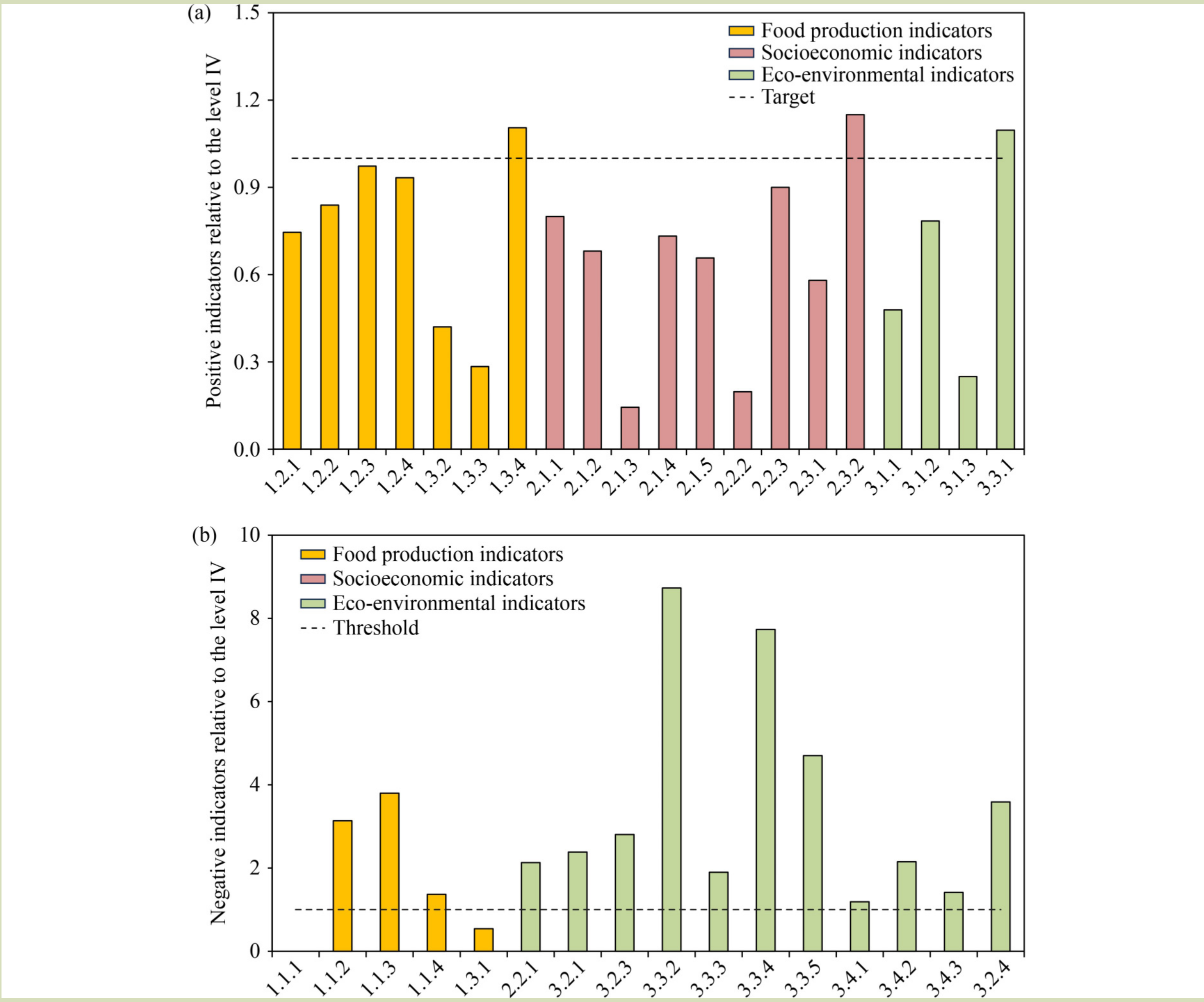


Fig. 5 Status of positive (a) and negative (b) indicators compared to the target values. Indicator codes are given in Table 1.

480 $m^3 \cdot person^{-1} \cdot yr^{-1}$ for the agricultural water footprint from the United Nations, 86,600 $yuan \cdot yr^{-1}$ for farmer income from the World Bank, and less than 1.2 for income equality as occurs in developed countries[30–36]. Nevertheless, while some of the high standards may not be immediately reachable, the overall score effectively reflects progress toward high food security, low environmental impact, and rural prosperity.

It is worth noting that the scope of this study was limited to the national scale, and we have tailored target values to accommodate China's unique circumstances. For other countries, our methods for establishing target values could serve as a guide. In future research, a more detailed indicator system at the regional or provincial scale will be necessary, given that a regional scale indicator system would differ from one applied to a national scale. For example, at the provincial scale, food security may not hold the same importance as other considerations, due to interprovincial trade, factor endowment and comparative advantages. The regional indicators would also require different target values and scoring standards for specific provinces. The eco-environmental dimension, which is particularly sensitive to population pressures, would vary significantly among provinces. In the western mountainous regions of Tibet, for example, ecological value may outweigh food production. A well-designed, transparent methodology is required to optimize indicators more accurately at provincial scale, which is an important future research direction.

4.2 AGD in China: experience, drivers and outlook

This quantitative analysis demonstrates that the AGD score has been gradually increasing since 2010, but it is still far from the high-level standard. Currently, only a few indicators meet the high-level standard, including protein intake, phosphorus use

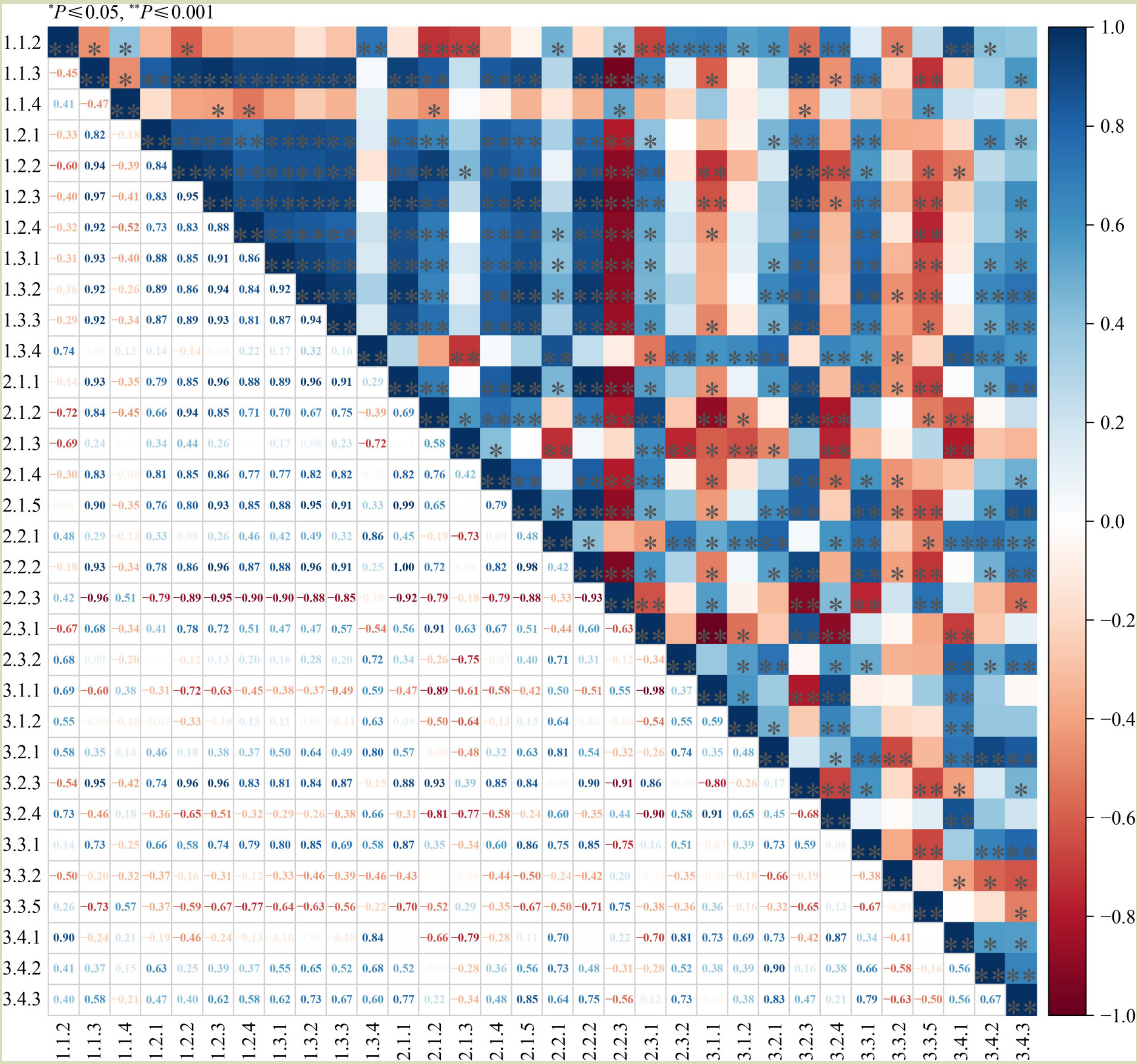


Fig. 6 Spearman-correlation matrix of the AGD indicators system. Indicator codes are given in Table 2.

efficiency, animal waste recycling and energy use efficiency. Overall, China's agricultural model remains relatively traditional, with small-scale farming being the predominant form. To maintain high yields, smallholders often overuse mineral fertilizers, resulting in substantial inputs and losses of nitrogen and phosphorus additions to farmland, leading to low resource use efficiency.

The AGD score has been increasing since 2015 and this transformation is indisputably linked to the increased policy support and financial investment in the agricultural sector. In recent years, the government has implemented development projects aimed at enhancing the quality of arable land, reducing pollution and increasing waste recycling. Notable action plans include the protection and improvement of cultivated land quality (2015), soil pollution prevention and control (2016), straw processing actions in North-east China (2017), and organic fertilizer substitution in fruit, vegetable and tea productions (2017). According to statistical data, the investment in fixed agricultural assets increased by nearly a hundredfold, i.e., from 14 billion to 1.3 trillion yuan, from 1997 to 2020. The High-Standard Farmland Project, an example of this investment, covers 41.7% (53.3 Mha) of China's arable land. It has resulted in a 10% to 20% increase in yield and a 7500 yuan increase in revenue per hectare by reducing irrigation, fertilizer, pesticide and labor inputs, as well as decreasing risks of flood and drought.

Since 2015 when the AGD was first proposed, the Chinese government has implemented a series of policies and key actions that have contributed to the rapid increase in the overall AGD score. For example, in February 2015, the former Ministry of Agriculture introduced the "Action Plans of Zero Increase of Chemical Fertilizer and Pesticide Use by 2020," which was later extended to become the "Action Plan for the Reduction of Chemical Fertilizers and Pesticides by 2025." In May 2017, the former Ministry of Agriculture launched the five actions for AGD, which included measures such as livestock and poultry manure recycling, organic fertilizer substitution in fruit, vegetable and tea production, straw returning in the north-east region, mulching film recycling and Yangtze River aquatic life protection, aimed at reducing input intensity and promoting resource utilization of agricultural waste[37]. Also, in September 2021, the first special plan for AGD was released, providing systematic deployment and specific arrangements for the Fourteenth Five-Year Plan.

AGD has undergone significant historical evolution (Fig. 7). The Thirteenth Five-Year Plan in 2015 emphasized the importance of the environment for sustainable development and global ecological security, and called for adherence to the national policy of resource conservation and environmental protection [38]. In 2016, the No. 1 Central Document included the promotion of AGD for the first time, proposing to strengthen resource protection and ecological restoration. The concept of AGD was further developed in official documents and policies [39], including opinions on innovating systems and mechanisms to promote AGD from the General Office of the CPC Central Committee and the General Office of the State Council in 2017. The opinions made a significant emphasize on ensuring national food security, resource security, and ecological security [40]. Later in the year, the first batch of national pilot areas were launched with the aim to build a comprehensive platform and to promote AGD at a national scale. The next year, the government effected the regional implementation, emphasizing on ecological protection and high-quality development in the Yangtze River Economic Belt (2018) and the Yellow River Basin (2020). In 2022, the No. 1 Central Document highlighted the importance of AGD in promoting rural development and synchronously enhancing ecological environment production and industrial development. Overall, China's AGD actions can be categorized into three phases: concept proposal, initial exploration and regional implementation (Fig. 7). AGD has become an important research topic in exploring the pathway of high-quality and sustainable agricultural development in China.

Future agricultural development must take action to break the trade-off relationship among dimensions and improve the less

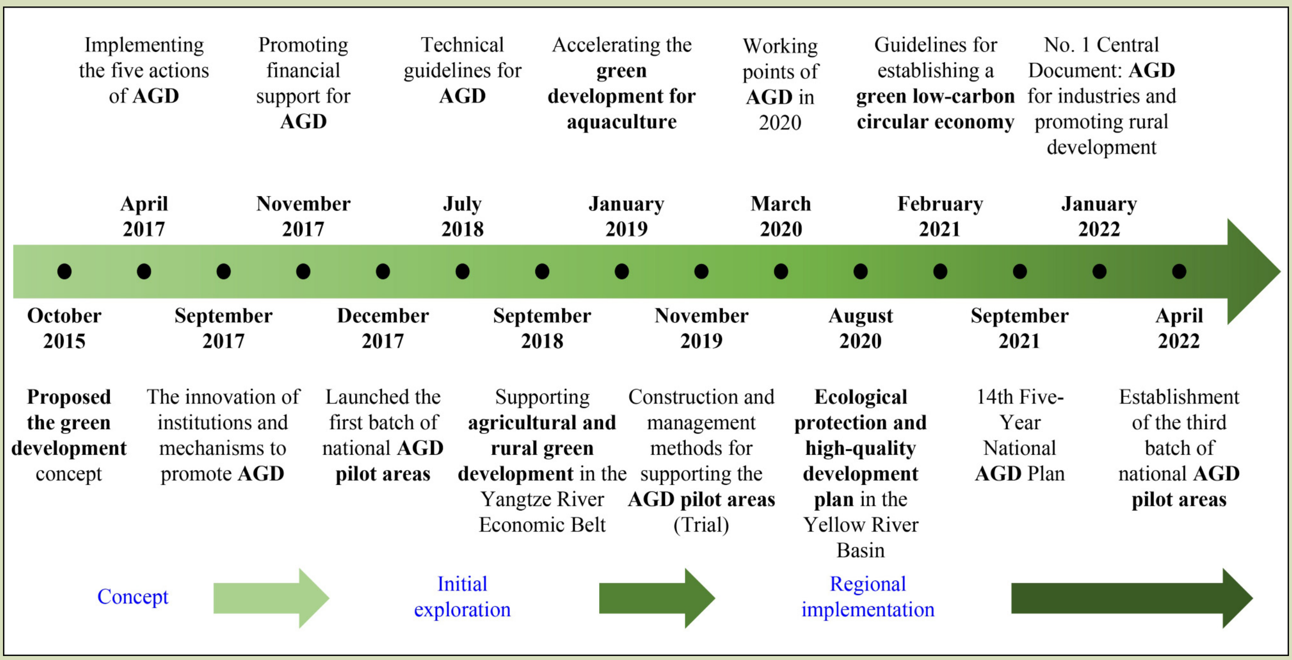


Fig. 7 Policies and key actions in China's agriculture green development (AGD).

developed indicators. The Spearman-correlation matrix (Fig. 6) highlights a trade-off relationship between the eco-environmental dimension and the other two dimensions, possibly due to the increasing demands from population, economic and urban growth, which puts pressure on agricultural production and negatively impacts the environment. Specifically, air quality (3.3.5), GHG emissions (3.4.3) and ammonia emissions (3.4.1) are significantly and negatively correlated with most socioeconomic indicators. This pattern indicates a coupling relationship between air pollutants and economic growth, and the emissions can also damage the living environment and have negative impacts on socioeconomic conditions [41]. Additionally, surface water quality (3.1.1) and air quality (3.3.5) are in a trade-off relationship with most of the food production indicators, as food production consumes resources and has negative impacts on the environment. It is crucial for China to overcome these trade-offs and prioritize water and atmospheric protection to achieve coordinated development among the three dimensions. Some potential measures include improving agricultural resource use efficiency, tracing agricultural pollution sources, implementing atmospheric environment governance plans and effecting watershed non-point pollution control.

To drive the agricultural green transformation, more attention should be given to underperforming indicators. Figure 5 highlights significant gaps from target values for rural education (2.1.3), farmer income (2.2.2), animal nitrogen use efficiency (1.3.3) and plastic film recycling (3.1.3), while groundwater quality (3.3.2) and soil heavy metal pollution (3.3.4) have exceeded their thresholds by more than 7.5 times. These indicators and their sub-dimensions should be prioritized for improvement. Currently, the AGD score remains at a moderate level, indicating the need for targeted focus in future development. To achieve this, increasing agricultural investment, agricultural technology implementation and promoting agricultural extension are crucial to boost rural economic development. The exploration and promotion of new agricultural systems, such as a coupled animal-crop production system that improves waste recycling and resource utilization, are also essential. Additionally, a greater emphasis is needed on the protection of soil, water, and atmospheric environments to achieve coordinated development with ecological environment protection.

5 Conclusions

AGD represents a vital transformation pathway for China to achieve sustainable development, provide affordable and nutritious food and elevate living standards. In this study, we assessed historical trends and status of agriculture in China by establishing an indicator evaluation system. The results showed an increasing AGD score since 1997 with continued improvement after 2010. In 2020, 8.3% of indicators have reached the target level, while 63.7% of indicators remained at a low or moderate level. A synergistic relationship between socioeconomic and food production, and a trade-off relationship between eco-environmental and the other two dimensions were revealed. Overall, China's agricultural transformation is moving in the right direction. Future development will require systematic coordination among socioeconomic, food production and eco-environmental systems to reduce the unbalanced development and trade-off.

Supplementary materials

The online version of this article at https:doi:org/10.15302/J-FASE-2023512 contains supplementary material (Table S1).

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Compliance with ethics guidelines

Haixing Zhang, Yuan Feng, Yanxiang Jia, Pengqi Liu, Yong Hou, Jianbo Shen, Qichao Zhu, and Fusuo Zhang declare that they have no conflicts of interest or financial conflicts to disclose. All applicable institutional and national guidelines for the care and use of animals were followed.

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