RESEARCH ARTICLE

Comparison of indicators for agricultural green development and the Sustainable Development Goals, and mapping the way forward

Jianjie ZHANG[1,2], Xiangwen FAN (✉)[3], Ling LIU[3], Lin MA[3], Zhaohai BAI[3], Wenqi MA (✉)[1]

1 College of Resources and Environmental Sciences, Hebei Agricultural University, Baoding 071001, China.
2 College of Resources and Environment, Shanxi Agricultural University, Taiyuan 030031, China.
3 Center for Agricultural Resources Research, Institute of Genetics and Development Biology, Chinese Academy of
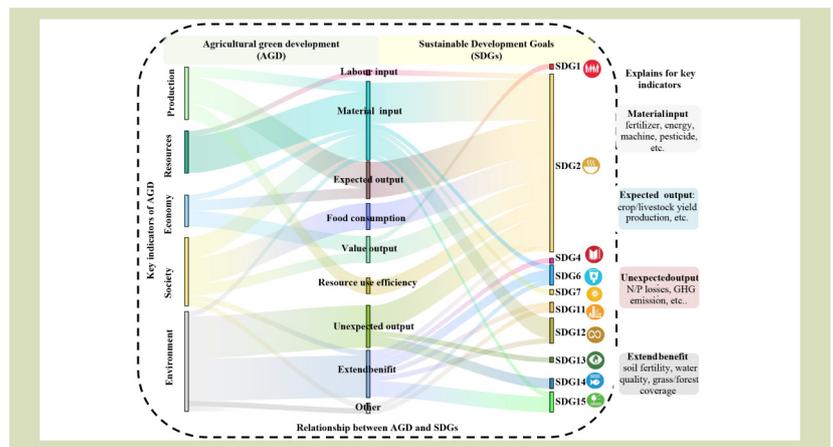 Sciences, Shijiazhuang 050022, China.

HIGHLIGHTS

● Relationships between agricultural green development (AGD) and 10 UN SDGs are presented.

● Historical changes and characteristics of AGD in China are analyzed.

● Knowledge gaps in AGD indicators in China are identified.

GRAPHICAL ABSTRACT

ABSTRACT

While agricultural green development (AGD) is highly recognized and has become a national strategy in China, it is imperative to bridge the knowledge gaps between AGD and the UN Sustainable Development Goals (SDGs), and to evaluate the contribution of AGD to meeting the SDGs. The first aim of this study was to compare the AGD goals and indicators with those of the SDGs so as to identify their relationship. The next aim was to examine the historical evolution of AGD indicators and analyze the gaps between the current status of various indicators and their benchmarks. Limiting factors were identified in China's transition toward AGD. These findings reveal that the indicators of AGD align with those of the SDGs, but have greater specificity to the context in China and are more quantifiable. There has been a significant increase per capita calorie and protein intakes in China, as well as a notable rise in agricultural output per unit of arable land and rural incomes from 1980 to the 2010s. However, these achievements have been accompanied by a high resource use and environmental pollution, highlighting the need for a more sustainable, environmentally responsible agriculture in China.

1   Introduction

The Green Revolution was pivotal for enhancing agricultural productivity, addressing food security challenges and mitigating rural poverty. However, it has also led to significant environmental risks due to increased use of pesticides and fertilizers, and to public health concerns due to micronutrient imbalance[1]. With the ongoing surge in global population, the strain on resources and the environment is set to intensify[2], raising issues like climate change, land use alteration, biodiversity loss and the depletion of freshwater resources[3]. These challenges, transcending national borders, demand a unified response from the international community. The UN Summit on Sustainable Development in Rome in 2015 established Agenda 2030 and the 17 Sustainable Development Goals (SDGs), which encompass a broad spectrum of global objectives[4], including eradication of poverty, ensuring food safety, providing clean water and sanitation and taking climate action. Given central role of agriculture in these goals, its sustainable advancement is imperative for achieving many SDGs and the overall sustainability of the planet[5].

The agriculture sector in China faces unique challenges compared to its developed counterparts, grappling simultaneously with ensuring food security and tackling environmental issues. Despite having only 8% of the global arable land, China supports 20% of the global population[6] and is the largest producer and consumer of animal products[7]. In 2017, about 30% of the total amount of nitrogen fertilizers produced in the world were applied to croplands in China[8]. The large nitrogen and phosphorus fertilizer use has led to soil acidification[9], water eutrophication[10] and increased nitrogen deposition[11]. In response, agricultural green development (AGD) has emerged as a sustainable model, attracting significant attention, as AGD focuses on securing food supply through enhanced production efficiency, minimizing environmental impacts, and fostering social sustainability[12]. To advance AGD and address its challenges faced in agricultural production, Chinese Government has implemented several strategic plans, including the National Agricultural Sustainable Development Plan (2015–2030), the Opinions on Innovative System Mechanisms to Promote Green Development of Agriculture, the Technical Guidelines for Agricultural Green Development (2018–2030), and the Fourteenth Five-Year National Agricultural Green Development Plan. These plans delineate China's objectives and strategies at various levels, directing agricultural modernization and the development of the food industry toward a comprehensive national food security strategy. Also, scholars have assessed the historical characteristics of agricultural green production in China, focusing on aspects like supply capacity, resources utilization, environment quality, ecosystem maintenance and farmer livelihoods[13]. They have compared AGD objectives and policy approaches between China and the UK[14], and discussed the necessity of AGD in balancing food security with carbon reduction under dual carbon goals in China[15]. However, the connections between AGD and the SDGs, and the knowledge gaps in achieving AGD in China remain areas that need further exploration. An explorative analysis would help measure the correlation between the SDGs and national-level AGD policies in China, thereby identifying overlaps and potential differences. Such comprehensive analysis could guide China in better aligning its national development goals with the global sustainable development agenda while pursuing them simultaneously.

In this study, we begin by elucidating the conceptual parallels and differences between AGD and SDGs, drawing on existing literature. We then qualitatively demonstrate how AGD in China represents a tangible implementation of SDGs within Chinese context, achieved through a comparative analysis of their respective indicator systems. This is followed by a quantification of the historical evolution of AGD in China. Subsequently, we identify the primary challenges for AGD in China by examining the knowledge gaps in the AGD indicator system. The findings of this research are not only pertinent to China but also hold significant value for other developing countries worldwide.

2   Materials and methods

Government plans for AGD in China primarily focus on the sustainable transformation and modernization of the agricultural sector, aiming to enhance agricultural productivity, reduce environmental impact and promote ecological balance. Similarly, the SDGs encompass specific targets addressing the agricultural sector, such as ending hunger, achieving food security and promoting sustainable agriculture.

Earlier, a comprehensive indicator system for AGD in China was developed, which encompassed five aspects: social development, economic growth, agricultural production, resource input, and ecological environment[16]. Each of these aspects has been meticulously defined with clear targets and grading standards (as shown in Table S1)[16]. Building on this indicator system framework, we have performed a detailed one-to-one comparative analysis between the AGD indicator system and that of the SDGs, offering a nuanced understanding of their interrelations and alignments.

2.1 Data sources

2.1.1 Sources of the SDGs indicators and AGD indicators

We sourced the official definitions of the SDGs indicators directly from the UN website[17]. This resource offers comprehensive explanations for each SDG indicator. Additionally, detailed descriptions and calculations for each indicator and sub-indicator can be found in the official metadata provided by the UN[18]. This authoritative information forms the foundation of our analysis and understanding of the SDG framework.

To evaluate the progress of AGD in China, we built on the earlier developed AGD indicator system (Table S1)[16]. The foundational data for all indicators within this system were meticulously gathered from several authoritative sources. This included the National Bureau of Statistics of China covering 1981 to 2018, the China Rural Statistics Yearbook for the same period, the China Environmental Statistics Yearbook for 1981 to 2018, and the FAO database as of 2020. This comprehensive data collection enables a robust and detailed assessment of AGD in China.

2.1.2 Calculation methodology for the AGD indicators

The calculation of food production, resource use and environmental pollution indicators in our study hinged on material flows and nutrient balances throughout the stages of food production, processing and consumption. To this end, we employed the NUFER model[19]. This model facilitates the calculation of regional resource inputs, utilization efficiency, productivity levels and losses to the environment. Key aspects of this analysis include nitrogen inputs to cropland, N harvests in crop and livestock systems, N use efficiency (NUE) and N surpluses in these systems, N runoff to surface water, N leaching to groundwater and the volatilization of ammonia from crop and livestock systems. The evaluation of social and economic indicators was based on comprehensive statistical data. The detail calculation process for each indicator is thoroughly documented in the referenced literature[16].

2.2 Data processing

To address the issue of missing data in specific indicators, we devised a time series model. This approach enabled us to estimate and subsequently fill in the gaps in our data set, particularly for indicators like pesticide usage and agricultural film consumption over various time periods. Beyond the time series modeling, we also implemented a weighted average interpolation method for handling missing data in intermediate years. We assigned equal weight to the data from the year before and the year after the missing year, to derive a well-balanced estimate for those years with missing data.

To maintain consistency in the economic indicators over various years, the data were adjusted for inflation and to neutralize the effects of price changes. To achieve this, we established 1980 as the baseline year for constant prices. For precise adjustments, we utilized the gross domestic product (GDP) deflator index. This allowed us to effectively convert per capita real GDP and agricultural output values into constant price indicators, ensuring an accurate comparison over time. To address the changes in living costs, we also applied the consumer price index from rural areas. This enabled us to accurately recalibrate per capita disposable income and consumption expenditure into constant price terms, providing a clear and consistent financial perspective across different time periods.

2.3 Data normalization

Considering the diverse nature of the data types and sources used in this study, indicators were standardized and transformed into a uniform, dimensionless scale ranging from 0 to 100. This normalization process mitigated the impact of scale variations among different indicators. Indicators that contributed positively to AGD progress were classified as positive indicators. Conversely, indicators that impeded AGD progress were identified as negative indicators. To achieve this standardization, we used Eq. (1) for the normalization of positive indicators and Eq. (2) for the normalization of negative indicators. This approach ensured a consistent and comparable evaluation across all indicators.

$$Y_{ij} = (x_{ij} - \min x_j)/(\max x_j - \min x_j) \times 100 \qquad (1)$$

$$Y_{ij} = (\max x_j - x_{ij})/(\max x_j - \min x_j) \times 100 \qquad (2)$$

where, x_{ij} is the value of variable x_j in the year i, $\min x_j$ is the lowest value of x_j across the entire date series, $\max x_j$ is the highest value of x_j in the same series, and, following normalization, Y_{ij} is the value of the data, scaled from 0 to 100. This framework allows for a standardized and coherent representation of indicators over time, ensuring consistency and comparability across all assessed years.

2.4 Comparative analysis of the AGD and the SDG indicator systems

Understanding the alignment between AGD and the SDGs is essential for recognizing the contribution of AGD to the SDGs. To determine this alignment, we followed a structured

72

Front. Agr. Sci. Eng. 2024, 11(1): 69–82

approach. The initial step involved compiling a comprehensive list of SDG indicators, with a particular focus on those relevant to sustainable agricultural development and food systems. We then examined the specific meanings and calculation methods of these selected indicators. The subsequent step was to establish a direct correspondence between the AGD indicators and the relevant SDG indicators. This part of the process required an in-depth comparative analysis, focusing on several critical aspects. These included the definition of the indicators, the challenges in data acquisition, the target values for each indicator and their quantification in relation to the AGD indicator system. This approach ensured a thorough and insightful alignment analysis between AGD and the SDGs.

3   Results

3.1   Comparison of AGD and the SDGs indicator systems

The AGD indicator system represents an advanced evolution and refinement of the agricultural sustainable development indicators found within the SDG framework. The AGD indicator system is notable for its exceptional alignment with the specificities of agricultural progress in China. This congruence is prominently reflected in the accessibility of data, as well as the specificity and pertinence of the indicators chosen. These factors collectively enhance the process of quantifying and evaluating advancements in China toward realizing AGD objectives. The tailored design of this system ensures a precise measurement of progress, attuned to the unique context of the Chinese agricultural landscape.

This newly developed AGD indicator system encompasses a total of 53 indicators, each exhibiting a robust alignment to the SDG indicators. In terms of their objectives, 10 of the 17 SDG goals bear relevance to AGD, as indicated in Table 1. Compared to the SDG indicator system, the AGD indicators are characterized by greater accessibility, specificity and quantifiability. This makes them particularly effective for detailed and precise assessments, aligning closely with the requirements and targets of AGD.

In comparison to the SDG indicator framework, the data required for calculating indicators of AGD are more readily accessible. For example, SDG 2.1.1 that aims to gauge the prevalence of undernourishment by estimating the proportion of the population with insufficient food consumption for a healthy and active life. While this is a valuable measure, it necessitates extensive research and is expressed as a percentage, on the basis of parametric probability density function. In

contrast, AGD has three distinct indicators to assess undernourishment: mean per capita calorie intake, mean per capita protein intake and the mean proportion of animal protein in the diet. These indicators collectively provide a comprehensive view of the mean regional nutritional levels, encompassing calorie consumption, nutritional quality and dietary structure[23], but they do not provide insight in the variation in consumption level among people within regions. Significantly, data on per capita consumption of grains, vegetables and fruits at provincial and national levels can be easily sourced from yearbooks.

Also, AGD indicators are often more specific. For example, SDG 2.4.1.1 focuses on farm output value per hectare, encompassing various agricultural outputs. Building on this, AGD has defined more precise indicators such as agricultural value added per unit area, calorie and protein production per unit area, and protein production per unit of livestock.

Finally, AGD indicators are simpler to quantify than those of the SDGs. Consider SDG 2.4.16, which emphasizes the management of fertilizers and outlines eight criteria for assessing fertilizer pollution risks. However, obtaining all this data for China is challenging, and the scoring system is semiquantitative, resembling a red-yellow-green system. In contrast, AGD employs a material flow-based approach, utilizing the NUFER model to quantitatively analyze the entire process. This includes nitrogen inputs, surpluses, utilization efficiencies and losses to the environment, thereby offering a more comprehensive and quantifiable evaluation of the agriculture impact on the environment.

Our approach to data acquisition for AGD indicators was to prioritize three distinct methods. Firstly, we utilize official statistics, which provide the most authoritative and straightforward data source. Secondly, we incorporate statistical data in conjunction with modeling techniques, offering a relatively accessible method for data interpretation and analysis. Lastly, extensive field research is considered, although it is acknowledged as the most challenging approach due to its resource-intensive nature. Our methodology primarily focused on the first two methods, leveraging their ease of use and reliability to inform our indicators effectively.

3.2   Characterization of agriculture transition in China

China has made significant progress in its agriculture sector. The rapid growth has successfully satisfied national food requirements. A detailed illustration of this agricultural

Table 1 Comparison of agricultural green development (AGD) and Sustainable Development Goals (SDGs) indicator systems

SDGs				AGD		Optimization	
Goal	SDG indicator	Theme	Sub-indicator	AGD category	AGD indicator	Explanation	Improvement
Goal 1 No poverty	SDG 1.1.1a Proportion of the population living below the international poverty line by sex, age, employment status and geographic location (urban/rural)			Economy	GDP per capita	GDP per capita is often used to measure a country's poverty level.	● ■ ▲
Goal 2 End hunger	SDG 2.1.1 Prevalence of undernourishment			Society	Per capita calorie consumption	We have enriched this indicator in terms of calories, protein, and dietary structure, these indicators can all be calculated using the NUFER-AGD simulation	● ■ ▲
					Per capita protein intake		● ■ ▲
					Proportion of animal protein in protein intake		● ■ ▲
					Level of food industrialization		■ ▲
	SDG 2.1.2 Prevalence of moderate or severe food insecurity in the population, based on the Food Insecurity Experience Scale (FIES)			Society	Food self-sufficiency rate		● ■ ▲
	SDG 2.3.1 Volume of production per labor unit by classes of farming/pastoral/forestry enterprise size			Resources	Labor input per unit cultivated land		● ■ ▲
				Society	Agricultural mechanization level		● ■ ▲
	SDG 2.4.1 Proportion of agricultural area under productive and sustainable agriculture	1 Land productivity	Farm output value per hectare	Economy	Agricultural output value per unit cultivated land area[20]	The definition of SDG 2.4.1 includes economy and productivity, and we have further refined it. In terms of economy, it is quantified through agricultural added value per unit area, while in terms of productivity, it includes calories and proteins from plant production systems, and animal systems are characterized by proteins	● ■ ▲
					Percentage of agricultural output value in GDP[21,22]		● ■ ▲
				Production	Caloric production per unit cultivated land		● ■ ▲
					Protein production per unit cultivated land		● ■ ▲

(Continued)

SDGs				AGD		Optimization	
Goal	SDG indicator	Theme	Sub-indicator	AGD category	AGD indicator	Explanation	Improvement
					Protein production per livestock unit		● ■ ▲
					Vegetable yield		● ■ ▲
					Fruit yield		● ■ ▲
		2 Profitability	Net farm income	–	–	The focus of this sub-indicator is on income from farming operations，however, limited by the access to data, we define the "Rural disposable income" for SDG 2.4.1.9 instead of it	–
		3 Resilience	Risk mitigation mechanisms	–	–		–
		4 Soil health	Prevalence of soil degradation	Environment	Soil organic matter		● ■ ▲
					Modulus of soil erosion		● ■ ▲
		5 Water use	Variation in water availability	Resources	Irrigation water use intensity[20]		● ■ ▲
				Environment	Footprint of agricultural water		● ■ ▲
		6 Fertilizer pollution risk	Management of fertilizers	Resources	N use intensity[20-22]	SDG 2.4.1.6 used a questionnaire survey to qualitatively describe, and based on the material flow model, we conducted quantitative analysis from resource input to environmental emissions, these indicators can be obtain directly from statistical yearbooks or calculated by NUFER-AGD simulation	● ■ ▲
					P use intensity[19,20,23]		● ■ ▲
				Production	N use efficiency in crop systems		● ■ ▲
				Production	N use efficiency in animal systems		● ■ ▲
				Production	N use efficiency in food systems (NUEf)		● ■ ▲
				Environment	N surplus[21]		● ■ ▲
				Environment	NH_3 emission		● ■ ▲
				Environment	Reactive N losses per unit food N		● ■ ▲
		7 Pesticide risk	Management of pesticides	Resource	Pesticides use intensity[19,20,23]	Data from earlier periods are less readily available	■ ▲

(Continued)

SDGs				AGD		Optimization	
Goal	SDG indicator	Theme	Sub-indicator	AGD category	AGD indicator	Explanation	Improvement
		8 Biodiversity	Use of agro-biodiversity-supportive practices	–	–		
		9 Decent employments	Wage rate in agriculture	Economy	Rural disposable income[19,20,22]		● ■ ▲
		10 Food security	Food Insecurity Experience Scale (FIES)	Society	Rural Engel coefficient[20]		● ■ ▲
		11 Land tenure	Secure tenure rights to land	Society	Per capita arable land[20]		● ■ ▲
				Society	Proportion of land transfer		● ■ ▲
	SDG 2.a.1 The agriculture orientation index for government expenditures			Economy	Proportion of agricultural financial investment		● ■ ▲
Goal 4 Quality education	SDG 4.1.2 Completion rate (primary education, lower secondary education, upper secondary education)			Society	Education level of agricultural population[20]		● ■ ▲
Goal 6 Clean water and sanitation	SDG 6.3.2 Proportion of bodies of water with good ambient water quality			Environment	Surface water quality		● ■ ▲
				Environment	Ground water quality		● ■ ▲
	SDG 6.4.2 Level of water stress: freshwater withdrawal as a proportion of available freshwater resources			Society	Irrigation level of farmland[19,22]		● ■ ▲
				Environment	Rural sewage treatment rate		■ ▲
Goal 7	SDG 7.3.1 Energy intensity measured in terms of primary energy and GDP			Resource	Energy consumption per unit agricultural output value		● ■ ▲
Goal 11 Sustainable cities and communities	SDG 11.3.1 Ratio of land consumption rate to population growth rate			Social	Urbanization rate		● ■ ▲
	SDG 11.6.2 Annual mean levels of fine particulate matter (e.g., PM2.5 and PM10) in cities (population weighted)			Environment	Atmosphere quality		■ ▲
					Ecological environment quality		●
Goal 12 Responsible consumption and production	12.4.1 Number of parties to international multilateral environmental agreements on hazardous waste, and other chemicals that meet their commitments and obligations in transmitting information as required by each relevant agreement			Resource	Antibiotic input per livestock unit		● ■ ▲

							(Continued)
SDGs				**AGD**		**Optimization**	
Goal	SDG indicator	Theme	Sub-indicator	AGD category	AGD indicator	Explanation	Improvement
				Environment	Agricultural film use intensity[20]		● ■ ▲
					Livestock capacity per unit cultivated land		● ■ ▲
	SDG 12.5.1 National recycling rate, tons of material recycled			Production	Manure recycling rate		● ■ ▲
				Production	Straw recycling rate		● ■ ▲
				Environment	Rural waste treatment rate		● ■ ▲
Goal 13 Climate action	SDG 13.2.2 Total greenhouse gas emissions per year			Environment	Agriculture greenhouse gas emissions		■
Goal 14 Life below water				Environment	N leaching		● ■ ▲
				Environment	N runoff		● ■ ▲
Goal 15 Life on land	SDG 15.1.1 Forest area as a proportion of total land area			Environment	Forest coverage rate[21,24]	Based on the actual situation, we also considered grassland coverage in pastoral and semi-pastoral areas	● ■ ▲
				Environment	Grass coverage rate[21,24]		● ■ ▲

Note: Solid circles (●) indicate improvements in obtaining data, solid squares (■) indicate improvement in specificity of the indicator and has clear target value, and solid triangles (▲) indicate improvements in quantifiability.

evolution is presented in Fig. 1. From the 1980s to the 2010s, there was a substantial increase in the mean per capita calorie intake in China, rapidly rising from 2358 to 3130 kcal·d⁻¹ per person as shown in Fig. 1(d). In tandem, the mean per capita protein intake effectively doubled, from 53 to 101 g·d⁻¹ per person from the 1980s to the 2010s. Concurrently, there was a significant shift in dietary patterns, with the mean proportion of animal protein in total protein intake dramatically increasing from 15% to 40% as shown in Fig. 1(e).

Over the past 40 years, Chinese agriculture has undergone a remarkable economic transformation, particularly in rural areas. When adjusted for inflation, the total output value per unit of arable land in agriculture in the 2010s rose to 1.38×10^4 yuan, which marks a 7.7 times increase since the 1980s, as shown in Fig. 1(f). This growth reflects an impressive average annual rate of 5.0%. Concurrently, there has been a significant rise in the income of rural residents. After adjusting for price factors, the per capita disposable income of rural residents in the 2010s grew at an average of 7.0% per year, reaching 1662 yuan per person (Fig. 1(g)), an increase of 5.7 times since the 1980s.

The Engel coefficient for rural residents, which measures the proportion of income spent on food, has decreased by 22 percentage points since the 1980s, settling at 36% in the 2010s (Fig. 1(h)). This decline is a clear indicator of the shift from poverty toward relative prosperity among rural populations. The spending habits of rural residents have gradually elevated, nearing the moderate prosperity threshold of 20% to 30% as defined by the UN[13].

Another striking development in the changing role of agriculture in overall economy of China is the decrease in the relative agricultural output value. In the 2010s, the agricultural output value constituted 13% of GDP in China, a stark contrast to the 42% recorded in the 1980s. This trend underscores the need for the government to further strengthen its support and safeguard the agriculture sector, ensuring its sustainable growth and continued contribution to the national economy.

Over the past 40 years, agricultural production performance in China has shown a remarkable upward trend, as evidenced by the increasing yields in both crop and livestock production. In the 2010s, the calorie production per unit of arable land was 1.9
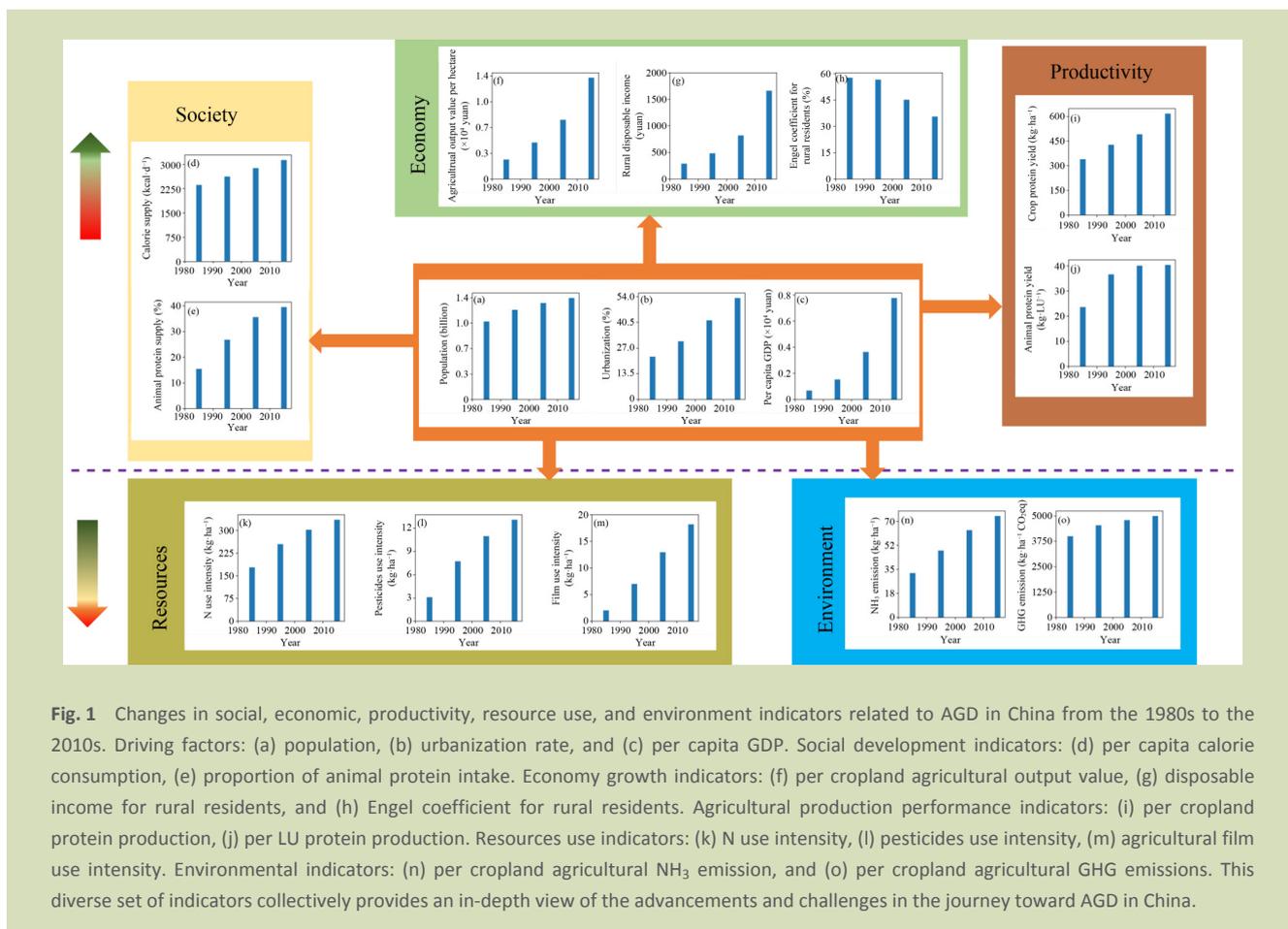
Fig. 1   Changes in social, economic, productivity, resource use, and environment indicators related to AGD in China from the 1980s to the 2010s. Driving factors: (a) population, (b) urbanization rate, and (c) per capita GDP. Social development indicators: (d) per capita calorie consumption, (e) proportion of animal protein intake. Economy growth indicators: (f) per cropland agricultural output value, (g) disposable income for rural residents, and (h) Engel coefficient for rural residents. Agricultural production performance indicators: (i) per cropland protein production, (j) per LU protein production. Resources use indicators: (k) N use intensity, (l) pesticides use intensity, (m) agricultural film use intensity. Environmental indicators: (n) per cropland agricultural NH_3 emission, and (o) per cropland agricultural GHG emissions. This diverse set of indicators collectively provides an in-depth view of the advancements and challenges in the journey toward AGD in China.

times larger than that of the 1980s, achieving a mean of 190 million kcal·ha^{-1}. Similarly, protein production per unit of arable land increased by a factor of 2.2 times since the 1980s, and reached a mean of 617 kg·ha^{-1} in the 2010s (Fig. 1(i)). The animal husbandry sector also witnessed notable enhancements, with protein production per livestock unit (LU) growing annually by 2.4% to reach 40.4 kg·LU^{-1} in the 2010s, which was 2.5 times higher than that of the 1980s (Fig. 1(j)).

The NUE in crop systems (NUEc) slightly decreased from a mean of 45.5% in the 1980s to a mean of 44.6% in the 2010s. Over the time span from the 1980s to the 2010s, the NUE in animal systems (NUEa) exhibited a steady rise, from 8.1% to 17.3%. Vegetable yields have increased at an average annual rate of 1.1%, climbing from a mean 27 t·ha^{-1} in 1995 to a mean of 35 t·ha^{-1} in 2017. Fruit yields increased on average by 4.8% per year, from 4 t·ha^{-1} in the 1980s to 23 t·ha^{-1} in 2017. These developments collectively highlight the significant strides made in the agricultural sector in China, showcasing the increased productivity.

However, these achievements have come with the trade-off of

high input of resources. There has been an excessive N usage in crop production. The N use intensity per unit of cropland increased by a factor of 2, from a mean of 178 kg·ha^{-1} in the 1980s to a mean of 335 kg·ha^{-1} in the 2010s (Fig. 1(k)). In parallel, the mean intensify of pesticide use increased by 5.5% per year, reaching 13.1 kg·ha^{-1} in the 2010s (Fig. 1(l)). The usage of agricultural film increased 18.6 times between the 1980s and the 2010s, peaking at 18.7 kg·ha^{-1} in the 2010s (Fig. 1(m)). These figures underscore the growing concern over the sustainability of agriculture practices in China, highlighting the need for more efficient and environmentally friendly approaches.

Interesting, essentially all environmental indicators followed a single peak curve, with the turning point around 2015. This pattern resembles that of the environmental Kuznets curve[25]. The N surplus in the crop production systems increased from a mean of 92 kg·ha^{-1} in the 1980s to a mean of 184 kg·ha^{-1} in the 2010s. This surge is primarily attributed to increased N inputs in crop production. The excessive N input has amplified NH_3 and N_2O emissions into the atmosphere, and has exacerbated water pollution, which in turn elevated the risk of

78

Front. Agr. Sci. Eng. 2024, 11(1): 69–82

eutrophication of surface waters and the contamination of drinking water.

In the same time frame, mean N runoff doubled, climbing from 16 to 32 kg·ha^{-1}. Similarly, mean N leaching doubled from 10 to 19 kg·ha^{-1}. Volatilization of NH_3 from the entire food production process increased from 30 to 74 kg·ha^{-1} (Fig. 1(n)). Greenhouse gas (GHG) emissions from agriculture increased over the past 40 years from 4346 to 4999 kg·ha^{-1} CO_2eq. These trends clearly underscore the urgent need for mitigating the environmental impacts of agricultural production.

3.3 Analysis of the gap in progress of AGD indicators in China

The analysis of the gaps in progress of AGD indicators reveals that China has effectively addressed its food security issues, as illustrated in Fig. 2. In 2017, mean calorie consumption reached 106% of the targeted value (3000 kcal·d^{-1} per person), while mean protein intake was 170% of the target (59.7 g·d^{-1} per person). These numbers affirm that food production in China successfully meets its basic demand. Additionally, the food self-sufficiency rate, indicated by the food N content, reached the 100% mark. The mean proportion of animal protein in total protein consumption in 2017 was 71% of the target value (56%), indicating a gap in per capita animal protein intake.

The agricultural mechanization currently stands at 64% of the target value (11.5 kW·ha^{-1}) as shown in Fig. 2. This indicates that the level of support for agricultural mechanization is insufficient and points toward a need for enhanced investment and development in the sector. The Engel coefficient for rural households was at 94% of the target value (30%) in the 2010s, which indicates that the living standards of rural residents are approaching the level of affluence as defined by the UN[13]. This indicator reflects the material quality of life and reduced need for expenditure on basic necessities like food. However, the proportion of the agricultural output value in national GDP was only 26% of the target value (2%). This disparity highlights a need for a more diversified economic approach to better distribute economic growth across various sectors, ensuring a more sustainable and balanced development trajectory for the county.

Although China has made substantial progress in agricultural production over recent decades, there remains a notable gap when compared to the efficiencies achieved in developed countries in Europe and North America. Specifically, NUEc in China currently stands at 71% of the target value (63%), while NUEa is at 81% of the target (20%). Additionally, the yield of vegetables in China is only 39% of the target value (58 t·ha^{-1}). These figures indicate that there is still considerable room for improvement and optimization in the agricultural sector in China.

Given the constraints of limited land resources, China has heavily invested in the use of fertilizers, pesticides and agricultural film to sustain its food production. As a result, nutrient efficiency is low. The intensity of pesticides use per unit cropland area cropland is much higher than the target value (2.5 kg·ha^{-1}). The N surplus is also much higher than the target value (80 kg·ha^{-1}). The same applies to N leaching, which has a target value of 7.6 kg·ha^{-1}. GHG emissions from agriculture are also higher than the target value (3570 kg·ha^{-1} CO_2eq), as depicted in Fig. 2. These figures underscore the need for more effective management of agricultural inputs and a greater focus on improving resources use efficiency.

4 Discussion

4.1 Conceptual similarities and differences between AGD and the SDGs

AGD in China and the SDGs share common conceptual roots, yet they diverge significantly in some aspects due to different interpretations of sustainable development and large differences between countries in development. For example, combating hunger is a critical priority in sub-Saharan African countries, leading to an emphasis on increasing fertilizer inputs as a key strategy to increase food production and food self-sufficiency. In contrast, many developed countries focus on reducing chemical inputs as a primary means to environmental protection.

China introduced the concept of AGD in 2015, centered around the principles of greenness, openness, and sharing. This approach represents a significant evolution in the concept of sustainable development, offering more specific components and broadening its applicability for practical implementation. Unlike the prior approach, pollution-first manage-later, green development advocates for integrating environmental considerations in food production systems at the outset. In particular, AGD underscores a symbiotic mechanism where green (sustainability) and development mutually reinforce each other[12].

The Chinese Government has enacted several regulations to underscore the importance of AGD. The 2016 Central
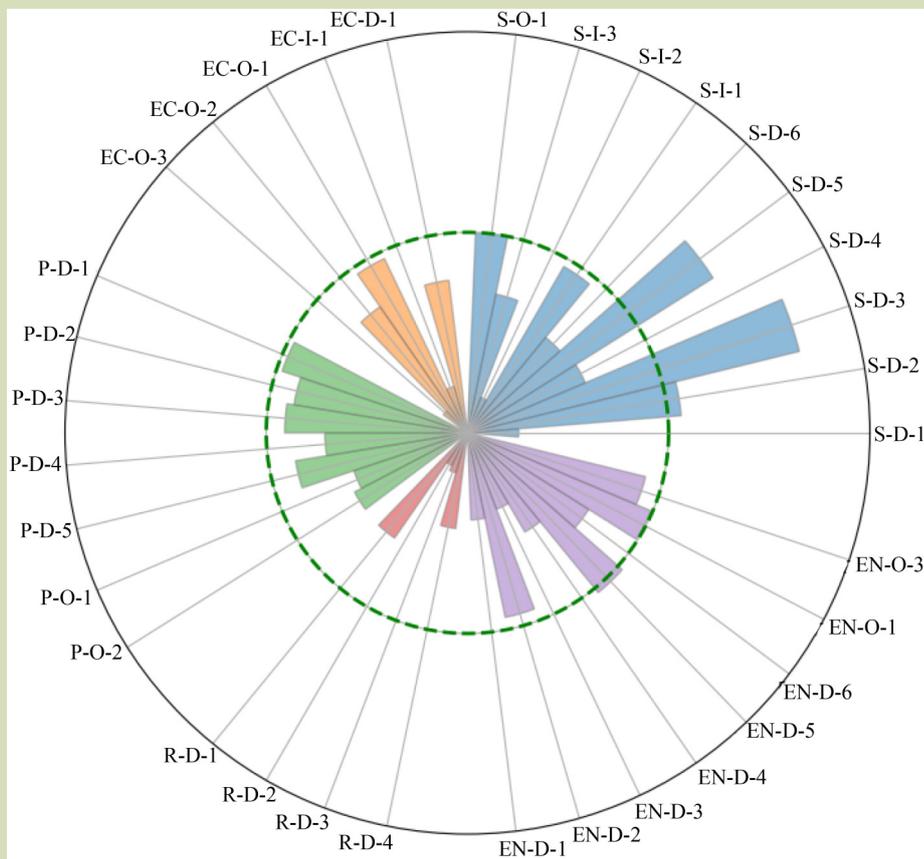
Fig. 2 Indicators gaps for AGD in China in 2017. S-D-1, proportion of agricultural financial investment; S-D-2, per capita calorie consumption; S-D-3, per capita protein intake; S-D-4, agricultural mechanization level; S-D-5, irrigation of farmland; S-D-6, education level of agricultural population; S-I-1, urbanization rate; S-I-2, per capita arable land; S-I-3, proportion of animal protein in protein intake; S-O-1, food self-sufficiency rate; EC-D-1, agricultural output value per unit arable land; EC-I-1, per capita gross domestic product (GDP); EC-O-1, Engel coefficient for rural residents; EC-O-2, rural disposable income; EC-O-3, percentage of agricultural output value in GDP; P-D-1, calorie production per unit arable land; P-D-2, protein production per unit arable land; P-D-3, protein production per livestock unit; P-D-4, N use efficiency (NUE) for crops; P-D-5, NUE for animals; P-O-1, vegetable yield; P-O-2, fruit yield; R-D-1, N use intensity; R-D-2, P use intensity; R-D-3, pesticides use intensity; R-D-4, agricultural film use intensity; EN-D-1, N surplus in farmland; EN-D-2, N runoff in farmland; EN-D-3, N leaching in farmland; EN-D-4, NH$_3$ volatilization in agricultural system; EN-D-5, reactive N losses per unit food N; EN-D-6, greenhouse gas emission per unit arable land; EN-O-1, forest coverage rate; and EN-O-3, livestock capacity per unit arable land.

Committee Document No. 1 explicitly called for "strengthening resource protection and ecological restoration, and promoting green agriculture". The momentum continued in 2017 with the release of "Opinions on the Innovation of Institutional Mechanisms to Promote the Green Development of Agriculture", jointly issued by the General Office of the Central Committee of the Communist Party of China and the General Office of the State Council. This marked a firm positioning of green development as the mainstream direction for both agricultural and national progress.

AGD in China fundamentally aligns with several SDGs, and represents a localized manifestation of sustainable development within the Chinese context. To progress further toward achieving the ambitious objectives of the SDGs by 2030, China must focus on enhancing its capabilities in sustainable development through AGD. This commitment not only advances China's own sustainability goals but also contributes significantly to the global pursuit of sustainable development. By doing so, China can substantively contribute to driving the worldwide agenda toward a more sustainable and environmentally-conscious future.

4.2 Advantages of the AGD indicator system

SDG 2.4.1 deals with the proportion of agricultural area under productive and sustainable agriculture and has 11 sub-

indicators. However, the specificity and measurability of these indicators in China and other countries present challenges. To address these challenges, alternative frameworks have been proposed, such as the sustainable agriculture matrix (SAM), with several agricultural performance indicators[26]. The SAM provides a transparent and standardized approach to evaluate sustainability, greatly aiding in cross-country comparisons. It is important to recognize that the effectiveness of SAM indicators is expected to improve progressively with the gathering of more comprehensive data over time. As such, the current version of the SAM may have certain limitations due to data constraints. However, as data availability expands, the precision and applicability of the SAM in assessing agricultural sustainability are anticipated to increase significantly.

The study by Sarkar et al.[27] examines the interplay of key indicators of sustainable agriculture within the Bangladeshi agriculture sector. This research uncovers connections between environmental and economic indicators, as well as between environmental and social indicators. A limitation of this study is the relatively narrow range of indicators considered, which might not fully capture all complexities of sustainable agriculture. Chaplitskaya et al.[28] used a composite indicator system to assess the agricultural sustainability in the Stavropol Territory. Their indicator system integrates economic, social and environmental factors, highlighting the benefits of analyzing a spectrum of indicators. Such an approach can shed light on the various factors influencing the evolution of regional agriculture[28]. Nevertheless, composite indicators bring their own challenges, particularly when the sub-indicators lack a unified, meaningful metric. This discrepancy can complicate comparisons of these indicators. Thus, careful selection of sub-indicators is of paramount importance.

The AGD indicator system exemplifies a practical approach to assessing and monitoring agricultural sustainable development in China. Tailored to the unique aspects of food production and consumption in China, it encompasses a comprehensive range of indicators covering five key areas, namely social, economic, resource inputs, productivity and environmental factors. These indicators, along with their grading criteria, have been carefully designed to align with both international and domestic development objectives.

The AGD indicators effectively capture the distinct characteristics of AGD in China. The indicators resonate with global agricultural sustainability indicators and reflect interconnectedness with SDG indicators, as shown in Table 1. By conducting thorough gap analyses between individual AGD indicators and their respective targets, we can scientifically pinpoint the bottlenecks and constraints within AGD. This process facilitates a deeper understanding of the areas that require focused attention, thereby guiding targeted strategies to advance sustainable agricultural practices in China.

Overconsumption of certain food ingredients (notably unsaturated fats, refined sugar and some animal sourced foods) can lead to obesity and chronic diseases, highlighting the importance of dietary moderation and balance[29]. China has implemented various national policies and programs to address obesity and to promote healthy lifestyles, yet these measures have been insufficient to reverse the rising rates of overweight and obesity. To address this, "China Blue Paper on Obesity Prevention and Control" was developed, aiming to encourage more vigorous efforts from policymakers, professionals and other stakeholders to combat the obesity epidemic[30]. Therefore, we have also taken this into consideration when setting indicators such as per capita calorie consumption and per capita protein intake, as seen in Table S1.

4.3   Limitations and outlook

The AGD indicator system for China, when compared with the SDG indicator framework, is more useful due to its enhanced specificity and quantifiability. This system will enable to rapid quantification of the progress toward AGD in China. This system will also allow identification of challenges encountered in the implementation of AGD in practice, and will facilitate a scientific analysis of the pathways to realizing AGD. However, it is important to note that some of the social and economic indicators, based on data from statistical yearbooks, are not suitable for examining the interactive effects of technological advancements and policy interventions on the socioeconomic landscape.

Also, ecological indicators are critically important, but obtaining data for quantification remains a challenge. Future efforts should focus on strengthening interdisciplinary cooperation and data collection. Enhancing dynamic monitoring of social, economic and ecological indicators will be equally crucial. This comprehensive approach will not only deepen understanding of AGD but also strengthen the efficiency of strategies aimed at sustainable agricultural development.

The SGDs constitute a multifaceted indicator framework, which serves also as a foundational base for AGD. The SDG indicator system has complex web of interactions among indicators across various goals, with a single indicator often intertwining with numerous others from different goals[31]. Likewise, changes in any AGD indicator can have direct or

indirect ripple effects on multiple SGDs. Quantifying these multifaceted impacts necessitates further in-depth research in this area. Future studies should endeavor to dissect and understand these dynamic interrelations, paving the way for a more holistic and informed approach to achieving both AGD and the broader objectives of the SDGs.

5   Conclusions

We conducted a comprehensive comparison between AGD and the SDGs, focusing on their definitions and indicator systems. The AGD indicator system in China consists of 53 indicators, which show congruence with the SDG indicators. We found that the AGD indicators are in general more accessible, precise and quantifiable compared to those of the SDGs. The AGD indicator system meticulously refines the objectives of sustainable agricultural development and resonates with the distinct national context of China. This tailored adaptation improves the precision in quantifying the progress in meeting the AGDs, and streamlines the process of identifying challenges and development paths.

Despite considerable advances in Chinese agriculture production from 1980 to 2017, it is also clear that the resource-intensive practices have led to large environmental challenges. Notably, nitrogen use intensity increased twofold, and plastic film use surged 19-fold during this period. Further, there has been steep rises in NH_3, N_2O and GHG emissions, and in nitrogen runoff and leaching to groundwater and surface water. Addressing these issues effectively in China's pursuit of AGD calls for a strategic balance between enhancing productivity, optimizing resource efficiency and implementing emission mitigation measures.

Compliance with ethics guidelines

Jianjie Zhang, Xiangwen Fan, Ling Liu, Lin Ma, Zhaohai Bai, and Wenqi Ma declare that they have no conflict of interest or financial conflicts to disclose. All applicable institutional and national guidelines for the care and use of animals were followed.

REFERENCES

1. Pingali P L. Green revolution: impacts, limits, and the path ahead. *Proceedings of the National Academy of Sciences of the United States of America*, 2012, **109**(31): 12302−12308

2. Tilman D, Balzer C, Hill J, Befort B L. Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, 2011, **108**(50): 20260−20264

3. Springmann M, Clark M, Mason-D'Croz D, Wiebe K, Bodirsky B L, Lassaletta L, de Vries W, Vermeulen S J, Herrero M, Carlson K M, Jonell M, Troell M, DeClerck F, Gordon L J, Zurayk R, Scarborough P, Rayner M, Loken B, Fanzo J, Godfray H C J, Tilman D, Rockström J, Willett W. Options for keeping the food system within environmental limits. *Nature*, 2018, **562**(7728): 519−525

4. Zheng X, Streimikiene D, Balezentis T, Mardani A, Cavallaro F, Liao H. A review of greenhouse gas emission profiles, dynamics, and climate change mitigation efforts across the key climate change players. *Journal of Cleaner Production*, 2019, **234**: 1113−1133

5. Ma L, Bai Z, Ma W, Guo M, Jiang R, Liu J, Oenema O, Velthof G L, Whitmore A P, Crawford J, Dobermann A, Schwoob M, Zhang F. Exploring future food provision scenarios for China. *Environmental Science & Technology*, 2019, **53**(3): 1385−1393

6. Zhang Q, Chu Y, Xue Y, Ying H, Chen X, Zhao Y, Ma W, Ma L, Zhang J, Yin Y, Cui Z. Outlook of China's agriculture transforming from smallholder operation to sustainable production. *Global Food Security*, 2020, **26**: 100444

7. Bai Z, Ma W, Ma L, Velthof G L, Wei Z, Havlík P, Oenema O, Lee M R F, Zhang F. China's livestock transition: driving forces, impacts, and consequences. *Science Advances*, 2018, **4**(7): eaar8534

8. Yu Z, Liu J, Kattel G. Historical nitrogen fertilizer use in China from 1952 to 2018. *Earth System Science Data*, 2022, **14**(11): 5179−5194

9. Guo J H, Liu X J, Zhang Y, Shen J L, Han W X, Zhang W F, Christie P, Goulding K W T, Vitousek P M, Zhang F S. Significant acidification in major Chinese croplands. *Science*, 2010, **327**(5968): 1008−1010

10. Conley D J, Paerl H W, Howarth R W, Boesch D F, Seitzinger S P, Havens K E, Lancelot C, Likens G E. Ecology. Controlling eutrophication: nitrogen and phosphorus. *Science*, 2009, **323**(5917): 1014−1015

11. Liu X, Zhang Y, Han W, Tang A, Shen J, Cui Z, Vitousek P, Erisman J W, Goulding K, Christie P, Fangmeier A, Zhang F. Enhanced nitrogen deposition over China. *Nature*, 2013, **494**(7438): 459−462

12. Shen J, Zhu Q, Jiao X, Ying H, Wang H, Wen X, Xu W, Li T, Cong W, Liu X, Hou Y, Cui Z, Oenema O, Davies W J, Zhang F. Agriculture Green Development: a model for China and the world. *Frontiers of Agricultural Science and Engineering*, 2020, **7**(1): 5−13

13. Liu Y, Sun D, Wang H, Wang X, Yu G, Zhao X. An evaluation of China's agricultural green production: 1978−2017. *Journal of Cleaner Production*, 2020, **243**: 118483

14. Lu Y, Norse D, Powlson D S. Agriculture Green Development in China and the UK: common objectives and converging policy pathways. *Frontiers of Agricultural Science and Engineering*, 2020, **7**(1): 98−105

15. Yin Y, He K, Chen Z, Li Y, Ren F, Wang Z, Wang Y, Gong H, Zhu Q, Shen J, Liu X, Cui Z. Agricultural green development to achieve food security and carbon reduction in the context of China's dual carbon goals. *Frontiers of Agricultural Science and Engineering*, 2023, **10**(2): 262−267

16. Zhang J, Cui S, Ma L, Meng F, Song C, Li Y, Ma W. Construction of a green development index system for the agriculture in China and examples. *Chinese Journal of Eco-Agriculture*, 2020, **28**(8): 1113−1126 (in Chinese)

17. United Nations Statistics Division (UNSD) Development Data and Outreach Branch. SDG Indicators Global Indicator Framework for the Sustainable Development Goals and Targets of the 2030 Agenda for Sustainable Development. New York: *UNSD*, 2023. Available at UNSD website on January 20, 2024

18. United Nations Statistics Division (UNSD) Development Data and Outreach Branch. SDG Indicators Metadata Repository. New York: *UNSD*, 2023. Available at UNSD website on January 20, 2024

19. Ma L, Ma W Q, Velthof G L, Wang F H, Qin W, Zhang F S, Oenema O. Modeling nutrient flows in the food chain of China. *Journal of Environmental Quality*, 2010, **39**(4): 1279−1289

20. Chen Z, Sarkar A, Rahman A, Li X, Xia X. Exploring the drivers of green agricultural development (GAD) in China: a spatial association network structure approaches. *Land Use Policy*, 2022, **112**: 105827

21. Yuan J. Empirical analysis of green development level and influencing factors in rural area of China. *Journal of Shanxi Agricultural University* (*Social Science Edition*), 2019, **18**(06): 46−53 (in Chinese)

22. Jin S. Evaluation of the green development level and regional differences of agriculture between provinces in China. *Seeker*, 2019, (2): 89−95 (in Chinese)

23. Springmann M, Wiebe K, Mason-D'Croz D, Sulser T B, Rayner M, Scarborough P. Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail. *Lancet. Planetary Health*, 2018, **2**(10): e451−e461

24. Sun W, Wang R, Jiang Q, Huang S. Study on connotation and evaluation of the agricultural green development. *Chinese Journal of Agricultural Resources and Regional Planning*, 2019, **40**(4): 14−21 (in Chinese)

25. Sharma G D, Shah M I, Shahzad U, Jain M, Chopra R. Exploring the nexus between agriculture and greenhouse gas emissions in BIMSTEC region: the role of renewable energy and human capital as moderators. *Journal of Environmental Management*, 2021, **297**: 113316

26. Zhang X, Yao G, Vishwakarma S, Dalin C, Komarek A M, Kanter D R, Davis K F, Pfeifer K, Zhao J, Zou T, D'Odorico P, Folberth C, Rodriguez F G, Fanzo J, Rosa L, Dennison W, Musumba M, Heyman A, Davidson E A. Quantitative assessment of agricultural sustainability reveals divergent priorities among nations. *One Earth*, 2021, **4**(9): 1262−1277

27. Sarkar A, Azim J A, Asif A A, Qian L, Peau A K. Structural equation modeling for indicators of sustainable agriculture: prospective of a developing country's agriculture. *Land Use Policy*, 2021, **109**: 105638

28. Chaplitskaya A, Heijman W, Van Ophem J. Composite indicators and sustainable development of regional agriculture applied to the Stavropol Territory in Russia. *Apstract, Applied Studies in Agribusiness and Commerce*, 2017, **11**(3−4): 81−88

29. Swinburn B A, Kraak V I, Allender S, Atkins V J, Baker P I, Bogard J R, Brinsden H, Calvillo A, De Schutter O, Devarajan R, Ezzati M, Friel S, Goenka S, Hammond R A, Hastings G, Hawkes C, Herrero M, Hovmand P S, Howden M, Jaacks L M, Kapetanaki A B, Kasman M, Kuhnlein H V, Kumanyika S K, Larijani B, Lobstein T, Long M W, Matsudo V K R, Mills S D H, Morgan G, Morshed A, Nece P M, Pan A, Patterson D W, Sacks G, Shekar M, Simmons G L, Smit W, Tootee A, Vandevijvere S, Waterlander W E, Wolfenden L, Dietz W H. The global syndemic of obesity, undernutrition, and climate change: the lancet commission report. *Lancet*, 2019, **393**(10173): 791−846

30. Wang Y, Zhao L, Gao L, Pan A, Xue H. Health policy and public health implications of obesity in China. *Lancet. Diabetes & Endocrinology*, 2021, **9**(7): 446−461

31. Wang M, Janssen A B G, Bazin J, Strokal M, Ma L, Kroeze C. Accounting for interactions between Sustainable Development Goals is essential for water pollution control in China. *Nature Communications*, 2022, **13**(1): 730