Front. Agr. Sci. Eng. 2024, 11(1): 5–19 https://doi.org/10.15302/J-FASE-2024535

REVIEW

Agriculture green development in China: insights and advances

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KEYWORDS

Agriculture, ecosystem services, environmental protection, food security, green development, multi-sectoral cooperation, sustainable development

HIGHLIGHTS

- Agriculture green development (AGD) has been undertaken in China for 5 years.
- New insights and advances on the four themes of AGD in China are elucidated.
- AGD involves interdisciplinary research innovation, multistakeholder participation, multi-objective realization and regional-specific technology implementation.
- Implementation of AGD in China will provide valuable experience paradigm for the world.

Received October 17, 2023;
Accepted December 19, 2023.

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GRAPHICAL ABSTRACT

ABSTRACT

Reconciling the tasks of producing adequate amounts of nutritious food for the increasing global population while preserving the environment and natural ecosystems simultaneously is an enormous challenge. The concept of agriculture green development (AGD) and the necessary governmental policies were developed to address the aforementioned challenge in China and to help achieve the related global sustainable development goals. Agriculture green development emphasizes the synergy between green and development; current agriculture has to transform from the intensive farming with high inputs, high environmental impacts and low resource-use efficiency to a more sustainable agriculture, in order to ensure an adequate supply of nutritious food while delivering environmental integrity, improved economic profitability, and social equity. A research program on AGD was established by China Agricultural University with four research themes, namely: green crop production, green integrated crop-animal production, green food and industry, and green ecological environment and ecosystem services, to provide a scientific basis for future developments and to facilitate the implementation of AGD in practice. AGD requires a multistakeholder approach, fueled by innovative and interdisciplinary research. Joint actions have to be taken by governments, farmers, supply industries, consumers, educators, extension services and researchers to support AGD. This requires strong coordination and public awareness campaigns. This review presents the progress that has been made over the past 5 years and makes recommendations for more research and development, in order to better deliver agricultural green and sustainable development on national and international scales.

1 Introduction

1.1 Recent developments in agriculture in China

China transformed from an agrarian society into an economic powerhouse following the introduction of the open-door policy in the 1980s[1,2] and Chinese agriculture has undergone a rapid transformation over the past 40 years. Agricultural production has increased substantially, facilitated by improved crop and animal husbandry practices and genetics, while the proportion of people working full time in agriculture has decreased significantly[3–5]. By 2015, China was able to largely meet the growing demand for food based on domestic production. Grain harvest increased for 19 consecutive years and then remained stable at over 650 Mt for eight consecutive years[6]. Yet, the import of animal feed (notably soybeans, maize and forage) has also strongly increased over the past 20 years, because domestic feed production has been insufficient to meet the growing feed demand of the rapidly increasing animal production sector. Over 40 years, agriculture largely transformed from subsistence farming systems to market-driven farming systems, while an increasing proportion of rural household income is derived from off-farm sources. Over the past 40 years, the annual growth of real agricultural gross domestic product averaged 4.5%. The development of agriculture and the increase in off-farm employment strongly has reduced rural poverty[7].

However, agricultural development in China has been accompanied with unprecedented environmental degradation. Increased food production has been largely achieved by high resource inputs with a high environmental footprint of the food produced[8,9]. Additionally, the urban-rural income gap has widened[7], while an increasing proportion of the urban population is suffering poor health from consumption of poor-quality food and is overweight[10]. Further, the Central Conference on Rural Work in December 2022 indicated that 50 Mt more grain must be produced in the next few years in order to meet the increasing food demand of an increasing population and an improving standard of living[6]. Evidently, the challenges for agriculture in China are large; there is an urgent need for agricultural development which increases productivity, strongly decreases environmental pollution and improves environmental-economic-social resilience.

1.2 Toward agriculture green development

The concept of green development in China was announced as a priority of the Central Government in 2015[11], while the concept agriculture green development (AGD) was subsequently detailed in 2017. The first AGD special plan was released in 2021 to provide directions for the 14th Five-Year Plan (2021–2025). AGD ultimately aims to achieve multiple societal goals, including food security, resource conservation, environmental sustainability, and social equity, thereby promoting rural revitalization and building a more beautiful countryside. The AGD special plan distinguishes three main systems, including the natural system, the food system, and the human and social system. The food system has four subsystems (i.e., green crop production, green integrated crop-animal production, green food and industry, and green ecological environment and ecosystem services)[11,12].

To realize AGD in practice, there is a need for coupling the aforementioned subsystems in order to develop a coherent whole food production-consumption chain (Fig. 1). There is also a need for interdisciplinary research and multistakeholder interactions as a key to bridge the gap between theory and practice, thus taking AGD from concept to action. The realization of AGD in practice is complex; it is a process that

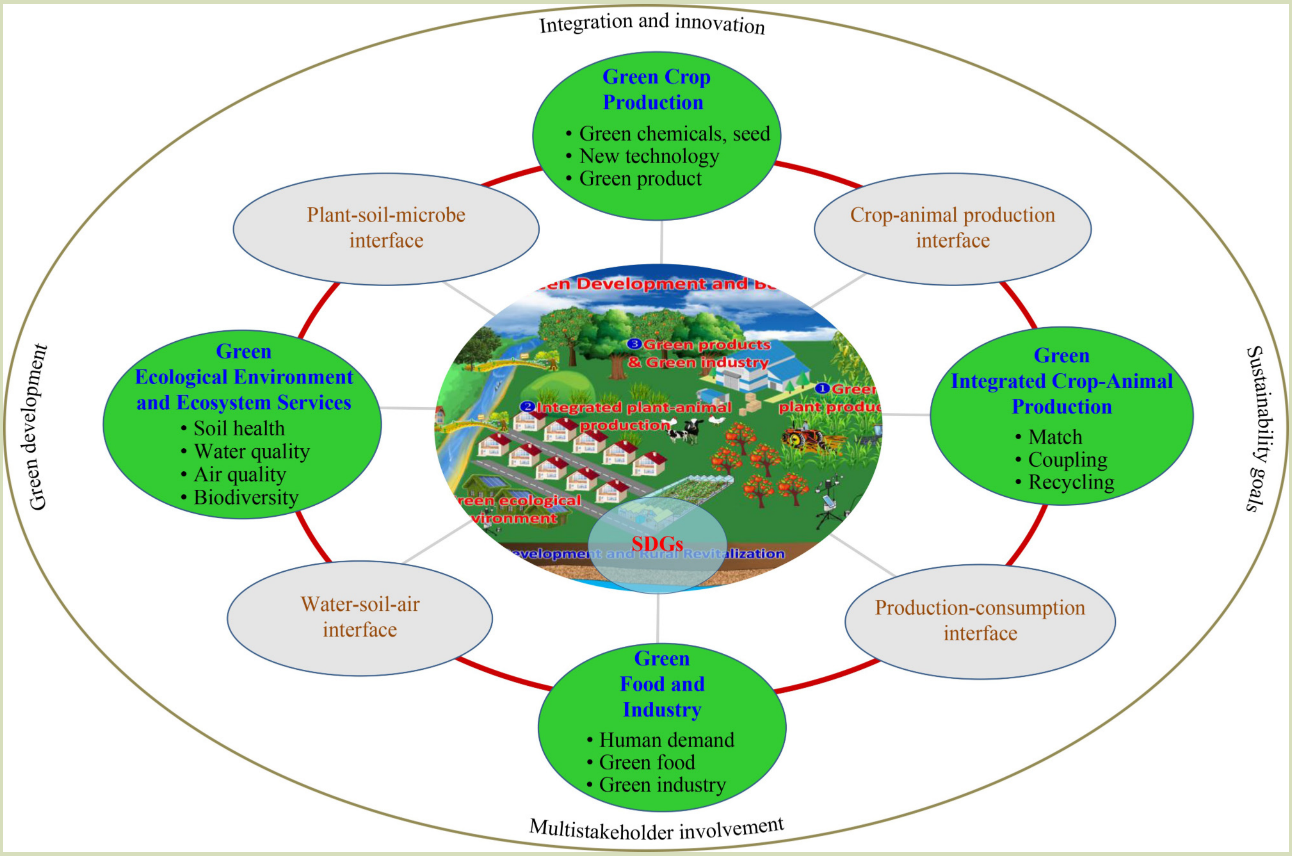

Fig. 1 The four subsystems of agriculture green development; i.e., green crop production, green integrated crop-animal production, green food and industry, and green ecological environment and ecosystem services, with their interlinkages. Some of the innovations may have to take place at these interlinkages. SDGs, UN Sustainable Development Goals.

requires collaborative involvement of multiple stakeholders[11]. Governments with the help of the private sector and scientists have a coordinating and guiding role. There is a need for long-term (environmental) targets to help make clear to producers which production methods and resource inputs may be employed. Concurrently, there is also a need for education of consumers about healthy and nutritious food and consumption of junk food must be discouraged. Importantly, farmers have to receive a proper remuneration for delivery of ecosystem services and for producing healthy and nutritious food. Additionally, the new technology based on interdisciplinary research must receive an evaluation and feedback by end user, including farmers. Also, the technology can then be further improved and more adapted to the specific agricultural conditions relevant to the end users, reflecting a bidirectional feedback mechanism via iteration. Evidently, agreements have to be made about ways forward involving collaboration between public and private sectors, policymakers, scientists, entrepreneurs and farmers as to the way forward on research and development collaboration and technology rollout.

Over the past 5 years, significant efforts have been made to make the concept, ideas and targets of AGD clearer to all[11]. Both top-down, including some strategies and policies released by the Chinese Government, and bottom-up approaches, including the network of nutrient management, and Science and Technology Backyards (STBs), have been employed to implement research findings and our innovations and ideas into practice in various regions[3,13–15]. The two-way approaches have established multi-stakeholder teams, and have made the methodology of AGD (from theoretical concept to implementation) clearer.

The aim of this paper is to briefly review the progress that has been made in both theoretical and conceptual developments as well as in practical implementation of AGD in China. We present also some new insights and actions, and imagine a pathway for the development of AGD between the 2020s and 2050.

2 Research progress in the four research themes

The AGD research program was established as a collaboration between several universities, governments and the private sector in China, under the guidance of China Agricultural University in Beijing. Also, international universities are involved; for example, there is an ongoing joint PhD research program between Wageningen University and China Agricultural University involving 90 PhD students over a period of 7 years (2019–2025). The four research themes of the AGD research program each receive roughly similar financial research support.

2.1 Green crop production

The research theme of Green Crop Production focuses on developing innovative crop production methods and technologies for producing adequate amounts of healthy and nutritious plant-based food with reduced agrochemical inputs and lower environmental impacts. The research has three key and interlinked foci, involving (1) green cropping systems with high resource use efficiency, (2) healthy soil systems which deliver multiple ecosystem functions and which have a high resilience, and (3) soil-crop system management with green intelligent fertilizers.

Green cropping systems are designed with diversified cropping and improved sustainability with greater economic benefits to farmers. For example, complementary and facilitative interspecific interactions in intercropping can lead to an absolute yield gain of 2 $t \cdot ha^{-1}$ and protein yield bonus of 10% compared to the respective monocultures[16,17]. In addition, a methodological framework was developed for the design crop rotations, using multiple sustainability objectives while catering to demands of various stakeholders such as farmers and cooperatives[18].

To develop healthy soil systems, the potential and mechanisms of biodiversity-enhanced soil multifunctionality have been explored in order to match soil nutrient supply to nutrient demand at key crop growth stages, also during extreme climatic conditions, which may help ease field management[19]. High-quality soils may reduce the sensitivity of crop yields to climate variability leading to both higher mean crop yields and higher yield stability[20]. A modeling tool has been developed to assess soil health status and provide new ways of field management to improve soil multifunctionality on the North China Plain[21].

The subtheme of Soil-Crop System Management focuses on the development of precision nutrient management practices and techniques to maximize root-zone and rhizosphere biological potential. This should help the delivery high crop yields with reduced nutrient input. Rhizosphere engineering was explored as a means to improve crop production in heterogeneous soils and rhizosphere environments[22–24]. Maximizing root/rhizosphere efficiency through rhizosphere nutrient management can be an effective way to improve crop productivity and nutrient use efficiency in intensive agriculture[8,25,26]. Green intelligent fertilizer has been developed as a means of matching soil properties and crop demands. The approach exploits knowledge of soil-crop-fertilizer interactions and rhizosphere principles. These techniques can improve soil-crop system management[27]. The recently developed steady-state nitrogen (N) balance approach may reduce fertilizer use by 20% to 28% while maintaining or increasing yields by 6% to 7% in wheat-maize systems managed by smallholders[28]. This technology has also been transferred to vegetable farming to produce more vegetables with lower environmental costs[29]. An integrated N optimization technology (including optimal N rates, deep fertilizer placement and application of urease inhibitors) for winter wheat and summer maize, covering a total area of 1067 ha, has been established through the cooperation with STBs, and local governments, fertilizer companies and smallholders. Compared with traditional small-scale farming system, the ammonia (NH_3) volatilization from wheat and maize fields decreased by 49% and 39%, respectively, while N utilization efficiency increased by 28% and 40%, and farm profitability increased by 25% and 19%, for wheat and maize, respectively[30]. The net benefit has been estimated at 7 million USD for Quzhou County. Overall, the combination of top-down and bottom-up strategies appear effective for promoting agriculture green production, a result which confirms earlier findings[31].

2.2 Green integrated crop-animal production

The theme of Green Integrated Crop-Animal Production aims at exploring ways to better integrate crop and animal production systems for improved nutrient cycling, enhanced feed production and feed use efficiency, and increased animal productivity. Animal-source food is an important source of protein and bioavailable minerals for humans, but has a large environmental footprint. Current animal production systems in China are highly specialized, and many have little or no land for crop production and appropriate manure recycling. Thus, most animal feed is imported from elsewhere, and the manure N and phosphorus (P) recycling to cropland is low[32].

Various pathways to aid recoupling of crop and livestock production systems have been explored[33,34] and a framework with three key strategies has been developed for this research theme. Subtheme of Efficient Utilization of Feed Resources aims to improve the utilization of feed sources. It has been found that lowering dietary crude protein content and adding phytase to feed while lowering mineral P supplementation, decreased total N and P excretion by around 25% to 30%[35]. Increased utilization of low-opportunity-cost feed products in China may save 25% to 32% of feed-producing cropland area without impairing livestock productivity, and may reduce feed-related emissions by about one third[36].

The subtheme of Integrated Technologies along the Whole Manure Management Chain aims at reducing multiple nutrient losses along the manure management chain. This is involves utilizing innovative and more integrated technology for feed crop production and manure management and this may reduce N losses by up to three-quarters and P losses by one-third from pig farms in China, as well as delivering modest reductions in greenhouse gas (GHG) emissions[37].

The subtheme of Spatial Recoupling of Crop and Livestock Production aims at exploring novel and promising strategies for recoupling crop and livestock production systems in order to increase exchange of feed and manure between crop and livestock production systems. Cooperation between crop and livestock farmers in Inner Mongolia has led to both economic and environmental benefits[38]. Also, total feed (energy and protein) production may be increased by 18% to 32% through optimizing the spatial distribution of feed crops across provinces, without the requirement of additional cropland input. Nitrogen and P inputs per MJ of feed produced may be decreased by 18% to 23% and 16% to 21%, respectively[39].

Strategies to enhance the circularity and environmental benefits of more integrated crop-animal production systems have been explored and are now in common practice in STBs. These have proven to be an effective model for technology and knowledge transfer[13,40]. Preliminary results show that integration of NH_3 emission abatement measures in the whole feeding-housing-manure storage/treatment-manure application chain reduced NH_3 emissions by 37% and increased egg production by 10% in Quzhou County, Hebei Province[41]. It is clear that integration of crop-animal production systems can greatly contribute to AGD.

2.3 Green food and industry

The theme of Green Food and Industries aims at adding value to food products for both consumers and producers, at lowering the environmental footprint of food products and at boosting and transforming food industries. Thereby, this theme contributes to the provision of safe, nutritious and culturally-acceptable food products, and puts sustainable consumption into practice, while minimizing environment impacts of the industries and boosting social equity.

Current food production and processing industries face several challenges: (1) current agricultural products in China are mainly basic products, with low value and low diversity, meaning that the industry does not respond well to changes in consumer demands. In addition, incomes for farmers and food industries are generally low; (2) there is often a mismatch between food supply and demand, which leads to food waste and imbalanced human nutrition (often causing obesity and hypertension) and to low resource-use efficiency; and (3) the large diversity of non-transparent and poorly linked food markets and their low-level management hinders the integration of agricultural production and consumption.

The trends in diets, food quality and environmental impacts of food production in China from 1997 to 2011 reflect a period of rapid urbanization. During this period, the Chinese Healthy Eating Index (CHEI2016 score) increased by 11%, while GHG emissions increased by 24% and agricultural land use also increased by 29%. The inflation-corrected cost of the average diet increased by 80%[42]. The recently-developed Food Life Cycle Assessment Database confirmed that overall dietary quality in China has improved, but the environmental and economic costs of the diet have also increased[43]. As a possible solution to this challenge for the nation, the concept of green-labeled food was developed. This system, with a reduced stringency of certification standards, indicates to consumers that particular foods have been grown in an environmentally-friendly fashion, thereby defining a middle position between traditional and often-expensive organic food.

The production of green-labeled food is rapidly increasing across China, as shown up by increased cultivation areas and increasing sales. In 2019, 15,984 green food companies provided 36,345 green-labeled products[44]. The cultivation area of green products expanded from 0.8 Mha in the 1990s to 11.1 Mha in 2019, accounting for 8.2% of the total farmland area in China. Green-labeled food requires that producers must reduce the use of mineral N fertilizers by half compared with local farm fertilization levels, and prohibit the use of about 72% of commercially available pesticides in China. A framework has been developed for assessing the potential impacts of green-labeled food products on the environment, economy and society at a country level. We suggest that broader application of this approach can lead to increased consumption of healthy and nutritious food and increased environmental protection.

Fueled in part by developments in Europe, UK and USA, a trend of reduced meat consumption is emerging among young affluent people, to increase human health and to lower the environmental footprint of the food consumed[45]. The central government is increasingly aware that imbalanced human nutrition is giving rise to serious diet-related health problems, in particular obesity, and hypertension, and that increasing health costs are a burden for both families and society. More efforts are needed to increase the awareness among consumers of the importance of nutritious food with modest intake of animal-sourced food.

2.4 Green ecological environment and ecosystem services

The theme of Green Ecological Environment and Ecosystem Services focuses on quantifying and minimizing the overall impact of food production and consumption on the environment, and on developing landscapes and measures to improve biodiversity and ecosystem services[46]. A green eco-environment necessitates the implementation of green practices throughout the whole food production-consumption chain. From green fertilizers and pesticides, to plant breeding to farming, processing and consumption; each step in the food production-consumption chain must give greater priority to environmental sustainability in order to ensure a sustainable agricultural system and a healthy environment[46].

Over the last few years, our research team has made significant progress with green ecological environment theory (Fig. 2). An updated version of the NUFER (nutrient flows in food chain, environment and resource use) model has been developed and applied to accurately assess the impacts of various crop and animal production systems on N and P losses in agriculturally-important regions of China, including Quzhou County[47] and Erhai Lake Basin[48]. The NUFER model allows (1) quantification of the specific contributions of different

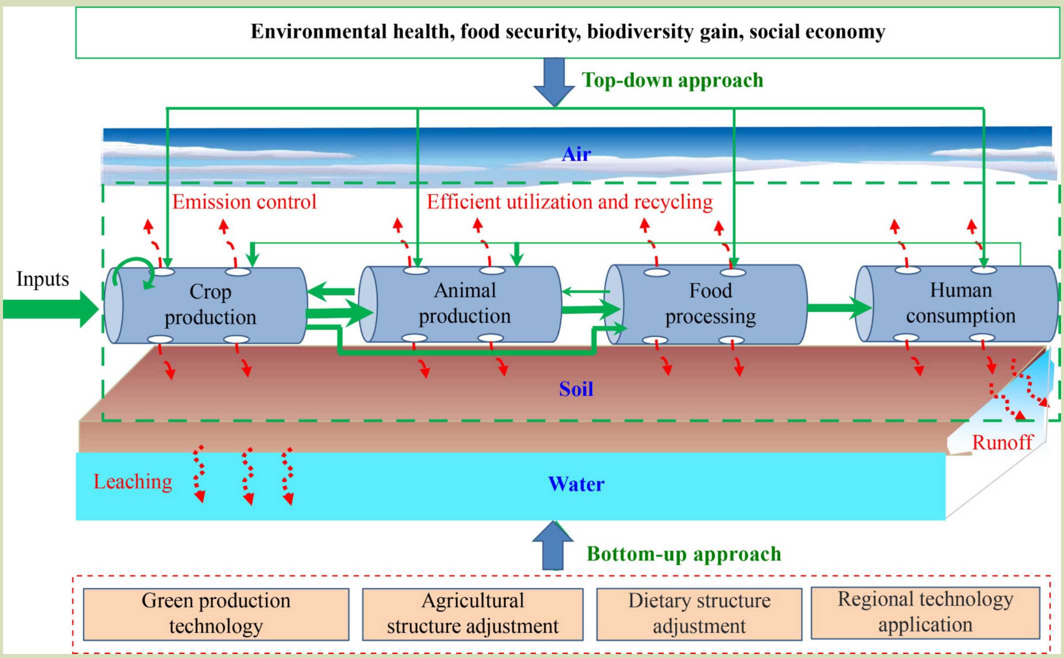

Fig. 2 Theoretical framework of green ecological environment in agriculture. It includes three subthemes on: (1) material flow and environmental impact analysis at the water-soil-air interface, (2) the construction of regional water-soil-air environmental thresholds, and (3) exploring the impacts of green environmental scenarios in typical regions of China. The top-down approach involves setting environmental limits for nutrient and pollutant emissions in the agricultural food system while also considering the crucial aspect of food security. This approach focuses on establishing clear guidelines and regulations to ensure sustainable farming practices from the top levels of the production chain. The bottom-up approach refers to achieving top-level environmental thresholds through technological innovations in the whole food production-processing-consumption system, through for example structural adjustments in agriculture, adjusting dietary structures, and disseminating green production technologies.

agricultural practices to N and P losses (and impacts of other pollutants such as pathogens microplastics and some pesticides), and (2) to assess the impacts of targeted interventions and novel strategies. To quantify the impact of food systems on water environments at a larger scale, two versions of the MARINA model (MARINA-Multi Global 2.0 and MARINA-Plastics China 1.0) were developed to better understand the current and future impacts of nutrients, pathogens (*Cryptosporidium*) and plastic pollution in 395 Chinese subbasins[49]. In addition, pathways toward green and sustainable agriculture development have been explored in typical agriculture-based regions (Quzhou County in Hebei Province and Erhai Lake Basin in Yunnan Province). Consequently, consideration has been given to the three pillars of sustainability: the environment, the economy and the society. For example, an NH_3 mitigation campaign was successfully implemented with smallholder farmers in wheat-maize cropping systems, which was subsequently recognized as a successful case of AGD by the Ministry of Agriculture and Rural Affairs of the People's Republic of China[30].

Currently, in China, there is increasingly interest and importance given to comprehensive exploration of solutions and environmental targets for reducing multiple pollutants in the environment, with a specific focus on supporting decision-making for sustainable agricultural development. Therefore, the aim is to provide valuable insights and guidance for policymakers and stakeholders involved in planning and management. By considering the interplay between various pollutants and their impacts on the environment, key strategies and targets will be identified to achieve a more sustainable agriculture and green environment. These expected findings can inform the development of effective policies and practices that balance agricultural production with environmental conservation, biodiversity, landscape protection and conservation and restoration, and help China achieve its agricultural development goals.

Exploring the interaction between climate change and the agrifood system, in terms of adaptation and mitigation, is also increasingly important[50,51]. In a rapidly changing world that puts large pressures on natural ecosystems, there is a need to reshape the interplay of agricultural development and environmental sustainability, and to understand how to be able to live equitably and sustainably. Finite resources and ecosystem services require our full attention. Ultimately, the more resilient food systems are needed, without over-consuming natural capital and damaging environmental integrity, to optimize food supply chains and provide sufficient and nutritious food to the increasing human population.

3 New cognition

Over the last five years of innovative development in theory and practice within the AGD research program, our group has acquired a series of new understandings in all four themes, which have important implications for the implementation of AGD in practice. The most important new insights are briefly summarized in this section as they relate to the importance of (1) multi-objective collaboration and multi-agent participation, (2) interdisciplinary research and multisystem research, and (3) integrated implementation of concepts and techniques at regional level.

3.1 Synergistic realization of multiple goals is a key requirement for AGD

China has recognized the urgent need to transform its agriculture to green development. The primary goals of AGD are to increase the supply of healthy, safe and nutritious food, to increase resource use efficiency, farm income and environmental protection, and to strengthen biodiversity conservation. The AGD program has been recognized by the government as an effective way to achieve these ends[52]. It is likely that achieving these primary goals will also contribute to greater equality between farmers and citizens. There are six specific goals for the short-term: (1) increase grain production by 30%, (2) increase nutrient use efficiency by 30%, (3) reduce GHG emissions and N and P losses by 50%, (4) increase farm income by 100%, (5) improve food quality, and (6) conserve and increase natural biodiversity.

AGD aligns with many of the UN Sustainable Development Goals (SDGs)[11,53]. AGD puts emphasis on the benefits of increasing agricultural productivity and improving human nutrition and health while respecting nature and environmental carrying capacity. The increasing need to conserve the nature and biodiversity and to improve human well-being has motivated researchers to seek the best management toward sustainable intensification in agriculture. It is crucial to intensify the use of biodiversity and local crop best management practices toward sustainable food system. This includes the use of local crop germplasm, intercropping, rotation, zero-tillage, and other approaches. AGD advocates green low-carbon agriculture and reduced carbon emissions as much as possible based on innovative technologies. However, it is difficult to achieve zero carbon emission even by using the best management strategy of agriculture practiced currently. Transdisciplinary research innovation to achieve carbon offsets is crucial. For example, through tree planting, forest quality, ecosystem resilience and carbon sink potential can be improved. Evidently, the possible synergies and tradeoffs between these objectives have to be considered fully, and (potentially) conflicting aims have to be reconsidered. The AGD program aims at developing a multifunctional agriculture, with enhanced ecosystem services and nature and landscape conservation and maintenance.

3.2 Interactions and coupling mechanisms within systems require more attention

AGD encompasses green crop production, green integrated crop-animal production systems, green food and industry, and green ecological environment and ecosystem services (Fig. 1). To achieve AGD, it is essential to understand the coupling and interaction mechanisms and processes between the different components of the whole food system (Fig. 3). This understanding can help to optimize production systems.

For greater understanding of the coupling mechanisms, current research disciplines have to broaden their focus. Research has to focus more on the interfaces between subsystems, connecting belowground soil-rhizosphere-root research to aboveground crop production and to research on the earth-atmosphere interface. This interlinking and integration may contribute to the generation of new insights that lead to more efficient production system, greater resource-use efficiency, and more green, nutritious and healthy food, thereby achieving greater understanding of key variables, understanding that may not be developed by mono-disciplinary research alone.

3.3 Interdisciplinary and transdisciplinary research innovations are crucial

Improved coordination and integration of developments in science, technology, and practice are an important starting point for the development of AGD structures and practices. Emphasizing interdisciplinary and transdisciplinary approaches in research, teaching and application can foster the cultivation of multidisciplinary talents. This, in turn, may facilitate the generation of scientific breakthroughs that are key to solving problems in agriculture. China needs a new generation of young scientists, trained in interdisciplinary and transdisciplinary research approaches in the agriculture-food-environment nexus.

Science and Engineering of AGD has emerged as an interdisciplinary focus emphasizing cross-innovation research

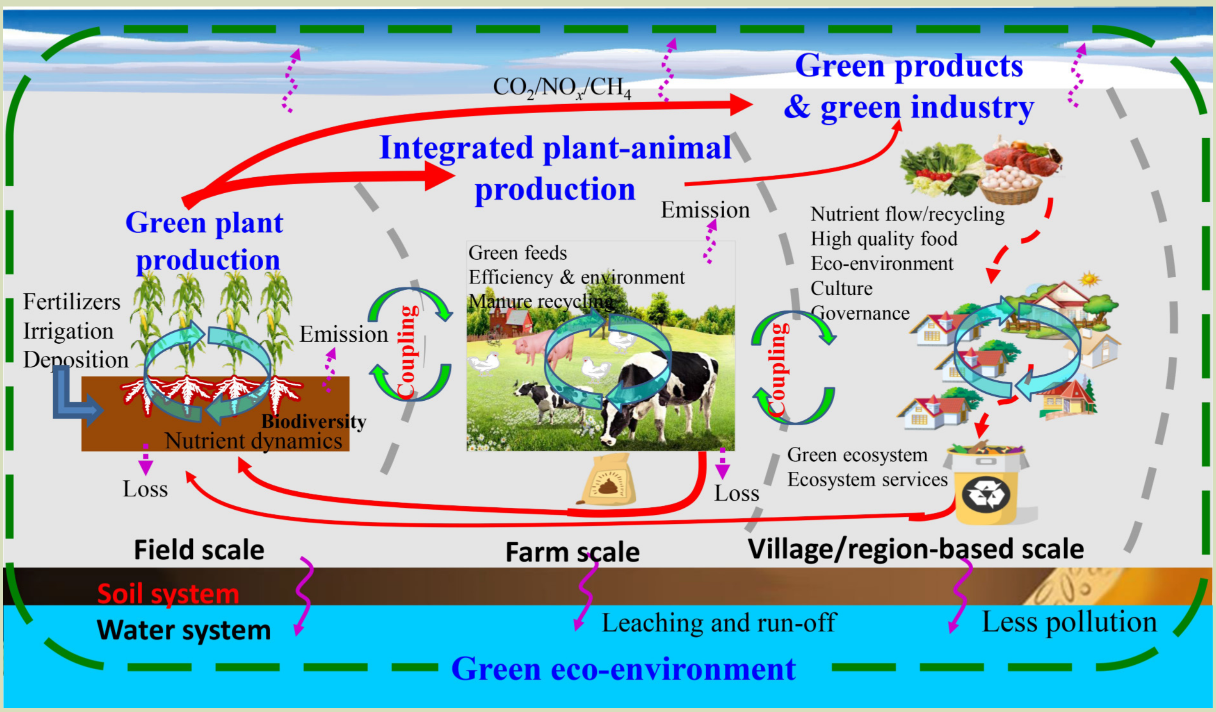

Fig. 3 The multi-system coupling of the agriculture green development (AGD). Achieving the AGD targets requires systematic interlinking and integration of green crop production, green integrated crop-animal production, green food and industry, and green ecological environment and ecosystem services.

at the interfaces of material and energy flows in the agricultural industry chain. The study of Science and Engineering of AGD is formed by the fusion of several disciplines in the fields of agronomy, science, engineering and management. Science and Engineering of AGD has three interrelated pillars as secondary subdisciplines, i.e., AGD Science, AGD Engineering, and AGD Regional Application. The objectives of STBs-based talent training are to cultivate high-level interdisciplinary talents that can master the international frontier theory of AGD science, and provide leadership, solve the practical problems of AGD technology and engineering, and promote implementation of AGD regional application.

3.4 A whole food chain approach is needed to realize AGD

A substantial part of the food chain for most people in China comprises crop production, livestock production, food processing and retail, and food consumption (Fig. 4). Improved coordination and integration of the activities in the food chain are needed, to be able to properly match the supply of nutritious food to the food demand by consumers. Thus, activities of upstream industries and downstream industries both in urban and rural area have to be aligned more as a holistic large food system, in order to decrease unnecessary food losses, food wastes and thereby environmental emissions. Meanwhile, the recycling of residues and wastes in the various compartments of the food chain has to be improved. The corresponding management entails a combination of resource reduction, process control and end-of-line treatment[14,54]. Also, the issue of overcompensation of food production and overconsumption needs to be considered. These problems can be avoided or mitigated through rational agricultural zoning and dietary recommendations.

Also, there is a need to increase the nutritional value and quality of food products in the whole food chain, which is to the benefit of both producers and consumers. Creating increased economic and social value for food products will be done through a combination of various approaches: (1) technological improvements in food storage and processing, (2) increased market competitiveness through better labeling and liberalizing markets, (3) introduction of standards and certified high-quality products, (4) biofortification of food products and best nutrient management, and (5) developing agricultural tourism, recreation, and education, in order to increase the ecological and cultural resource endowments and the multifunctionality of agriculture. These approaches will contribute to reforming the food chain and will add economic and social values to food products.

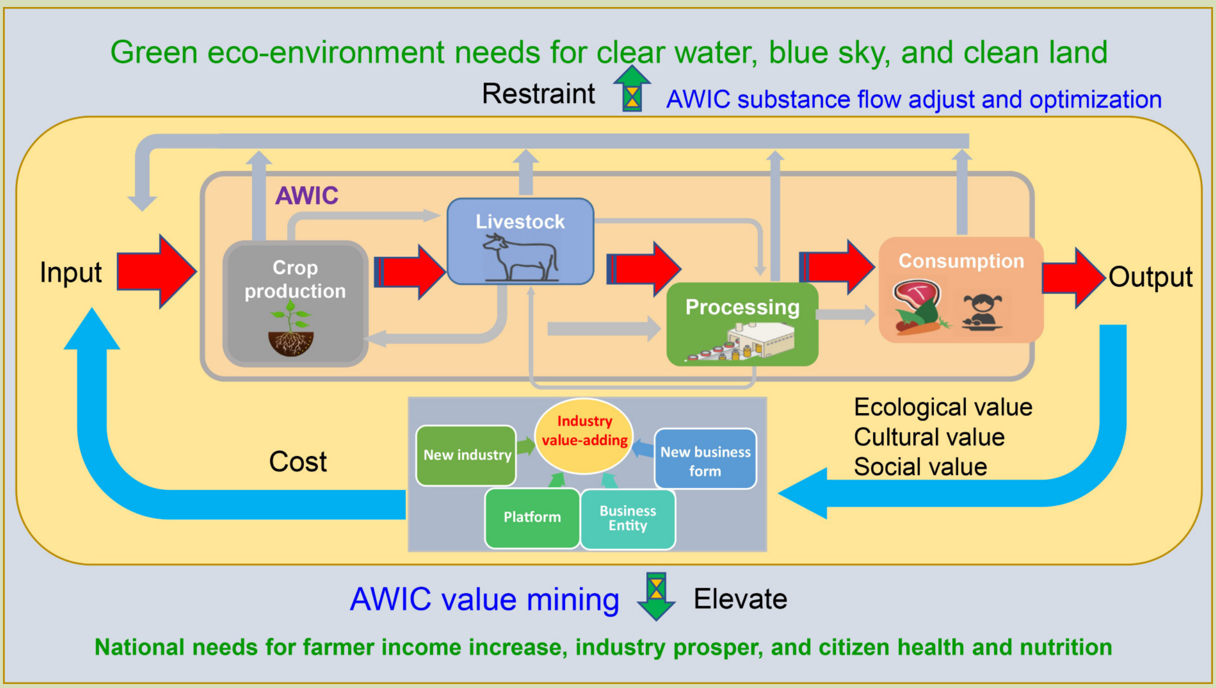

Fig. 4 Optimization of activities in the whole food production, processing and consumption chain. AWIC, agricultural whole industry chain.

3.5 Building transformative partnerships to realize AGD

Realizing AGD in practice requires building transformative partnerships to link knowledge and action, and to integrate the interests of multiple stakeholders, including farmer organizations, governments, enterprises, universities, research institutes and non-governmental organizations (NGOs)[51,55] One approach is to build an integrated joint service and technology platform, based on increased cooperation within the whole chain of government-enterprise-university-researcher-farmer-NGOs (Fig. 5).

Commonly, national governments promote new and improved technology from researchers and extension workers to farmers through policy incentives, technical standards and industry norms[56]. Thus, the Chinese Government has issued a series of AGD guidelines, and has initiated the construction of pilot demonstration zones for AGD across the country. The Chinese Government has started the development of the building of a number of green development zones as demonstration sites to drive green development in major cities across the country. Concurrently, research initiatives have built stakeholder collaborative innovation platforms, such as the STBs (Fig. 5). STBs connect multi-actors to co-innovate, build bridges between different stakeholders, complement each other, and find innovative solutions to specific problems, as a bottom-up approach[57]. In STBs, farmers, researchers, students, suppliers, local governments, and extension personnel collaborate to improve capacity of farmers in field management, learning and communication, and this approach has been adopted from county level to national scale in China[13,58].

3.6 Toward integration of national policy and social action

The drivers for the top-down approach for AGD implementation are governmental incentives and regulations. The drivers of the bottom-up approach for AGD implementation are predominantly social action and technology improvements. The challenge is to create synergistic benefits from top-down and bottom-up approaches; their mutual influence will create a basis and driving force for AGD (Fig. 5). Evidently, this is very challenging area of research and development needing to determine how to align national policy and social action, and how to improve the effectiveness and efficiency of AGD implementation in practice.

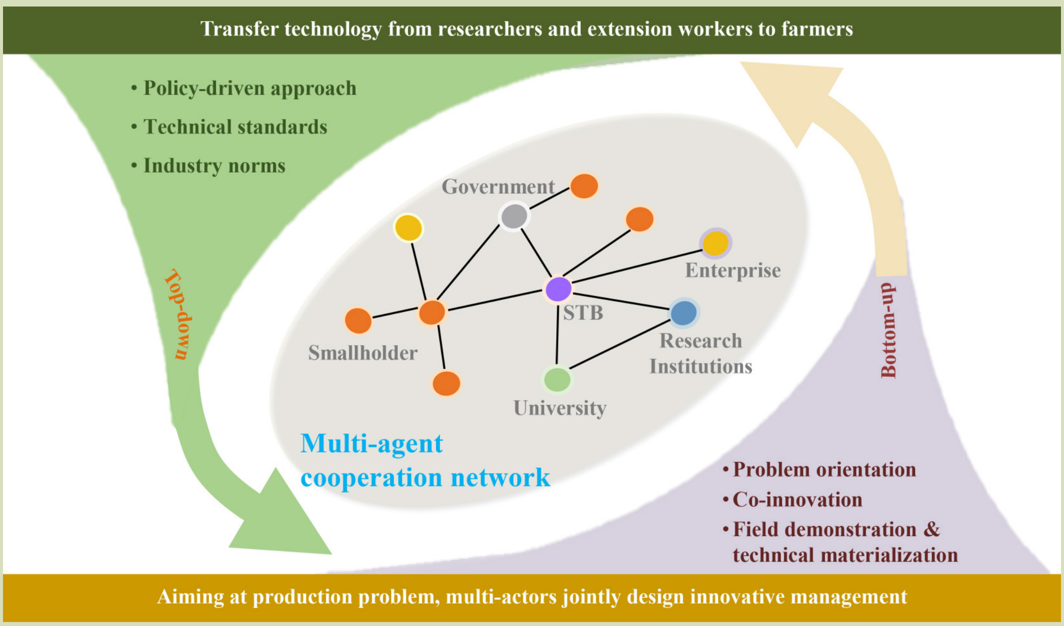

Fig. 5 Conceptual framework of the integrated joint service and technology platform based on the cooperation of government, enterprise, university, researcher, farmer and NGOs through combination of top-down and bottom-up strategies. The green arrow indicates the top-down path and the orange arrow represents the bottom-up path. The circles of various colors in the middle represent different stakeholders. STB, Science and Technology Backyard; NGOs, non-governmental organizations. Enterprise include entities covering the whole chain of agricultural production, including crop and animal production enterprises as well as fertilizer companies.

AGD in China still must address great scientific, practical and implementation challenges. AGD has to become embedded in politics, economy, society, culture and ecology. Institutional innovation, technological improvement, market reform, trade liberalization and investment in infrastructure, education and technology are already contributing to agricultural development, indicating that combinations of top-down and bottom-up approaches can be successful (Fig. 5).

3.7 Toward interlinking and integration of research approaches

There are also top-down and bottom-up approaches in research (Fig. 6). The top-down research approach includes: (1) quantitative analysis of resource constraints such as water, arable land, minerals, and energy in various regions, along with the potential for agricultural production; (2) defining thresholds for air, water and soil pollution at the watershed scale, and use of these thresholds as a basis for optimizing the spatial configuration and layout of agricultural activities within the watershed; (3) constructing a county-level green development index system, analyzing bottlenecks in green transformation across the entire production chain, and proposing optimization strategies for a green food system; and (4) benchmarking key aspects of pioneer farmers (enterprises), analyzing limiting factors for green development across the entire chain of crop and animal production and processing, and proposing comprehensive solutions.

The bottom-up research approach involves: (1) increasing crop and animal production and production efficiency; (2) decreasing GHG and nutrient losses through developing new mitigation measures; (3) increasing resources use efficiency in the whole food production and consumption chain, through recycling and waste reduction; (4) enhancing soil ecosystem functions and services through diversified crop rotation, intercropping, agroforestry and improved management; (5) investigating and monitoring farm enterprises, analyzing bottlenecks in the entire industry chain for developing critical technologies, and exploring models for achieving AGD across the entire chain; (6) comparing key indicators for AGD at the county level, discussing technological bottlenecks and pathways for county-level agricultural green transformation, and proposing systematic solutions for specialized green industries; (7) enhancing the watershed ecological monitoring network, integrating it with models, and establishing a management mechanism that combines ecological environment monitoring, assessment and policy solutions for AGD; and (8) providing technological and policy support for the AGD strategy and offering successful case studies for the achievement of SDGs.

4 Perspectives

The challenges to agriculture in China and to the establishment of AGD structures are enormous. The current high-input and low-efficient smallholders' production systems have to be

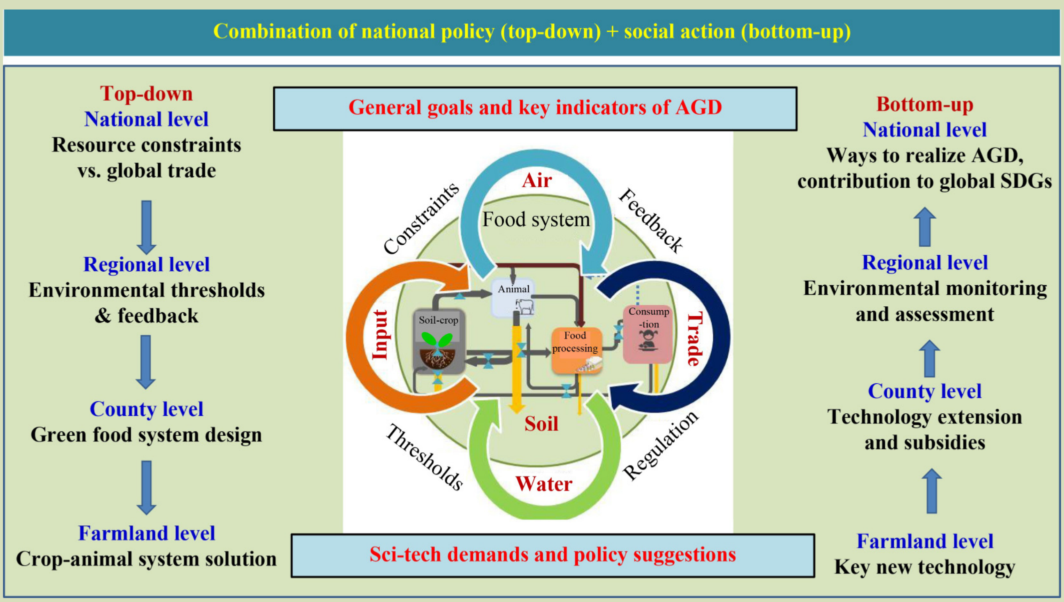

Fig. 6 Implementation approach of agriculture green development through top-down and bottom-up pathways.

transformed to productive, high-efficient, resilient and sustainable systems which provide more adequate amounts of nutritious and affordable food for the increasing national population and a fair income for farmers. This transformation has to be adopted by a diversity of farming systems and environments, and involves some 200 million smallholders and a complex network of suppliers, traders, markets, processing industries, extension officers and regional governmental officers. Such a transformation is likely to take many decades of concerted effort.

The current agriculture in China has been successful in producing increasing amounts of food for the increasing human population[1] but at an enormous cost to the environment and biodiversity[9,59]. Current agricultural practices are not sustainable. The Chinese Government considered AGD as the path forward now. AGD is a process and pathway to a productive, high-efficient, resilient and sustainable agriculture. There is no blueprint for AGD, it is a developmental process requiring learning by doing and doing for learning. To continue to make progress in this area it is important to strengthen systematic regional-based research and innovations of AGD to gain practical experience under different regional environments. Our team has chosen two contrasting regions for developing the ideas and implementation modes of AGD in practice further. The first one is Quzhou County in Hebei Province as a major grain production area on the North China Plain with sensitive non-point source pollution, water and soil resource limitations and nutrient imbalances[47,60]. The second one is Erhai Lake Basin of Yunnan Province in south-west China as a characteristic hilly plateau agricultural area with cash crops and a sensitive and fragile ecosystem[48]. Our perspective has been that a combination of top-down and bottom-up approaches in research as well as in implementation will greatly facilitate AGD in both regions.

AGD is a joint effort of multiple stakeholders, in different regions. Thus, we have established six AGD sub-centers across the country, including North-west Dryland Agriculture Green Development Research Center, South-west Agriculture Green Development Research Center, Yunnan Agriculture Green Development Center, North-east Black Land Agriculture Green Development Research Center, Yangtze River Phosphorus Resource Efficient Utilization Center, and South-west China Agriculture Green Development Research Center, all of which are affiliated with the National Academy of Agriculture Green Development. These constitute the AGD network that radiates the spatial and temporal pattern in the whole of China. This network should be strengthened further by international cooperation and exchange. The AGD network in China will focus also on cultivating innovative talents in agriculture-related colleges, in order to provide an impetus for achieving transformation of agricultural systems, economic and social development, and rural revitalization.

AGD greatly contributes to achieving the SDGs[11,53]. Chinese agriculture has a large impact on the global agriculture market and the global environment. Improvements in agricultural development in China will have positive impacts on the global agricultural market and the global environment. China aims at contributing to global sustainable development through designing clear objectives and development plans for agriculture, improving agricultural infrastructure, empowering the capacity of small farmers, and implementing rural reform and implementing policies. The paradigm shift associated with AGD will be an example also for other countries with similar status around the world to explore sustainable agricultural development.

Our additional perspective is that international and regional cooperation, knowledge sharing, technology transfer, talent training and consultation are essential for AGD. Great effort to innovate for AGD has been made by developing the Sino-Dutch Agriculture Green Development cross-innovative talent training project, with 90-PhD programs, as an important implementation platform for the Agrifood 5 University Alliance. This training involves a so-called T-shape training program (i.e., a combination of specialized fundamental research and training, and learning cross-discipline competencies and the ability to collaborate with professionals in other industries or roles). The alliance includes China Agricultural University, Wageningen University, Cornell University, University of California-Davis, and University of Sao Paulo. China is ready to work with other countries to deepen cooperation, help more countries and more people share the benefits of development, and make new and greater contributions to building a community with a shared future for humankind without poverty and with common development goals.

Acknowledgements

This study was financially supported by a project of Beijing's Top-Precision-Advanced Disciplines, the CSC-AGD PhD Program from China Scholarship Council, the National Key Research and Development Program of China (2023YFD1901500, 2023YFD1901502), the Key Consulting Project of the Chinese Academy of Engineering, Yunnan Rural Revitalization Science and Technology Project, PR China (202104BI090004) and the 2115 Talent Development Program of China Agricultural University.

Compliance with ethics guidelines

Jianbo Shen, Qichao Zhu, Yong Hou, Wen-Feng Cong, Wen Xu, Jiuliang Xu, Zhichao An, Xiaoqiang Jiao, Kai Zhang, Tianxiang Yu, Lin Ma, Oene Oenema, William J. Davies, and Fusuo Zhang 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.

REFERENCES

1. Jiao X, Lyu Y, Wu X, Li H, Cheng L, Zhang C, Yuan L, Jiang R, Jiang B, Rengel Z, Zhang F, Davies W J, Shen J. Grain production versus resource and environmental costs: towards increasing sustainability of nutrient use in China. *Journal of Experimental Botany*, 2016, **67**(17): 4935–4949
2. Huang J, Yang G. Understanding recent challenges and new food policy in China. *Global Food Security*, 2017, **12**: 119–126
3. Cui Z, Zhang H, Chen X, Zhang C, Ma W, Huang C, Zhang W, Mi G, Miao Y, Li X, Gao Q, Yang J, Wang Z, Ye Y, Guo S, Lu J, Huang J, Lv S, Sun Y, Liu Y, Peng X, Ren J, Li S, Deng X, Shi X, Zhang Q, Yang Z, Tang L, Wei C, Jia L, Zhang J, He M, Tong Y, Tang Q, Zhong X, Liu Z, Cao N, Kou C, Ying H, Yin Y, Jiao X, Zhang Q, Fan M, Jiang R, Zhang F, Dou Z. Pursuing sustainable productivity with millions of smallholder farmers. *Nature*, 2018, **555**(7696): 363–366
4. Liu J, Fernie A R, Yan J. The past, present, and future of maize improvement: domestication, genomics, and functional genomic routes toward crop enhancement. *Plant Communications*, 2020, **1**(1): 100010
5. Jha U C, Nayyar H, Parida S K, Deshmukh R, von Wettberg E J B, Siddique K H M. Ensuring global food security by improving protein content in major grain legumes using breeding and 'Omics' tools. *International Journal of Molecular Sciences*, 2022, **23**(14): 7710
6. National Bureau of statistics of China (NBSC). "Grain production", 2023. Available at NBSC website on September 20, 2023 (in Chinese)
7. Yu W. Agricultural and agri-environment policy and sustainable agricultural development in China. Frederiksberg: *Department of Food and Resource Economics, University of Copenhagen*, 2017
8. Shen J, Li C, Mi G, Li L, Yuan L, Jiang R, Zhang F. Maximizing root/rhizosphere efficiency to improve crop productivity and nutrient use efficiency in intensive agriculture of China. *Journal of Experimental Botany*, 2013, **64**(5): 1181–1192
9. Shen J, Zhang F, Siddique K H M. Sustainable resource use in enhancing agricultural development in China. *Engineering*, 2018, **4**(5): 588–589
10. Food and Agriculture Organization of the United Nations (FAO). The State of Food Security and Nutrition in the World. Rome: *FAO*, 2022. Available at FAO website on September 20, 2023
11. 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, Davie 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
12. Davies W J, Shen J. Reducing the environmental footprint of food and farming with Agriculture Green Development. *Frontiers of Agricultural Science and Engineering*, 2020, **7**(1): 1–4
13. Zhang W, Cao G, Li X, Zhang H, Wang C, Liu Q, Chen X, Cui Z, Shen J, Jiang R, Mi G, Miao Y, Zhang F, Dou Z. Closing yield gaps in China by empowering smallholder farmers. *Nature*, 2016, **537**(7622): 671–674
14. 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
15. You L, Ros G H, Chen Y, Shao Q, Young M D, Zhang F, de Vries W. Global mean nitrogen recovery efficiency in croplands can be enhanced by optimal nutrient, crop and soil management practices. *Nature Communications*, 2023, **14**(1): 5747
16. Li C, Hoffland E, Kuyper T W, Yu Y, Zhang C, Li H, Zhang F, van der Werf W. Syndromes of production in intercropping impact yield gains. *Nature Plants*, 2020, **6**(6): 653–660
17. Li C, Stomph T J, Makowski D, Li H, Zhang C, Zhang F, van der Werf W. The productive performance of intercropping. *Proceedings of the National Academy of Sciences of the United States of America*, 2023, **120**(2): e2201886120
18. Liang Z, Xu Z, Cheng J, Ma B, Cong W F, Zhang C, Zhang F, van der Werf W, Groot J C. Designing diversified crop rotations to advance sustainability: a method and an application. *Sustainable Production and Consumption*, 2023, **40**: 532–544
19. Lehmann J, Bossio D A, Kögel-Knabner I, Rillig M C. The concept and future prospects of soil health. *Nature Reviews Earth & Environment*, 2020, **1**(10): 544–553
20. Qiao X, Wang X, Smith P, Fan J, Lu Y, Emmit B, Li R, Dorling S, Chen H, Liu S, Benton T G, Wang Y, Ma Y, Jiang R, Zhang

F, Piao S, Müller C, Yang H, Hao Y, Li W, Fan M. Soil quality both increases crop production and improves resilience to climate change. *Nature Climate Change*, 2022, **12**(6): 574–580
21. Zhang J, Li Y, Li Y, Zhang J, Zhang F. Advances in the indicator system and evaluation approaches of soil health. *Acta Pedologica Sinica*, 2022, **59**(3): 603–616 (in Chinese)
22. Wang X, Whalley W R, Miller A J, White P J, Zhang F, Shen J. Sustainable cropping requires adaptation to a heterogeneous rhizosphere. *Trends in Plant Science*, 2020, **25**(12): 1194–1202
23. Wang L, Rengel Z, Zhang K, Jin K, Lyu Y, Zhang L, Cheng L, Zhang F, Shen J. Ensuring future food security and resource sustainability: insights into the rhizosphere. *iScience*, 2022, **25**(4): 104168
24. Zhang K, Rengel Z, Zhang F, White P J, Shen J. Rhizosphere engineering for sustainable crop production: entropy-based insights. *Trends in Plant Science*, 2023, **28**(4): 390–398
25. Jing J, Gao W, Cheng L, Wang X, Duan F, Yuan L, Rengel Z, Zhang F, Li H, Cahill J F Jr, Shen J. Harnessing root-foraging capacity to improve nutrient-use efficiency for sustainable maize production. *Field Crops Research*, 2022, **279**: 108462
26. Wen Z, White P J, Shen J, Lambers H. Linking root exudation to belowground economic traits for resource acquisition. *New Phytologist*, 2022, **233**(4): 1620–1635
27. Zhang F, Shen J, Wei C, Ma W, Zhang W, Huang C, Lyu Y, Zhang L, Lu Z, Ying H, Cheng L, Jiang R, Qu L, Hou C, Wang X, Xiu X, Ma H. Green intelligent fertilizer: from interdisciplinary innovation to industrialization realization. *Acta Pedologica Sinica*, 2022, **59**(4): 873–887 (in Chinese)
28. Yin Y, Zhao R, Yang Y, Meng Q, Ying H, Cassman K G, Cong W, Tian X, He K, Wang Y, Cui Z, Chen X, Zhang F. A steady-state N balance approach for sustainable smallholder farming. *Proceedings of the National Academy of Sciences of the United States of America*, 2021, **118**(39): e2106576118
29. Wang X, Dou Z, Shi X, Zou C, Liu D, Wang Z, Guan X, Sun Y, Wu G, Zhang B, Li J, Liang B, Tang L, Jiang L, Sun Z, Yang J, Si D, Zhao H, Liu B, Zhang W, Zhang F, Zhang F, Chen X. Innovative management programme reduces environmental impacts in Chinese vegetable production. *Nature Food*, 2021, **2**(1): 47–53
30. Kang J, Wang J, Heal M R, Goulding K, de Vries W, Zhao Y, Feng S, Zhang X, Gu B, Niu X, Zhang H, Liu X, Cui Z, Zhang F, Xu W. Ammonia mitigation campaign with smallholder farmers improves air quality while ensuring high cereal production. *Nature Food*, 2023, **4**(9): 751–761
31. Black A W. Extension theory and practice: a review. *Australian Journal of Experimental Agriculture*, 2000, **40**(4): 493–502
32. 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
33. Ma Y, Zhang L, Bai Z, Jiang R, Hou Y, Ma L. Nutrient use efficiency and losses of industrial farms and mixed smallholdings: lessons from the North China Plain. *Frontiers of Agricultural Science and Engineering*, 2021, **8**(1): 58–71
34. Bai Z, Fan X, Jin X, Zhao Z, Wu Y, Oenema O, Velthof G, Hu C, Ma L. Relocate 10 billion livestock to reduce harmful nitrogen pollution exposure for 90% of China's population. *Nature Food*, 2022, **3**(2): 152–160
35. Wang H, Long W, Chadwick D, Velthof G, Oenema O, Ma W, Wang J, Qin W, Hou Y, Zhang F. Can dietary manipulations improve the productivity of pigs with lower environmental and economic cost? A global meta-analysis *Agriculture, Ecosystems & Environment*, 2020, **289**: 106748
36. Fang Q, Zhang X, Dai G, Tong B, Wang H, Oenema O, van Zanten H H E, Gerber P, Hou Y. Low-opportunity-cost feed can reduce land-use-related environmental impacts by about one-third in China. *Nature Food*, 2023, **4**(8): 677–685
37. Tong B, Zhang L, Hou Y, Oenema O, Long W, Velthof G, Ma W, Zhang F. Lower pork consumption and technological change in feed production can reduce the pork supply chain environmental footprint in China. *Nature Food*, 2023, **4**(1): 74–83
38. Ma Y, Hou Y, Dong P, Velthof G L, Lon, W, Ma L, Ma W, Jiang R, Oenema O. Cooperation between specialized livestock and crop farms can reduce environmental footprints and increase net profits in livestock production. *Journal of Environmental Management*, 2022, **302**(Part A): 113960
39. Dai G, Hou Y, Fang Q, Zhang X, Wang H, Wang S, Zhu X, Zhang F, Oenema O. Boosting domestic feed production with less environmental cost through optimized crop distribution. *Resources, Conservation and Recycling*, 2023, **194**: 106996
40. Shen J, Cui Z, Miao Y, Mi G, Zhang H, Fan M, Zhang C, Jiang R, Zhang W, Li H, Chen X, Li X, Zhang F. Transforming agriculture in China: from solely high yield to both high yield and high resource use efficiency. *Global Food Security*, 2013, **2**(1): 1–8
41. Wang S Q. The way to regulate environmental and economic benefits of supply chain of Quzhou laying hens. Thesis for the Master's Degree. Beijing: *China Agricultural University*, 2023 (in Chinese)
42. Chang Z, Cai H, Talsma E F, Fan S, Ni Y, Wen X, Van't Veer P, Biesbroek S. Assessing the diet quality, environmental impact, and monetary costs of the dietary transition in China (1997–2011): Impact of urbanization. *Frontiers in Sustainable Food Systems*, 2023, **7**: 1111361
43. Cai H, Biesbroek S, Wen X, Fan S, van 't Veer P, Talsma E F. Environmental footprints of Chinese foods and beverages: literature-based construction of a LCA database. *Data in Brief*, 2022, **42**: 108244
44. Xu J, Zhang Z, Zhang X, Ishfaq M, Zhong J, Li W, Zhang F, Li X. Green food development in China: experiences and challenges. *Agriculture*, 2020, **10**(12): 614
45. Cusworth S J, Davies W J, McAinsh M R, Stevens C J. Sustainable production of healthy, affordable food in the UK: The pros and cons of plasticulture. *Food and Energy Security*, 2022, **11**(4): e404
46. Liu X, Xu W, Sha Z, Zhang Y, Wen Z, Wang J, Zhang F, Goulding K. A green eco-environment for sustainable

development: framework and action. *Frontiers of Agricultural Science and Engineering*, 2020, **7**(1): 67–74

47. Meng F, Wang M, Strokal M, Kroeze C, Ma L, Li Y, Zhang Q, Wei Z, Hou Y, Liu X, Xu W, Zhang F. Nitrogen losses from food production in the North China Plain: a case study for Quzhou. *Science of the Total Environment*, 2022, **816**: 151557
48. Zou T, Meng F, Zhou J, Ying H, Liu X, Hou Y, Zhao Z, Zhang F, Xu W. Quantifying nitrogen and phosphorus losses from crop and livestock production and mitigation potentials in Erhai Lake Basin, China. *Agricultural Systems*, 2023, **211**: 103745
49. Zhang Q, Kroeze C, Cui S, Li Y, Ma L, Strokal V, Vriend P, Wang M, van Wijnen J, Xu W, Zhang F, Strokal M. COVID-19 estimated to have increased plastics, diclofenac, and triclosan pollution in more than half of urban rivers worldwide. *Cell Reports Sustainability*, 2023, 100001
50. Benton T. Climate change and agriculture: adaptation and mitigation. *Food Systems Academy*, 2019. Available at Food Systems Academy website on September 20, 2023
51. Barrett C B, Benton T G, Cooper K A, Fanzo J, Gandhi R, Herrero M, James S, Kahn M, Mason-D'Croz D, Mathys A, Nelson R J, Shen J, Thornton P, Bageant E, Fan S, Mude A G, Sibanda L M, Wood S. Bundling innovations to transform agri-food systems. *Nature Sustainability*, 2020, **3**(12): 974–976
52. The State Council, the People's Republic of China. Opinions on Innovating Systems and Mechanisms to Promote Agriculture Green Development. *The State Council, the People's Republic of China*, 2017 (in Chinese)
53. Zhang H, Feng Y, Jia Y, Liu P, Hou Y, Shen J, Zhu Q, Zhang F. China's agriculture green development: from concept to actions. *Frontiers of Agricultural Science and Engineering*, 2023 [Published Online] doi: 10.15302/J-FASE-2023512
54. Bai Z, Wu X, Lassaletta L, Haverkamp A, Li W, Yuan Z, Aguilera E, Uwizeye A, Sanz-Cobena A, Zhang N, Fan X, Zhu F, Dicke M, Wang X, Ma L. Investing in mini-livestock production for food security and carbon neutrality in China. *Proceedings of the National Academy of Sciences of the United States of America*, 2023, **120**(43): e2304826120
55. Pohl C, Klein J T, Hoffmann S, Mitchell C, Fam D. Conceptualising transdisciplinary integration as a multidimensional interactive process. *Environmental Science & Policy*, 2021, **118**: 18–26
56. Pachoud C, Labeyrie V, Polge E. Collective action in Localized Agrifood Systems: an analysis by the social networks and the proximities. Study of a Serrano cheese producers' association in the Campos de Cima da Serra/Brazil. *Journal of Rural Studies*, 2019, **72**: 58–74
57. Jiao X Q, Zhang H Y, Ma W Q, Wang C, Li X L, Zhang F S. Science and Technology Backyard: a novel approach to empower smallholder farmers for sustainable intensification of agriculture in China. *Journal of Integrative Agriculture*, 2019, **18**(8): 1657–1666
58. Zhang W, Qiao Y, Lakshmanan P, Yuan L, Liu J, Zhong C, Chen X. Combing public-private partnership and large-scale farming increased net ecosystem carbon budget and reduced carbon footprint of maize production. *Resources, Conservation and Recycling*, 2022, **184**: 106411
59. Zhao H, Chang J F, Havlík P, Van Dijk M, Valin H, Janssens C, Ma L, Bai Z H, Herrero M, Smith P, Obersteiner M. China's future food demand and its implications for trade and environment. *Nature Sustainability*, 2021, **4**(12): 1042–1051
60. Zhou J, Jiao X, Ma L, de Vries W, Zhang F, Shen J. Model-based analysis of phosphorus flows in the food chain at county level in China and options for reducing the losses towards green development. *Environmental Pollution*, 2021, **288**: 117768