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REVIEW

Agriculture Green Development: a model for China and the world

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Abstract Realizing sustainable development has become a global priority. This holds, in particular, for agriculture. Recently, the United Nations launched the Sustainable Development Goals (SDGs), and the Nineteenth National People’s Congress has delivered a national strategy for sustainable development in China—realizing green development. The overall objective of Agriculture Green Development (AGD) is to coordinate “green” with “development” to realize the transformation of current agriculture with high resource consumption and high environmental costs into a green agriculture and countryside with high productivity, high resource use efficiency and low environmental impact. This is a formidable task, requiring joint efforts of government, farmers, industry, educators and researchers. The innovative concept for AGD will focus on reconstructing the whole crop-animal production and food production-consumption system, with the emphasis on high thresholds for environmental standards and food quality as well as enhanced human well-being. This paper addresses the significance, challenges, framework, pathways and potential solutions for realizing AGD in China, and highlights the potential changes that will lead to a more sustainable agriculture in the future. Proposals include interdisciplinary innovations, whole food chain improvement and regional solutions. The implementation of AGD in China will provide important implications for the countries in developmental transition, and contribute to global sustainable development.

Keywords Agriculture Green Development, food security, interdisciplinary innovations, resource use efficiency, sustainable development, sustainable intensification, whole industry chain

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1 Challenges for future food production

1.1 New demands for Agriculture Green Development (AGD)

Over the last few decades, the Green Revolution initiated by Norman Borlaug, has saved the lives of millions of people in developing countries and involved the combined use of high-yielding crop varieties, mineral fertilizers, water and agro-chemicals. However, the Green Revolution cannot be considered to be truly “green”, due to significant and sometimes inappropriate use of agro-chemicals, especially chemical fertilizers. Highly productive new crop varieties generally need lots of fertilizer and water. Facing the great challenge of high resource use and environment cost of the current operation of the food system, leaders of many countries have agreed on a vision to realize sustainable development, particularly for agriculture as an important part of this global movement. China, a big agricultural country endowed with rich agricultural resources, has a long history of farming and tradition of intensive cultivation as well as a rural population of 800 million[1]. The Chinese government has placed high priority on the development of agriculture and especially on increased food security. Since 1978, China has implemented a policy of reform and opening-up gradually, bringing along a quickened pace in agricultural reform and development[2]. Particularly in recent years, the government has given first priority to research work on agriculture in rural areas and with smallholder farmers[3]. The new central collective leadership of China has clearly proposed a national concept of green development, aiming to seek fundamental solutions to the problems associated with agriculture, rural areas and rural people, the so called “Three Rural Issues”. One of the most important issues is to promote the transformation of China's agricultural development from a high-input and high-environmental footprint model to a model based upon sustainable intensification[4,5].

Due to the implementation of a green revolution for China and powerful food policy initiatives from government, in the past decades, China has succeeded in producing 25% of world's grain and feeding 20% of world's population while using less than 10% of world arable land, which is a great achievement in pursuit of increased food and nutrition security not only in China but also in other regions[1]. Moreover, the state-initiated poverty alleviation campaign has achieved great success. Currently, China is the largest producer of cereals, cotton, fruit, vegetables, meat, poultry, eggs and fishery products in the world[6].

Despite this progress, sustainable agricultural development in China has encountered many obstacles and constraints, including agricultural water shortage, cultivated land loss and soil degradation, low resource use efficiency in the food system (nutrients, water and other inputs) and environmental contamination[7–9]. For instance, China's grain production has doubled since 1978, however, along with this has come very substantial increases in use of input resources for agriculture, i.e., a threefold increase in the use of nitrogen (N) fertilizers, an 11-fold increase in use of phosphorus (P) fertilizers, and 50% increase in the use of irrigation water in croplands[10]. These statistics demonstrate that there is enormous waste of resources embedded in the food production processes. For example, from 1980 to 2010, partial N fertilizer production decreased from 34 to 18.5 $kg \cdot kg^{-1}$, and the annual N-use surplus increased from 69 to 203 $kg \cdot ha^{-1}$[11]. The increased N-use surplus has contributed to increased NH_3 and N_2O emissions to the air, decreasing air quality, and pollution of both surface water and ground water, increasing the risk of eutrophication and nitrate excess in drinking water. All these problems threaten the sustainability of grain production and human health and well-being for the future[6,12]. Therefore, it is urgent for China to transform its current agricultural practices from a high resource consumption and high productivity-oriented model to a model based on increased sustainability.

Transformation of food systems must be taken into account as production and supply practices are redesigned to meet new demands. Focus must be shifted from "feeding people" to "enabling people to nourish themselves"[13]. Such a strategy has key elements important for the environment, people, inputs, processes, infrastructure and institutions, and activities that are related to production, processing, distribution, preparation and consumption of food, and the outcomes of these activities[12]. Agricultural transformation represents a paradigm shift and a plan of action leading toward increased sustainable intensification for food production, with beneficial effects on farm income, landscape, ecosystem services, resource and environmental costs, prosperity, justice and partnerships[14]. Therefore, promoting AGD can involve re-engineering a complex and interdisciplinary system that integrates different fields, such as soil, plant and weed sciences, genetics, ecology, entomology, pathology, animal production, food science, human nutrition, environmental science, engineering sciences, social science and policy for sustainable development. To achieve the target of "producing enough nutritious food with fewer input resources" in the future, it is necessary for China and other economic entities to integrate a wide range of science and technology innovations as well as socio-economic aspects in the whole food system.

Achieving sustainable intensification and moving toward green development for millions of small household farmers is a great challenge, but it is crucial for China, and could be a key obstacle to putting broad scale green development into practice. Both the Chinese government and the public are aware that building an ecological civilization is vital to sustain China's national development. This is critical for China and other economies in the world with similar issues such as numerous small households, particularly those countries and regions along the Belt and Road Initiative currently being developed, in South-East Asia and Africa.

1.2 New challenges for AGD

Since the 1960s, China has gone through the process of increasing crop yields to meet domestic food demand, with strong support from the central government[2]. However, during the last decade, agricultural sustainability issues have raised public concerns[15]. Many people, from farmers to entrepreneurs and government officials, are calling for healthy food for a better life by activating appropriate changes in the food supply chain. This is due in large part to the recognition that input resources for food production have often been used irrationally and to excess. For instance, more than 200 $kg \cdot ha^{-1}$ N and 50 $kg \cdot ha^{-1}$ P have accumulated in China's major croplands annually over the past 15 years[16]. Many factors, involving the activities of government, entrepreneurs and farmers, may contribute to the mismanagement of resources in China's major croplands[16].

System analyses and interdisciplinary innovations for the whole food chain are fundamental if sustainable crop production is to be achieved. Such analyses and innovations will support both agricultural production and the provision of other ecosystem services[17]. Sustainable intensification involves integrative thinking and the practice of sustainable production and consumption draws on the principles of nutrient transformation, material cycling, and ecological services[18]. Facing these challenges, from the perspective of technological innovations, an array of knowledge and technologies is developing which can contribute to AGD. Approaches are being advocated that can be integrated into farmers' practice to produce significant quantities of high quality food with reduced environmental risk[19]. The related policies and incentives for farmers to realize high resource use efficiency and environmental protection need to be further developed. Urgent actions involving market structure, policies and knowledge institution should be taken to improve sustainability of the whole food system. The evolution of the food system can be achieved more successfully with systems analysis and includes cultural and social aspects. The transformation of agriculture systems can be realized only when people are food-secure and well-nourished, ecosystems are healthy and balanced, societies are resilient in the face of threats posed by climate change, and governance of development benefits is fair and just.

In this paper, we address the challenges faced by China's agriculture, a framework for development, pathways and potential innovations for realizing AGD. We also highlight the stages that will allow progress toward sustainable agriculture, in terms of interdisciplinary innovations, whole food chain improvement and regional solutions. This case study of China may be expected to provide important understanding and serve as an example of good practice for many other countries in South-east Asia and Africa where there are millions of smallholder farmers operating and will contribute to global sustainable development strategy.

2 Framework of AGD

Based on integration of new demands for development of Chinese agriculture and the United Nations Sustainable Development Goals (SDGs), the overall objective for AGD is to coordinate "green" with "development" to realize the transformation of Chinese agriculture into green development, from high resource consumption and high environmental costs to sustainable intensification with high productivity, high resource use efficiency and low environmental risk. The innovations contributing to the concept of AGD will focus on reconstructing the crop-animal production and production-consumption systems, with two key standards: high eco-environmental standards and quality food demands.

Three main systems are involved in AGD, i.e., the natural system, the food system and human and social systems (Fig. 1). The natural system provides all the basic required materials and energies to support the growth and evolution of living systems, plants and animals, including humans in the world. The food system includes crop-based food production and animal-based food production, as well as the related processes involved in food harvest, storage, transport, processing and human consumption. Human and social systems are affected by the natural system and the food system but also have a strong feedback to these two systems. Alternatively, the balanced or unbalanced relationships largely promote the development of society and civilization. However, for the realization of the AGD target, a balanced relationship among these three systems is a prerequisite. Therefore, interdisciplinary innovative research is required to close the knowledge gap among different areas and inspire the development of new understanding relevant to the AGD.

In addition, stakeholders from different sections should be linked and co-operate in the implementation of green development. For example, when new technologies are created by scientists and new products are produced by industries without the assistance of government, these technologies or products are not always adopted by farmers. However, farmers are the key agents who manage land and water, and the effects of management can be impacted by technology extension and public policy[20]. Farmers should be curious and willing to try and alleviate distrust of others in the food chain. The farming community needs to develop trust in scientists/industry/government, or at least should be curious and willing to implement change. Therefore, an effective linkage should be established among different stakeholders to accelerate technology innovation, transfer and application.

Based on the green development concept proposed by the Nineteenth National People's Congress, as well as the major goals for global sustainable development by 2030, four working themes have been proposed by the National Academy of Agriculture Green Development, China Agricultural University (CAU) to promote the transformation of Chinese agriculture toward green development (Fig. 2).

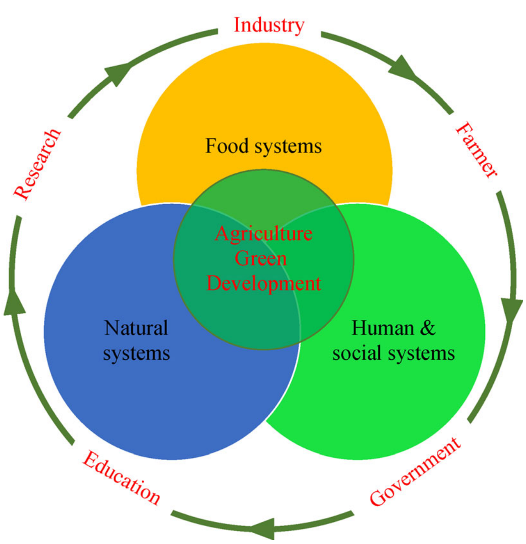

Fig. 1 Research framework for Agriculture Green Development, including three systems and five partnerships.

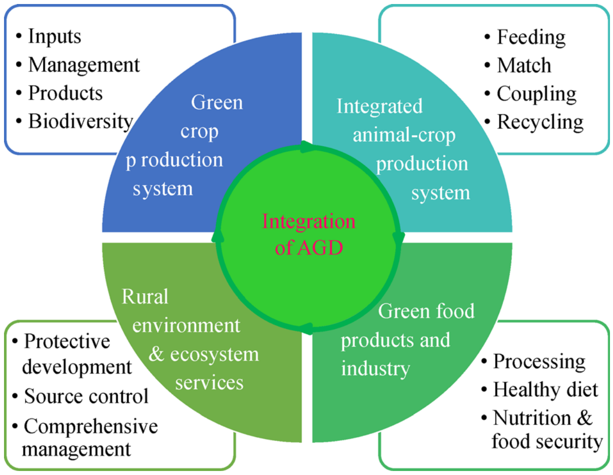

Fig. 2 Strategic research program of Agriculture Green Development (AGD), including specific directions and interactions among four subsystems: green crop production system, integrated animal-crop production system, green food products and industry, and rural environment and ecosystem services.

2.1 Green crop production system

Crop production delivers a key source of human food, which makes up 86% of the food consumed worldwide. Plant-based food is comprised of cereal crops (47%), sugar crops (17%), fruits and vegetables (12%) and oil crops (10%)[21]. In China, grain production increased more than three times from 1960 to 2014[4], but this production consumes nearly one third of global annual N fertilizer use[22]. The massive amount of N that have leached into water bodies in China, remained in soil, or has been lost to the atmosphere through ammonia volatilization or nitrification-denitrification, has created an unstable vicious cycle and thus has impaired the development of increased environmental sustainability[23–25]. Achieving green crop production is critical for addressing the challenges of ensuring food security and environmental protection[26,27].

Green input and green management are preconditions of a green crop production system. This consists of development of new crop varieties, new fertilizers and green pesticides, establishing an integrated soil-crop system management and designing cropping systems with rotation and intercropping to achieve sustainable intensification in food production with high yield, high resource use efficiency and environmental resilience. Green crop production must be implemented to promote the fundamental transformation of agricultural production from a traditional model with high resource consumption and high environmental costs into a high productivity, high resource use efficiency and low environmental impact, and thus realize the fundamental change of agricultural development from solely intensive food production to a sustainable system. Green crop production includes, but is not limited to green input, management and output of green products. For example, cropping system redesign will involve increased soil fertility and soil health, both fundamental to the provision of significant amounts of high quality food (products), i.e., achieving both food and nutrition security while sustaining biodiversity, a fundamental requirement if ecosystem functions are to be enhanced[28].

2.2 Integrated animal-crop production system

Livestock production is an important part of food production in all countries, providing animal-based food, such as meat, eggs and milk, which contain more easily-absorbed nutrients compared to much plant-based food. It can also provide some important raw materials for industry which are necessities for daily human life, for example feathers and leather in the textile and clothing industry. China is now the largest producer of livestock. However, the individual livestock productivity is low compared to the EU and the USA[29,30]. Livestock systems are an important contributor to agriculture-based pollution. The annual excretion of waste from livestock systems is about 3.8 billion tons in China, however, the comprehensive use efficiency is less than 60%[31]. The contributions of Chinese livestock to the total NH_3 emission and chemical oxygen demand (COD) in agricultural emissions are 44% and 96%, respectively[32]. These are all important contributors to the development of climate change but China is lacking appropriate technologies and measurements on animal excretion management, and the decoupling of livestock and crop production in China is one of the biggest barriers to green agriculture in the country[33].

A green products-oriented livestock system, similar to the crop system, also requires green management during the whole production process, including green feeding and clean housing. Currently, large scale intensive farms dominate the livestock production system in China[30]. In view of their important roles in environment pollution (site-source of pollutant emission), green disposal of the excretion from the intensive farm need to be addressed in this system. At a regional scale, crop systems and livestock systems are crucial for the life and happiness of local residents, since they provide necessary materials for daily life and contribute most of the income of the rural population. Also, as they are the primary producers providing raw materials for industry, these systems are treated as fundamental to the stability and sustainable development of the country[34]. In principle, the two systems should be coupled so that crop system provides almost all the materials for feeding livestock, and receives and uses the excreta from the livestock as part of the nutrient supply to crops[30,35]. Uncoupled or unmatched animal-crop systems will increase the risks of environmental pollution from emission of pollutants from the livestock system, which could be used as valuable nutrients for crop production[36]. The integrated animal-crop production systems should be developed through optimizing the agricultural industrial structure to transform it from a single to a diversified structure. Nutrient cycling can be coupled between arable agriculture and animal husbandry to increase nutrient use efficiency in the whole food chain, although in such systems attention must be given to food safety considerations.

2.3 Green food products and industry

Green food supply is one of the strongest demands of the Chinese people. Their priority is for safe, high quality, and nutritious food, as well as giving increased attention to rural ecological environmental protection[37]. Rapid progress of green food in economic, ecological and social terms, as well as brand influence, has been achieved over the last two decades. However, green food in China currently faces several significant challenges, which need to be addressed to make further progress. These challenges include mismatch of the current production scale and the increasing demand of people for high-quality, nutritious green food, as well as an unbalanced product structure comprising mainly agro-products with a short shelf life and a lack of input on market promotion[38]. The recommended healthy diet is one that includes cereals and fruit and vegetables that account for 20% and 49% of the whole food intake, respectively[39], whereas the production of cereals, and fruit and vegetables are 49% and 19% in the whole food production system, respectively, resulting in an imbalance in food production and consumption requirements[21].

In addition, the development of a green food industry also faces new challenges such as maintaining food and nutrition security, climate change, limiting water availability, and decreasing biodiversity[40]. In this theme of the National Academy of Agriculture Green Development, food processing, healthy diet and food (including nutrition) security were included to help realize targets for green food production, green processing and healthy human life. We argue that during the realization, the whole food system should be market-oriented. A target-based back-casting design is suggested for the development of green products and industry. To be explicit, the products produced from upstream and downstream in the industry should be consistent with the requirement for green inputs in crop-animal production and the quality criteria in the market-food system. Also, a green industry and market docking model should be implemented through building green industry-based e-commerce and big data platforms to promote green industry and market development. This would be achieved by connecting with the Internet and other means of information dissemination and retrieval, ultimately realizing the deep integration of agricultural production, food processing and marketing toward green, ecological, and high value-added industry. With the requirement of green products, technology innovation, knowledge transfer and precision management are urgently needed, and the related technology services should also be linked to developing crop-animal systems.

2.4 Rural environment and ecosystems services

With rapidly increasing population and living standards, China will have to produce more plant and animal products to meet food demand in the near future, but the environment faces huge pressure[27]. For example, under the current high N fertilization practice in the winter wheat-summer maize rotation system, more than 70% of N applied to crops is lost to the environment[41]. Since 2005, agricultural production has overtaken industry as the dominant source of water pollution in China, which contributed 44% of COD, 57% of nitrogen and 67% of phosphate in water bodies, being the main driving force for eutrophication and groundwater nitrate accumulation in many regions[42]. Livestock has become the main sources of discharges to water, contributing 96% of COD, 38% of N and 56% of P[30]. China's major rivers, especially the Yangtze River, received P from overuse of fertilizers in agriculture, which contributed greatly to degradation of water quality[43]. In addition, under current N management, cropland N discharge alone exceeds critical pollution thresholds (5.2 ± 0.7 $\mathrm{Mt \cdot yr^{-1}}$ N) in 14 of 31 provinces[25]. Due to the legacy effects of accumulated nutrients in water bodies, the polluted water cannot be cleaned in a short time period, even using innovative technology. In this context, a green eco-environment framework for balancing human demand and environmental sustainability is urgently needed in China's agriculture.

Ecological environment is the name generally encompasses the magnitude and quality of soil, water, climate and living resources, which are fundamental to all human existence and development. The increasing ecological environmental problems are seriously threatening human survival. The quality of the human living environment (habitat) and the natural environment (habitat surroundings, including the water, air and soil) are central to this. In view of the large effects from the emissions from crop-animal production and food processing and consumption systems, the fundamental principles needed to realize green eco-environment involve protective development, pollutant source control and comprehensive management of all ecosystems. The realization of green ecological environment consists of four major measures: (1) develop a green eco-environmental indicator system, (2) establish monitoring and warning networks, (3) set emission standards and environmental thresholds for key pollutants, and (4) develop new emission control measures and pollution remediation technologies. Measures 1–3, in turn, provide feedback to optimize measure 4 (for details see Liu et al.[44]).

3 Perspectives

3.1 Enhancing interdisciplinary research innovations

AGD involves many aspects of society, economy, environment, and food and nutrition security. It cannot be denied that independent fundamental research on a specific field is important for development of innovative technologies and to provide critical insights into the mechanisms behind the operation of different systems. However, fragmented research in individual disciplines is unlikely to successfully address the complex problems in the whole agricultural system. For example, resource conservation, environment sustainability, poverty, food and nutrition security, and underground water pollution, are all closely related to agricultural production, environmental protection and rural development. In view of the complexity of agriculture transformation toward green development, from intensive agriculture to sustainable intensification with high productivity, high resource use efficiency and low environmental risk in China, a focused interdisciplinary research program is needed through integrating these related subjects or research fields[45]. The interdisciplinary innovations are crucial for realizing AGD, exploiting new developments in research that are needed to break existing disciplinary boundaries[46]. Interdisciplinary research is recommended and has been applied to solve the complex problems and inspire innovation[47,48].

Interdisciplinary research innovation in AGD will focus on understanding the coupling mechanism in terms of material, energy, information and value flows between different subsystems, particularly at four interfaces: water-soil-air systems, plant-soil systems, animal-crop production system, and green production and consumption systems. To support the implementation of interdisciplinary research innovation in AGD, the National Academy of Agriculture Green Development and the International School of Agriculture Green Development were launched by CAU on July 22, 2018. An interdisciplinary education project training 90 CSC-PhD students with Wageningen University over 3 years, which is funded by the China Scholarship Council (CSC), has been approved recently with the aim of conducting cutting-edge, innovative research on subsystem coupling mechanisms throughout the whole agricultural industry chain. These actions are expected to substantially promote Chinese AGD. The advances in Chinese AGD could provide a valuable example for global sustainable development of agriculture, as a dominant part of several SDGs[49].

3.2 Innovating bottleneck technologies to improve the whole industry chain toward green development

New system approaches are needed to explore AGD from the perspective of the whole food chain. Quantitative approaches can be adopted to locate bottlenecks along the food chain which hamper green development. Moreover, innovations of science and technology are fundamental for promoting economic and societal development toward "green sustainability". However, technology application usually lags behind the pace of knowledge innovation. Therefore, considering the combination of the current technologies with innovative technology research is critical in order to efficiently address problems in the whole food chain. System approaches can promote innovation research across the knowledge boundaries, including life cycle assessment, mass balance and flow, value chain analysis, footprint assessment, and system modeling.

An industry chain can be established with the background of division of labor and value distribution, which is composed of a series of interdependent enterprises and R&D organizations. The upstream and downstream flows are involved in serving a specific demand or producing specific products and services and information feedback[50]. The principle can be used in industrial research of AGD to link the supply-demand relationship among different enterprises, and realize effective management and collaboration. An overall improvement of the whole agricultural industry chain is thus required to increase resource use efficiency and the value of the food chain. The approach is also capable of solving the bottleneck problems in different research themes in AGD. For example, manure excreted by animals is of huge risk to water and air pollution. Disposal of the manure in a proper way needs large investment by intensive livestock farms, which can be fined for over-emission of pollutants. However, manure is a resource for nutrient supply for crop production and for improving the soil texture/properties. Therefore, coupling the animal production system with the crop production system may greatly reduce the nutrient loss to the environment and increase nutrient use efficiency, but needs to consider the whole industry chain for achieving AGD. Taken together, the whole industrial chain linkage and management requires an innovative system approach to optimizing the agricultural system and food system toward green food production and a green environment.

3.3 Developing regional solutions for AGD

The realization of AGD at a regional level needs to integrate the four themes mentioned above, with a focus on the science and technology aspects for the three key food subsystems, i.e., crop system, livestock system and food-processing industry system. However, providing the means to realize these changes simultaneously at a regional scale is still a substantial challenge. The realization of AGD involves the cooperation of scientists, industries, farmers, educators and government in aspects of technology innovation and application, knowledge transfer and extension, policy support and guarantee, and talent education (Fig. 1; Fig. 3). Scientific and Technology Backyard (STB), as a new model for knowledge transfer, established by CAU, is a successful development which connects farmers with researchers, government and industry, by training farmers to transfer new technologies and products to a broader farming community. Also, this model has established a channel to transfer the feedbacks of existing problems and new requirements to related stakeholders, e.g., government and industry[9]. With the efforts of STBs, the average yield of combined wheat and maize increased from 12.0 $t \cdot ha^{-1}$ in 2008 to 15.6 $t \cdot ha^{-1}$ in 2013 countywide in China (93074 households)[51]. Government should have an important role in the regional realization of AGD. First, an effective top-down design can efficiently coordinate the relationships between environment, economy development and social impacts. To promote the realization of the design, effective policy and solutions should be released to encourage and guarantee implementation of corresponding actions[52]. Policies balancing incentives and penalties can be effectively designed to encourage positive actions and discourage negative ones[53]. Furthermore, the support of fundamental infrastructure, and increased investment in technology extension are also important components of any policy to encourage the realization of AGD.

To achieve regional objectives for AGD, CAU has proposed the development of a series of demonstration areas for green sustainable development, collaborating with Quzhou government and relevant enterprises from both China and abroad. These will be sites to conduct an extensive research and demonstration program for sustainable agriculture. From Quzhou County the program will be upscaled to a North China regional level, and then to the whole of China, further promoting the transformation of agriculture development in China. This development offers an excellent opportunity to realize several of the 2030 SDGs.

Fig. 3 The collaboration of different stakeholders to realize Agricultural Green Development (AGD).

In China, the county is a basic unit for implementation of AGD actions, hosting pilot experiments to test the top-down design of AGD and thus inspire extensive realization at a large scale and eventually even globally. Systems approaches need to be adopted to guide the regional realization of AGD. The approach should consist of system analysis (current weakness, related drivers and pressures), development (science and technology innovation and knowledge transfer), proto-typing (solution-based case study), synthesis (systematic evaluation on the effect) and reporting (recommendation, policy and law). Implementing green development in agriculture can help to promote rural revitalization, which is one of the most important national priorities in China. Given the complexity of AGD, interdisciplinary innovative research, participation of different stakeholders and systematic top-down designs for valued food chains and effective solutions of whole food system challenges are crucial for regional realization of AGD and the improvement of the quality of life of millions of Chinese people.

The ideas central to the development of AGD are consistent with the United Nations SDGs, to achieving a sustainable, efficiency and comfortable society for the global population. AGD offers more explicit ways to achieve targets by enhancing interdisciplinary research, and innovating technologies in the food chain and developing regional solutions for AGD. During the program, problem-oriented scientific research is combined with the training of a new generation of scientists by the China Scholarship Council (CSC) program to train PhD students, and the outreach to society through STBs. This combination makes AGD a powerful and potentially impactful program. It could serve as an example for other global regions, for developing and developed countries by introducing the experience of talent training, knowledge transfer and inspiration for global sustainable development.

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