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REVIEW

Enhancing green productivity and efficiency through innovative approaches to agricultural system research

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KEYWORDS

Agricultural green development, green productivity, green efficiency, agricultural system research approach, food production, transform pathways

HIGHLIGHTS

- Provides innovative agricultural system research approach that integrates interdisciplinary research, advocating for a combined top-down and bottom-up strategy.
- The integrated agricultural research approach has the potential to contribute to concurrently address food security challenges, enhance resource use efficiency, and safeguard the environmental sustainability.
- A network of Science and Technology Backyards not only addresses national strategic demands but also offers effective solutions to address bottleneck issues in production.

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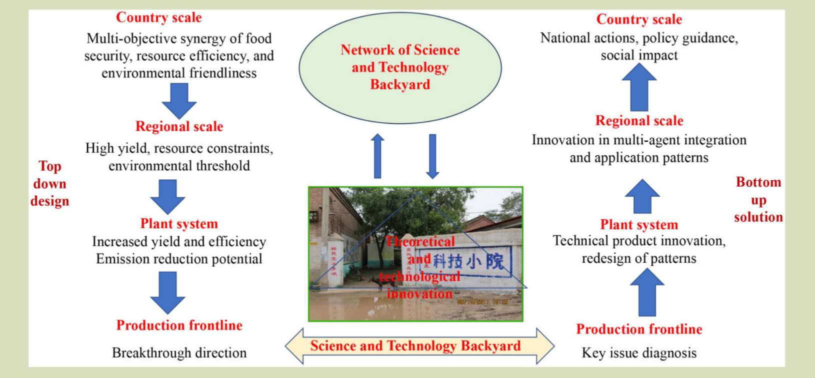
GRAPHICAL ABSTRACT



ABSTRACT

Agriculture is undergoing a pivotal transformation, shifting from a singular focus on food security to interdisciplinary research that encompasses food security, environmental protection and sustainable use of resources. The growing global population and climate change exert the urgency to adopt sustainable practices that balance crop productivity and environmental stewardship. The merit of the approach of past agricultural research, typically centered on single processes and limited to specific disciplines and goals, is now a subject to debate. There is need for a multi-objective approach, an enhancement of the whole industry chain enhancement (involves service from the initial raw material stage to the final consumer) and a holistic approach for sustainable agricultural development. To address these challenges, this article presents an innovative agricultural system research approach. This approach integrates interdisciplinary research and advocates for a combined top-down and bottom-up strategy. The concept of innovative agriculture refers to redesigning systems through technological integration for large-scale application, ultimately aiming to enhance overall crop production, environmental sustainability and efficiency. The top-down approach sets yield targets and environmental thresholds at various scales, aligning with national objectives for food security, resource use efficiency and ecological sustainability. This method determines the necessary technical systems and integration methods. In contrast, the bottom-up approach based on Science and Technology Backyard, analyzes the factors that constrain high crop yields and efficiency, and develops systematic methods to achieve high yield and high efficiency. The integrated agricultural research approach can simultaneously address food security challenges, enhances resource use efficiency, and protect the environmental sustainability. This is essential for advancing sustainable agricultural practices in the face of increasing global demands and environmental concerns.

1 Introduction

With the increasing population, the demand for agricultural food continues to increase[1]. To meet the food demand, agriculture must enhance its productivity to ensure a sufficient food supply. Driven by different goals at various development stages, the agricultural system has undergone a multifaced evolution in its pursuit of high yield and high efficiency. During the 1960s to 1970s period, the international agricultural research institutions prioritized the cultivation of high-yielding crop varieties to increase crop production[2]. The pre-1970 Green Revolution predominantly emphasized yield maximization to fulfill basic caloric requirements[2,3]. However, although this approach achieved remarkable production gains, it did not consider production efficiency and environmental quality. After 1980, there was a growing focus on the production efficiency and environmental quality of agricultural production. In this phase, the principal strategy was to enhance the development of integrated and organic farming systems to reduce dependence on external inputs, improve the self-sufficiency of farms, and maintain a healthy and productive agricultural system[4,5]. Post-1990, the agricultural system faced two major challenges: escalating crop demand driven by growth of population and economic well-being and intensifying environmental degradation from expanding cropland. To meet the demand for increased agricultural output within the limits of environmental thresholds, the focus of this phase shifted to moderate intensification. As Tilman et al.[6] noted, in countries with low yields, it is essential to focus on enhancing the productivity of existing arable land through a strategy of moderate intensification. This approach involves adapting and transferring high-yield agricultural technologies and promoting global technological progress[6]. However, this conceptual framework lacked operational implementation guidelines, resulting in a significant gap between research and practice gap[7]. Post-2010, with the refinement of macro-agricultural foundational databases, significant advancements have been made in agricultural research. Current research seeks to balance yield enhancement, resource efficiency and environmental sustainability through region-specific strategies[8–10]. These strategies include precision nutrient management, integrated crop-livestock systems and emission-reduction technologies, collectively constituting a multidimensional approach to agricultural modernization. Although agricultural development has transitioned from single-objective to a multi-objective coordination process, practical implementation within production remains a predominant challenge of modern agriculture system.

Currently, the factorial experiments and systems experiment are two commonly used methods for analyzing agricultural systems[11]. Factorial experiments are useful for evaluating the effects of different agricultural practices on crop performance. However, they may fail to fully account for the complexity and diversity present in farmer fields. The reason is that factorial experiments conducted at experimental stations are usually based on comparisons under controlled conditions. In contrast, many factors in actual agricultural systems may interact and collectively affect crop yield and quality[12]. Thus, systems experiments can consider the interplay and integrated functionality of various factors within agricultural system, contributing to a more comprehensive understanding of the agricultural system. However, systems experiments are usually conducted under favorable conditions, making it difficult to control all variables. This situation may impede the accurate attribute attribution of specific impacts to different management practices and is possibly related to the low adoption rates of technology in agricultural application[13]. To address these methodological limitations, novel research paradigms have been progressively developed since the late twentieth century. Approaches such as on-farm experimentation and the DEED (describe, explain, explore and design) framework aim to bridge the gap between researchers and farmers through participatory and context-embedded investigation[14,15]. Despite their conceptual advancements, these methodologies have yet to achieve widespread institutional adoption. Therefore, interdisciplinary systems approaches represent a crucial breakthrough for future food and agricultural research.

Current agricultural research methodology in China does not meet the requirements of agricultural green development. The lack of on-farm experiments and frontline data on agricultural production leads to the decoupling of agricultural technology innovation and its application. To facilitate the transition to sustainable agricultural development, it is crucial to understand the current needs and explore innovative research approaches that can enhance efficiency and yield while minimizing environmental impacts. Therefore, to achieve high yield and efficiency in the context of agricultural green development, the scientific research model needs to shift toward an interdisciplinary and integrated research model. This study proposes an innovative agricultural system research approach by integrating interdisciplinary research and advocating a combined top-down and bottom-up strategy. This approach not only helps achieve high yield and high efficiency, but also promotes the on-farm application of innovation agricultural technologies with the aim of enhancing agricultural productivity.

2 Framework for an innovative agricultural technology system

This paper presents a research framework aimed at enhancing crop green yield and efficiency. The framework is centered around a top-down and bottom-up multi-objective collaboration, multiscale coupling and multi-actor integration approach based on Science and Technology Backyards (STBs). By establishing STBs, frontline production data are collected. These data enable the development of large-scale, high-yield, high-efficiency system designs and methodologies based on farmer data. The developed system designs and methodologies include an hybrid-maize simulation model, in-season root-zone nitrogen management, strategies to increase soil productivity and the integration of high-yield, high-efficiency technologies. Driven by the goal of enhancing yield and efficiency, the integration of these technologies and system designs has facilitated agricultural system reform. It also taken into account the diverse soil and management conditions of smallholders, thereby improving the adoption rate of innovative technologies.

This study developed a framework for a high-yield and high-efficiency technology system based on principles of agricultural green development. Through interdisciplinary research, the framework presents potential pathways to transform current single-objective agricultural technology into a multi-objective innovation technology. As shown in Fig. 1, there are two key pathways top-down and bottom-up strategies. Both strategies focused on a high-yield and high-efficiency system with multi-target collaboration, multiscale coupling and multi-actor integration, centered around STBs[16]. The top-down approach commences with national-scale objectives that aligning food security, resource efficiency and environmental sustainability. These overarching goals are then cascaded to regions, where

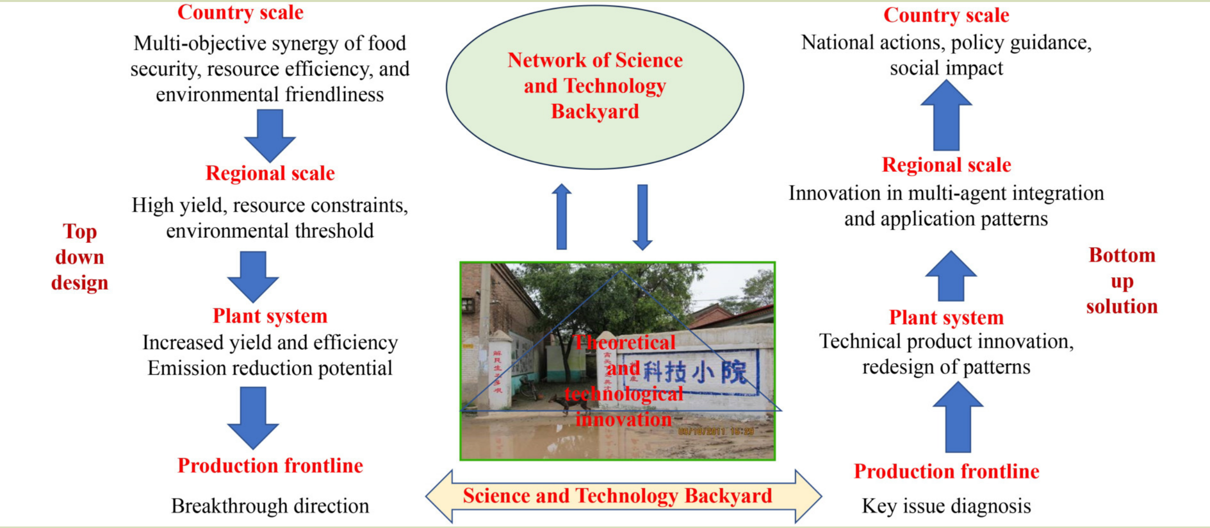


Fig. 1 Framework for a high-yield and high-efficiency innovation system.

they are tailored to crop-specific yield targets and emission thresholds. Regional crop systems are analyzed to identify yield potentials and emission reduction capacities, while also taking into account on-farm constraints. Conversely, the bottom-up approach initiates from the challenges encountered in frontline production. Diagnostic analyses are performed to develop context-specific technologies (e.g., drought-tolerant crops). Subsequently, these innovations are integrated into adaptable crop system models, enabling their replication across regions.

STBs are localized innovation hubs characterized by problem-oriented knowledge production, tailoring solutions to regional contexts (e.g., water-saving technologies in resource-scarce areas, conservation agriculture in fragile ecosystems). They expand from individual farms to regional clusters, optimizing industrial chains and technical services while demonstrating cross-regional adaptability (e.g., African and South-east Asian applications). By integrating top-down and bottom-up innovation, the STB network enhances smallholder productivity, reduces pollution and aligns with Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger) through yield improvements and SDG 11 (Sustainable Cities and Communities) via emission mitigation. The framework establishes the STB network as a core platform for multi-target collaboration (yield, environment and equity) and multiscale coupling (farm-to-national levels). Anchored in localized knowledge, it balances productivity with ecological integrity-increasing yields while addressing regional environmental challenges (water scarcity, soil degradation and air pollution). This integrated approach offers an innovative method for high yield and efficiency.

2.1 Top-down methodology for increasing production and efficiency

In the context of a top-down approach, designing a high-yield, efficient cropping system is critical to food security (Fig. 2). At a national scale, the first step of the top-down approach is to set production targets that are crucial for ensuring food security. The next step is to identify and establish thresholds for other factors that significantly influence grain yield. These factors encompass a range of determinants that can either enhance or constrain agricultural productivity (GHG emission, water restriction and land use). National crop production targets are disaggregated into regional scales based on population distribution. Regional water and land use thresholds are then derived from these targets, while GHG emission limits are calculated using a regression model linking SDGs and emission[17]. The NUFER model is used to calculate the status of yield and environmental emissions at different farmland scales. By comparing these calculated results with the preestablished targets, the potential for yield enhancement and the reduction in environmental emissions for each region and farm can be determined. Consistent with environmental emission reduction requirements and the potential for yield enhancement, four categories of technologies are needed: nutrient management, water-fertilizer integration, emission reduction technologies and land consolidation. These strategies

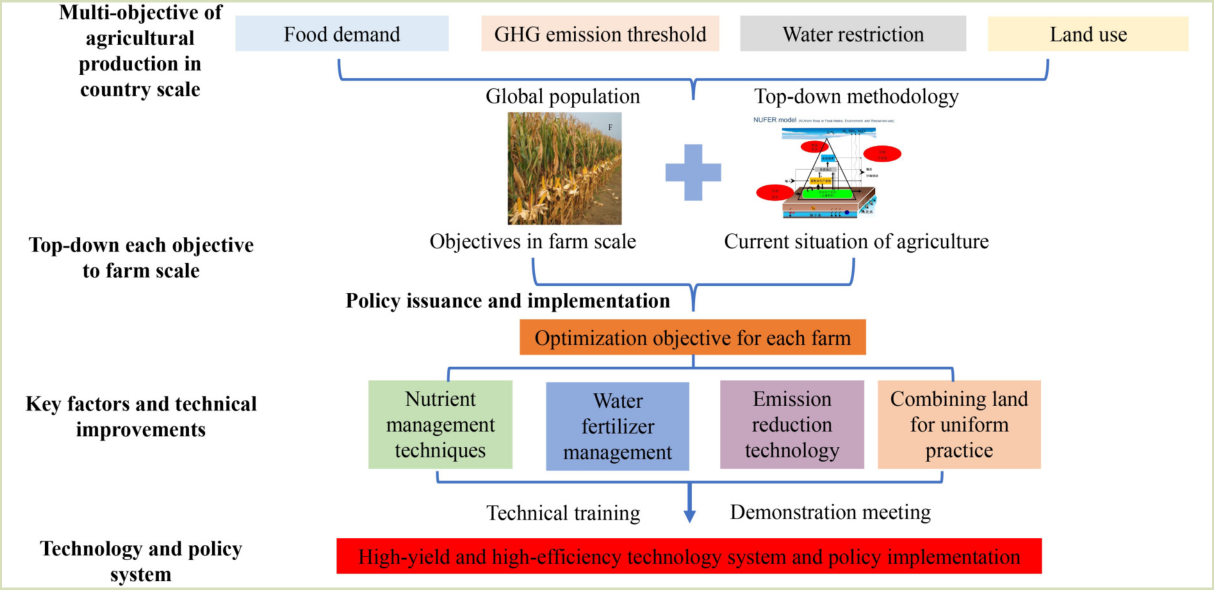


Fig. 2 Top-down technology for a high-yield and high-efficiency agricultural system.

aim to optimize agricultural inputs, minimize environmental pollution and maximize crop production potential. Ultimately, through technical training and demonstration meetings, a high-yield and high-efficiency system can be established by implementing the improved technology. Meanwhile, the implementation of relevant policies ensures the practical application and effective adoption of the system.

Numerous case studies have demonstrated the feasibility of top-down innovative technologies centered around STBs in improving crop yields and efficiency while reducing environmental pollution[18–20]. Zhao et al.[18] applied a top-down food system innovation framework, which integrated technological innovation, spatial planning and demand-side management. This framework enabled China to close 80% of its domestic protein gap within environmental thresholds. Liu et al.[19] used a top-down approach to allocate global phosphorus thresholds to various subbasins in China, identifying hotspots of water quality exceedance. An improved crop-livestock integration model was then used to reduce phosphorus, ensuring that water quality remained within acceptable threshold values. Additionally, to address the crises in future food systems, three pathways for optimizing sustainable food systems have been constructed in China[20]. These pathways not only contribute to the green development of Chinese agriculture but also have the potential to reduce the environmental emissions related to arable land, water resources, greenhouse gases, and nutrients by 7% to 55%[20]. At the national scale, Bai et al.[21] focused on addressing water body eutrophication, assessing agricultural nitrate and phosphorus erosion risks, and analyzing nutrient loss in manure management. They proposed the designation of nutrient vulnerable zones to control agricultural pollution, which can accurately identify key areas that require immediate policy and action[21]. Additionally, Bai et al.[22] proposed at the national scale that through spatial planning of livestock, reallocating manure resources and increasing the integration of agriculture and livestock, the problem of excessive nutrient emissions in the agricultural system can be effectively resolved. Due to the rapid changes in the food system of China, Wang et al.[23] quantified future reactive nitrogen losses under shared socioeconomic pathways and proposed an optimal development path for China's future food system. Although previous studies have shown that top-down methods can effectively optimize resource allocation, enhance agricultural productivity and improve product quality, top-down methods usually depend on macro-level data. As a result, they fail to fully account for regional individual differences and specific conditions, and lack targeted technological innovation to address specific problems in the production process. This paper, however, uses a top-down approach to define the direction of multi-objective coordinated development for regional food security, resource efficiency and environmental protection, thereby guiding technological and model innovation in frontline production.

2.2 Bottom-up methodology for increasing production and efficiency

The bottom-up approach to achieving high-yield and efficient agricultural solutions emphasizes starting from frontline production. It integrates local knowledge, practical experience of farmers and modern technology with innovative models to achieve sustainable development in agriculture (Fig. 3). First, it is essential to identify key production constraints at the production frontline. These critical challenges need to be diagnosed and thoroughly analyzed in depth, which then drives innovations in technical products and the redesign of models within the crop system to address the identified problems. Secondly, application models should be further refined to align with the environmental characteristics (including soil, weather and water) before scaling up promotion on a regional scale. Finally, national actions and policy guidance should be implemented to ensure the adoption of new technologies while protecting the rights and interests of farmers. This paper proposes a bottom-up approach based on the STB network, which mainly includes the DAIRE (diagnosis, analysis, innovation, redesign and extension) and ISSM (integrated soil-crop system management) methods. Specifically, DAIRE uses the STB network to construct a frontline production database. It diagnoses production bottlenecks through meta-analysis and quarter division. Analytical methods, including boundary line analysis, structural equation modeling and principal component analysis, are used to quantitatively assess the impact of limiting factors and select the optimal technological solutions. Based on these analyses, the DAIRE method further establishes innovative design and verification approaches for high-yield and efficient systems. It focuses on the innovation and dissemination of these models to achieve sustainable agricultural development and enhanced productivity[24–27]. ISSM is an agricultural management strategy designed to enhance the productivity, sustainability and environmental integrity of farming systems. Similar to the DAIRE method, ISSM begins by leveraging a database constructed from STBs to identify yield enhancement potential through field trials. This process involves analyzing existing data on crop performance, soil conditions and climate variables to predict the maximum attainable yields under optimal management practices. ISSM optimizes crop planting dates, densities and varieties by considering the synergies among soil, crops and the

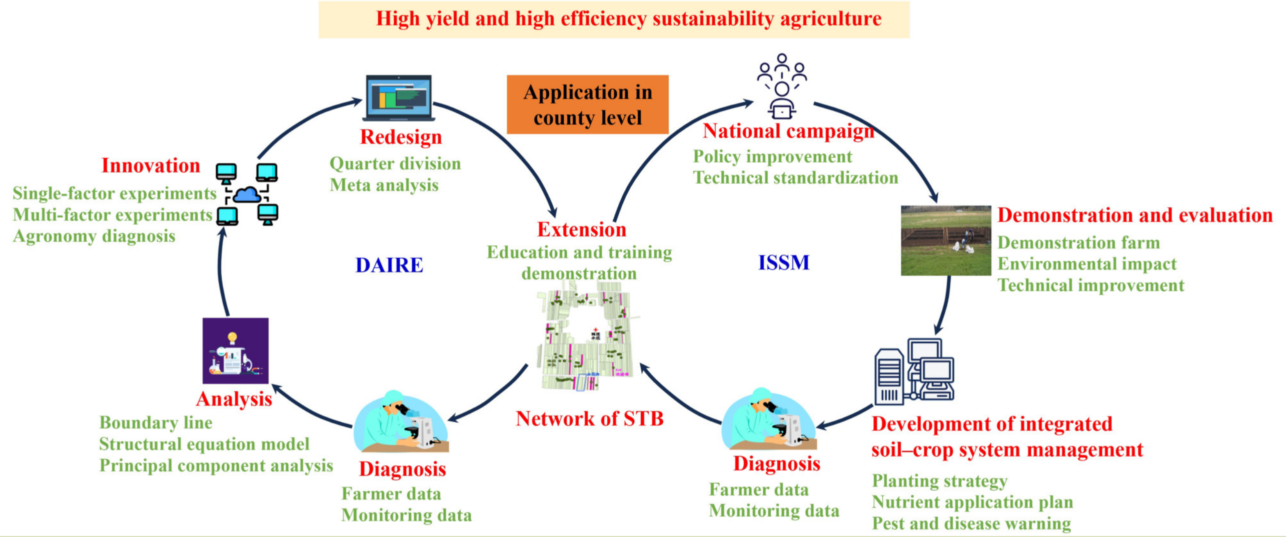


Fig. 3 Bottom-up technology for high-yield and high-efficiency agricultural system.

environment. It aims to maximize the use of solar radiation and favorable temperature periods, synchronizing the supply of nitrogen from soil and environmental inputs with crop demand. This method designs an efficient nitrogen fertilizer management plan that aligns the timing, spatial distribution and amount of nitrogen supply with the high-yielding crops[28–31].

Numerous case studies have demonstrated the feasibility of bottom-up innovative technologies based on the STBs in achieving high yield and high efficiency in crop systems[32–36]. Chen et al.[32] applied the ISSM method in 66 on-farm trials across northern China, achieving an average maize yield of 13 t·ha^{-1}. This yield is nearly double that of current farming practices, without increasing the use of nitrogen fertilizers[32]. Wang et al.[33] integrated survey data from over 11 million farmers, 4272 published data points on field nitrogen losses and various statistical yearbooks to model a scenario reducing sowing area (12%), nitrogen fertilizer application (34%), phosphate fertilizer application (24%), irrigation water usage (23%), reactive nitrogen losses (18%) and greenhouse gas emissions (20%) while meeting future grain demand in China[33]. Liu et al.[34] used data from over 1800 counties and the hybrid-maize model to estimate yield potential and gaps. Their findings showed that China could produce all the required maize and 45% of the soybeans, while simultaneously reducing nitrogen fertilizer use, reactive nitrogen loss and greenhouse gas emissions[34]. This study emphasized the importance of advanced management approaches, such as ISSM, for achieving higher yields with lower environmental impacts and advocated for a strategic approach to address food security and sustainability challenges[34]. Cui et al.[35] demonstrated that empowering smallholders with enhanced management technologies not only improves their productivity and environmental performance but also positive impacted on global food security, resources, and ecosystem health, providing solutions for the sustainable development of agriculture in the future. In addition, a target-driven system for increasing yield and efficiency is developed through multidisciplinary collaboration. This system is designed to address production issues by creating comprehensive solutions and conducting trials and demonstrations focused on integrated technologies. For example, Chen et al.[36] showed that by analyzing the primary factors limiting crop growth and implementing key new technologies, total production of maize, rice and wheat in China could meet human consumption demands while reducing environmental costs. Experimental validation demonstrated that the target-driven green technology system for enhancing crop yield and efficiency significantly increased the average yield of three major grain crops by over 30% and reduced GHG emissions by more than 50%[36]. Experimental and statistical data sets discussed in this paper provide empirical evidence for the feasibility of these agricultural technological innovations. Agricultural system innovation is shown to require the integration of heterogeneous technical modules. A synergetic approach enables the holistic optimization of agroecosystem performance through systemic coupling. Additionally, the bottom-up approach allows for a rapid response to policy changes and market signals, enabling timely adjustments to agricultural strategies to meet new opportunities and challenges[19,37,38]. These bottom-up successes highlight the advantages in localized problem-solving, farmer-scientist co-creation and adaptive scaling. However, traditional bottom-up approaches often lack macro-systemic analysis, which limits cross-regional transfer and comprehensive impact assessment. This paper fills this gap by integrating bottom-up technical innovations with top-down system optimization, forming a hybrid framework. This framework (1) couples field-level technologies with national sustainability goals, (2) quantifies cross-system interactions, and (3) ensures policy-responsive scalability through the STB network as innovation-policy intermediaries. By bridging micro-innovation and macro-systemic design, the framework promotes multi-objective collaboration, which optimizes yield (SDG 2), efficiency (SDG 12) and environmental sustainability (SDG 11) while overcoming a critical limitation of conventional bottom-up approaches.

2.3 Innovations in the quantitative modeling of nutrient flow systems in the food chain

Integrating top-down and bottom-up approaches in crop production requires innovative quantitative modeling of nutrient flow systems to precisely quantify pollutant emissions and environmental impacts across scales. The NUFER model has evolved from a basic nutrient flow model into a comprehensive food-resource-environment modeling framework. By integrating with models such as GLOBIOM model, PC Lake model, GLOBAL NEWS model, GAINS model and MARINA model, it has been used to develop a multi-scale, multi-indicator analytical platform that links food system with land use, water resources, nutrients and GHG emissions[39–44]. Wang et al.[45] used the NUFER model to quantitatively analyze improvements in nutrient use efficiency and reductions in environmental pollution through various technologies. That study demonstrated the feasibility of combining the NUFER model with both top-down and bottom-up innovative technologies to enhance agricultural yields and efficiency, while also synergistically reducing pollution. Therefore, using a combination of top-down and bottom-up research approaches and systematic methods, the advanced NUFER model can quantitatively assess the multi-objective optimization potential of crop systems at various scales. This integration represents a methodological advance in agricultural systems modeling, offering a blueprint for achieving SDGs 2 and 11 through data-informed, context-specific solutions.

3 Conclusions

The integrated top-down and bottom-up systemic approach presented in this paper facilitates an understanding of the interconnections between various components within agricultural systems. It allows for the quantitative analysis of agricultural production objectives and the identification of solutions, thus representing a novel paradigm for the development of agricultural research. In contrast to commonly-used single-factor experiments, this holistic approach addresses the multifaceted challenges of future agriculture (balancing productivity, resource efficiency and environmental sustainability). Empirical case studies have verified the feasibility of this approach, demonstrating that the STB network serves as the cornerstone for integrated innovation. As a dynamic bridge between science research and practical applications, the STB network has several key roles: (1) it captures specific problems and data from frontline production, (2) it develops technological innovation to break through bottleneck technologies, and (3) it disseminates solutions through adaptive extension models ultimately elevating productivity while minimizing environmental pollution. The paper contributes a systemic innovation framework that transcends conventional disciplinary boundaries. By integrating top-down system optimization with bottom-up adaptive management, it provides a robust methodology for future agricultural research. As global food systems face escalating climate and demographic pressures, this integrated approach represents a pivotal step toward achieving high yield and efficiency within environmental thresholds.

Compliance with ethics guidelines

Xiangwen Fan, Wenqi Ma, Zhaohai Bai, Fusuo Zhang, and Lin Ma declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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