

Innovations in green technology for increasing major grain crop production and efficiency in China

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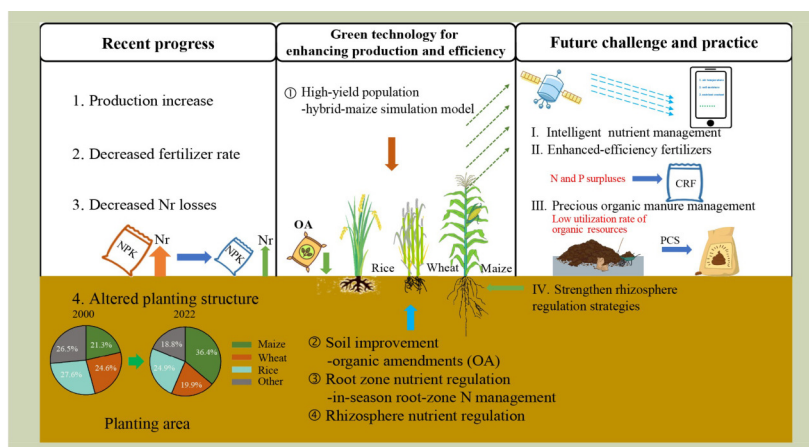
KEYWORDS

Green technology innovation, major grain crop, yield, efficiency, integrated soil-crop system management

HIGHLIGHTS

- China's achievements in green technologies of increasing production and efficiency is summarized.
- Development of theories and technologies for green yield enhancement and efficiency in major crops is described.
- Implementable strategies are proposed for dealing with new situations and challenges in the future.

GRAPHICAL ABSTRACT



ABSTRACT

The implementation of green technologies has facilitated the sustainable development of China's agriculture. However, the impact of green technologies in China's major crops production, their mechanisms of action and their future potential have not been systematically investigated. This study used national statistics data to summarize the impact of technological innovation on production and efficiency of major grain crops in China, and to identify which technologies have made the most important contributions. National statistics data showed changes in grain production (58% increase), total planting area (8.6% increase) and structure, nutrient input (0.83 Mt decrease) and reactive nitrogen losses, and optimized planting and fertilizer structure in 2022 compared to 2000. Of these, the proposal of integrated soil-crop system management significantly decreased reactive nitrogen losses and greenhouse gas emissions by 30% and 11%, respectively. Root zone nutrient regulation techniques, such as in-season nitrogen management, increased yields by 8% and decreased nitrogen rate by 25%. Rhizosphere nutrient regulation technology increased yield by 20.2% and decreased nitrogen rate by

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20%–30%. According to predictions, integrated soil-crop system management will demonstrate significant advantages in both unit area yield and total yield by the year 2050. The adoption of integrated soil-crop system management is expected to increase the total production of rice, wheat and maize by 45.8, 115 and 360 Mt, respectively. Currently, China's agriculture is confronted by significant challenges, including rising food demand, excessive inorganic nutrient inputs, and low utilization rates of organic resources. Three key recommendations arise from this study: the implementation of precise management for organic manure; the promotion of enhanced-efficiency fertilizers; and the adoption of new technologies including integrated soil-crop system management combined with rhizosphere nutrient regulation and intelligent nutrient management. These measures will drive the development of green, high-yield and efficient agriculture.

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1 Introduction

The global agricultural sector confronts the formidable challenge of ensuring food security while simultaneously lowering the environmental costs associated with food production^[1,2]. China is responsible for feeding 22% of the global population using less than 7% of global arable land^[3,4]. This situation arises from long-term high resource inputs in agriculture. However, the high inputs required for grain production incur significant environmental costs, including greenhouse gas emissions^[5], water eutrophication^[6] and land degradation^[7]. The National Cultivated Land Quality Grade Situation Bulletin of China of 2019 indicated that medium- and low-yield fields accounted for 68.8% of the total cultivated land in China. Therefore, such challenges have significantly constrained the improvement of China's sustainable grain production capacity^[8]. Over the last two decades, driven by increasing food demand and agricultural policies^[9], the development of green technologies to enhance production and efficiency has made crucial contribution to safeguarding food security. Nevertheless, the achievements of innovative green technologies development of China's major crops and the potential to address future challenges of food security remain unclear.

Since 2000, China's grain production has made substantial advancements through the adoption of green technologies^[10,11]. These advancements extend beyond mere production increases, encompassing environmentally friendly production technologies and enhanced fertilizer use efficiency^[12]. Green technology innovation has led to significant progress in total production, planting area, resource

input and fertilizer use efficiency. From 2001 to 2021, China's total crop production increased by 34.1% with only a 7.3% expansion in the total cropland area, and this is attributed to the application of improved cultivars and the advances in high-cultivation techniques^[13,14]. The total annual fertilizer use in China peaked at 60.2 Mt in 2015, subsequently declining to 50.8 Mt in 2022 (National Bureau of Statistics, NBS). Notably, this decline occurred in line with ongoing policy promotion and advancements in scientific and technological innovation, e.g., root zone nutrient regulation technology^[15], the integrated soil-crop system management^[16], the soil testing and fertilizer recommendation project^[17], and the national action of zero growth of chemical fertilizers and pesticides. These innovations contributed substantially to enhancing China's fertilizer use efficiency. Between 2000 and 2014, the overall nitrogen use efficiency (NUE) of crop production in China increased by 7%^[18]. Nevertheless, the rapid pace of developmental transitions has often overshadowed the systematical development and significant contributions of green technology for increasing crop production and efficiency in China.

In response, this study aimed to: (1) underscore the notable accomplishments in green technologies for increasing major grain crop production and efficiency in China; (2) provide a comprehensive examination of the development of related theories and technologies; (3) clarify new situations, challenges, and strategies for the future; and (4) predict the potential of practical technologies to meet future grain demand. We believe this study is essential for advancing the understanding of sustainable production theories and practices for major grain crops in China and worldwide.

2 Materials and methods

2.1 Data sources

This study used rice, wheat and maize as the representative of grain crops. From 2000 to 2022, the total production of rice, wheat and maize accounted for 84.3%–92.3% of the total grain production, which can be used as substitutes for grain crops for research (NBS). Limited by the timeliness of green technologies, the selected studied period was 2000–2022. The application per unit area of nitrogen, phosphorus and potassium fertilizers was obtained from National Agricultural Product Cost Benefit Information Compilation. The planting area, total production, and grain yield were sourced from the NBS and NUE was obtained from the Ministry of Agriculture and Rural Affairs of China.

2.2 Scenario analysis

The aim of this study was to predict the unit area yield and total yield of China's major grain crops (rice, wheat and maize) by 2050, and evaluate whether the promotion of rhizosphere nutrient regulation technology and intelligent nutrient management technology can meet the needs of food security. The data used were sourced from the grain planting area data released by the National Bureau of Statistics of China (2000–2022) and the yield growth ratio of major grain crops using rhizosphere nutrient regulation technology and intelligent nutrient regulation technology from the relevant literature (2000–2022).

We made two assumptions: (1) that the cultivated land area of China's major grain crops will remain unchanged from 2022 to 2050; and (2) that rhizosphere nutrient regulation technology and intelligent nutrient management technology have covered major grain crops nationwide. This study set four scenarios for technology promotion: (1) promotion of in-season root-zone N management strategy covers major grain crops across the country; (2) promotion of integrated soil-crop system management covers major grain crops across the country; (3) promotion of rhizosphere nutrient regulation technology covers major grain crops across the country; and (4) promotion of intelligent nutrient management technology covers major grain crops across the country.

2.3 Data analysis

All data were analyzed and visualized using Microsoft Excel 2021 (Redmond, WA, USA) and Origin 2024b (OriginLab, Northampton, MA, USA).

3 Achievements of green technologies for increasing major crop production and efficiency in China

3.1 Substantial increase in total production of major grain crops

Since the beginning of the 21st century, China has achieved remarkable advancements in total crop production^[19]. This achievement is closely related to the advancements of green technologies that improve crop yield and fertilizer use efficiency. Green innovative technologies, including high-yield cultivar and cultivation techniques, field management, agricultural machinery renewal and soil fertility improvement have a substantively underpinned these advancements. National statistical data shows that the total crop production has increased significantly over the past 20 years (NBS). In 2022, rice and wheat it reached 209 and 275 Mt respectively, and maize production reached 277 Mt. In 2022, the total crop production had increased by 70% compared to 2000 (761 vs 493 Mt). Collectively, the output of the three major grain crops (rice, wheat and maize) rose by 58%. Of these, maize had the most substantial increase of 162%. Wheat followed with a 38.2% increase whereas rice only had a modest increase of 11.0% (Fig. 1).

3.1.1 Increased grain yield of the major grain crops

Increased in grain production relies on the increase in grain yield and planting area. From 2000 to 2022, the planting areas of major grain crops in China were relatively stable, and the increase in mean grain yield mainly leading to the corresponding increase in total grain production with grain

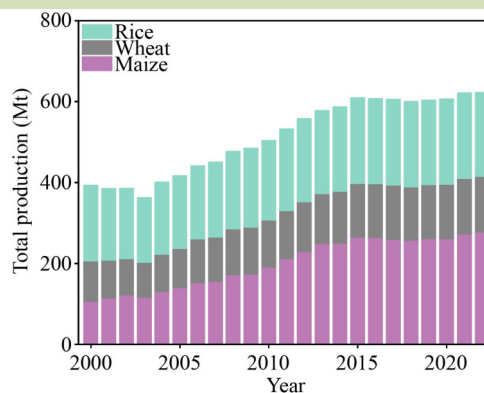


Fig. 1 Changes in total production of the three major grain crops in China from 2000 to 2022.

yields of these major grain crops consistently increasing over the past 20 years. The average grain yield of rice, wheat and maize in 2022 was 7.08, 5.86 and 6.43 t·ha⁻¹, respectively. Compared with 2000, the grain yield of wheat in 2022 had the highest increment of 56.7%, and the grain yield of maize and rice also increased by 40% and 12.9%, respectively (Fig. 2). These increments in grain yield of rice, wheat and maize are closely related to the advancement of green and innovative technologies.

Advancements in green technology have led to an increase in grain yield. The notable rise in grain yields for rice, wheat and maize is largely due to advances in domestic breeding science and technology, and in soil and crop management^[20,21]. High-yield cultivars can significantly increase crop yield potential, and advances in soil and crop management help realize the yield potential of these high-yield cultivars. This advancement is crucial for maintaining national food security.

3.1.2 Expanded total planting area and altered planting structure

The total planting area in 2022 was 170 Mha, which was 8.6% greater than that in 2000. The proportion of cropland used for the three major grain crops accounted to the total planting area increase from 51% in 2000 to 56.5% in 2022. In 2022, the planting area was 29.5 Mha for rice, 23.5 Mha for wheat and 43.1 Mha for maize. Maize planting area increased by 86.8% compared to 2000, while wheat and rice decreased by 11.8% and 1.7%, respectively (Fig. 3). The planting area of maize increased remarkably, especially after 2010, and peaked in 2015. In contrast, the planting area of wheat and rice has been relatively stable.

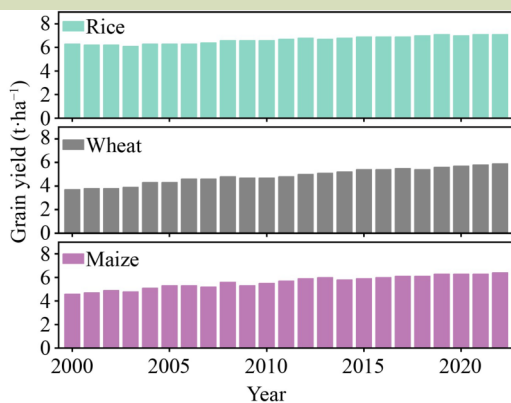


Fig. 2 Changes in grain yield of the three major grain crops in China from 2000 to 2022.

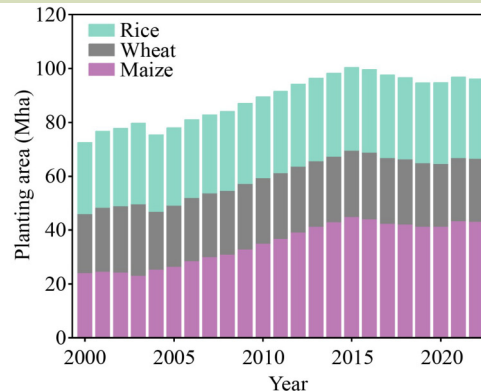


Fig. 3 Planting area of the three major grain crops in China from 2000 to 2022.

3.2 Decreased use amount and changed structure of fertilizers, and increased fertilizer use efficiency

In 2000, China's major grain crop fertilizer nutrient input (N, P₂O₅ and K₂O) was 21.4 Mt, and rose to peak at 37.1 Mt in 2016. Since 2016, the amount of nutrient input for major grain crops has decreased by 0.83 Mt (Fig. 4). The reduction in nutrient input primarily comes from a 9.4% decrease in N fertilizer use. Despite the decrease in nutrient input, there has been no negative effect on the overall crop production and the trend toward increased grain yield. In China, not only the amount of nutrient input decreased, but the use structure of fertilizer has been changed. Since 2000, the use of nitrogen-only fertilizers has decreased by 20 percentage points, and compound fertilizers use has increased by 25 percentage points in 2022. The proportion of potash fertilizer applied in 2022 was the same as in 2000, while the proportion of phosphate fertilizer applied decreased by six percentage points (Fig. 5).

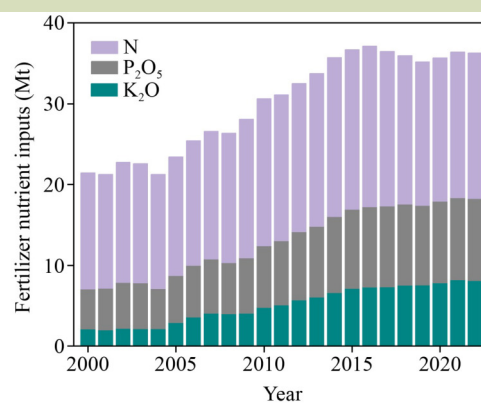


Fig. 4 Changes of nutrient inputs for the three major grain crops (rice, wheat and maize) in China from 2000 to 2022.

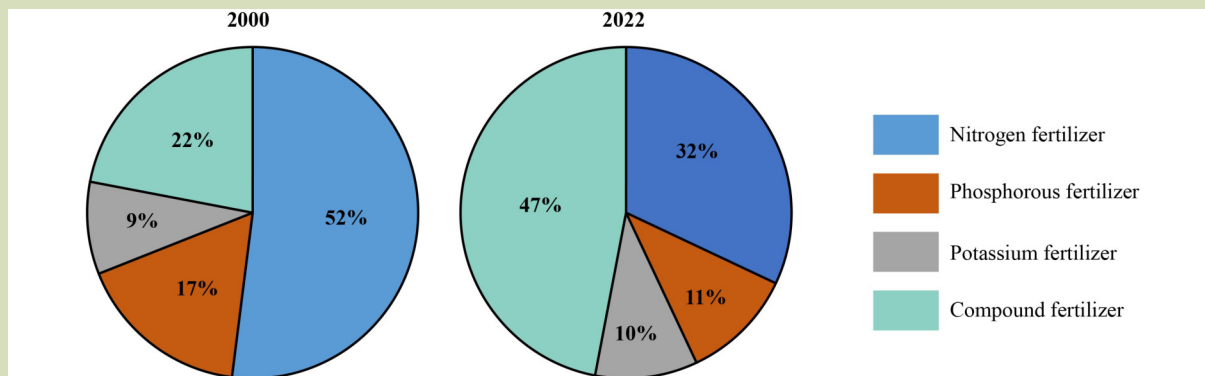


Fig. 5 Changes in fertilizer input structure of the three major grain crops (rice, wheat and maize) in China in 2000 and 2022.

Meanwhile, fertilizer use efficiency has gradually improved, supported by policy promotion and technological innovation. This can be mainly attributed to the promotion of root-zone and rhizosphere nutrient regulation technology and the application of enhanced-efficiency fertilizers, which significantly improve crop nutrient uptake and lower fertilizer application rate^[15,22,23]. Before 2000, the nitrogen fertilizer use efficiency of the three major grain crops was around 30%. However, by 2000, due to excessive use of fertilizers, the nitrogen fertilizer use efficiency dropped to 27.5%, but increased to 41.3% in 2022 (Fig. 6).

3.3 Decreased reactive nitrogen losses

The reactive nitrogen losses from farmland mainly involve N₂O emission, NH₃ volatilization, nitrate leaching and runoff^[24,25]. An earlier study demonstrated a deceleration in N₂O emission and NH₃ volatilization from agricultural land in China over

recent years^[26]. Specifically, the implementation of soil testing and a fertilizer recommendation project have been key to the decrease in total N₂O emission from 8.6 Gg·yr⁻¹ N before 1998 to 4.1 Gg·yr⁻¹ N from 1999 to 2017^[27]. Since the beginning of the 20-first century, improving management practices, such as the use of controlled-release fertilizers, has significantly decreased NH₃ volatilization^[28]. Another earlier study has shown that decreasing nitrogen fertilizer application by 20% can decrease NH₃ volatilization by 24%^[29]. A meta-analysis indicated that the adoption of drip irrigation technology in the new century has decreased NO₃⁻-N leaching loss by 71.2%^[30]. Two national pollution source surveys in China indicate that the nitrogen runoff loss from farmland in the Yangtze River Basin decreased from 1.60 Tg in 2007 to 0.72 Tg in 2017^[31]. This is closely related to the decrease in nitrogen fertilizer use.

Also, based on statistics from the Ministry of Agriculture and Rural Affairs of China, the nitrogen rates of the three major grain crops have first increased and then decreased, while the NUE has increased by nearly 14 percentage points over the past 20 years. These achievements were made possible through the promotion of government policies such as soil testing and fertilizer recommendation project^[32], the aim set for zero growth in the use of chemical fertilizers, and advances in green technology for increasing production and efficiency contributed by scientific communities and innovative fertilizer companies.

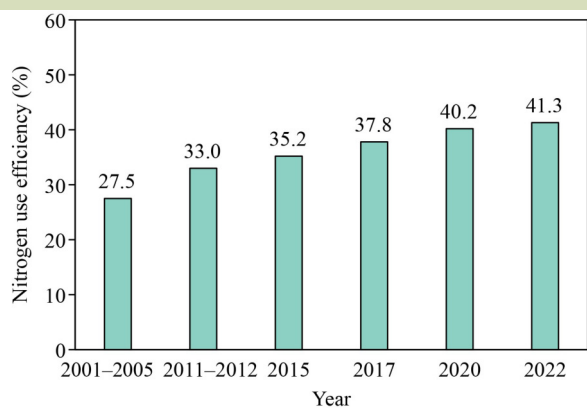


Fig. 6 Changes in nitrogen use efficiency of the three major grain crops (rice, wheat and maize) in China from 2000 to 2022.

4 Theories and technological innovations for green production increase and efficiency enhancement

4.1 Integrated soil-crop system management

To decrease the environment impact while increasing grain

production, an innovative integrated soil-crop system management (ISSM) has been established through the intersection of the disciplines of plant nutrition and agronomy in previous studies^[16]. Using long-term weather data and hybrid-maize simulation models, an ideal population of cropping systems was designed by considering cultivars, seeding dates, crop maturity, and plant densities for specific locations^[16,32]. ISSM maximizes the use of solar radiation and favorable temperature cycles, while also improving the synchronization between crop nitrogen demand and its supply from soil, environmental factors and applied inputs. In studies conducted in northern China, the adoption of elite cultivars, delayed sowing and increase planting densities designed through ISSM gave a 91.2% increase in maize grain yield, in comparison to common farmer practice. In addition, it has been demonstrated that achieving 80% of the yield potential under ISSM is adequate to satisfy the demand for direct human consumption and domestically produced animal feeds, while maintaining the stability of the planted area. Concurrently, reactive nitrogen losses and greenhouse gas emissions of ISSM for the major grain crops were cut by 30% and 11%, respectively, and the use of land and nitrogen fertilizer were lowered by 22% and 21%, respectively^[33]. This innovative technology offers millions of smallholders a practical solution for increasing grain yield while decreasing the need for nitrogen fertilizer and lowering environmental costs.

4.2 High-yield crop population construction

Between 1960 and 1980, crop yield increases were mainly due to improvements in the harvest index of the crop cultivars grown^[34]. However, over the past 20 years, harvest index has only risen slowly, with current yield gains now largely driven by increases in biomass^[35]. Thus, to overcome this bottleneck, constructing a high-yielding populations to increase biomass while maintaining a stable harvest index is particularly urgent. Taking maize as an example, constructing high-yielding populations uses a hybrid-maize simulation model to determine the most suitable combination of cultivars, sowing dates, climate conditions and plant density in a given locality.

The essence of building a high-yield population is to improve the plant density^[36,37]. It has been demonstrated that increasing planting density increases the population extinction coefficient and solar radiation interception while simultaneously improving the efficiency of light and nitrogen, thereby enhancing grain yield^[38–40]. Crops that have been shown to benefit from this practice are maize, wheat and rice. Maize planted at a density of $6.75 \times 10^4 \text{ ha}^{-1}$ in hilly areas of Sichuan has been shown to deliver the highest yield and

nutrient use efficiency^[41]. Wheat had favorable population characteristics and balanced source-stock population relationships when grown at a density of 2.3×10^6 to $3.0 \times 10^6 \text{ ha}^{-1}$ in Shunyi of Beijing^[42]. These successes due to improvements of crop growth parameters, included an appropriate leaf area index, a higher tiller spike formation rate, and an improved grain-to-leaf ratio. In rice, a planting density of $3.0 \times 10^5 \text{ ha}^{-1}$ is optimal, improving higher N use efficiency and yield. However, increasing plant density has not consistently increased yield^[43].

4.3 Soil amendment to supports green production and efficiency

The density at which crops should be grown depends on light use efficiency, as well as the soil quality^[44,45]. In China, many fields have low to medium yields due to poor soil conditions. The success of growing maize partially depends on soil bulk density, tillage depth and organic matter content. For example, in the major growing regions of north-western and north-eastern China, where the soils have relatively lower bulk density and higher organic matter content, the yield potential is high, making them more suitable for denser cultivation^[46,47].

Soil improvement is a demonstrated practical way to increase productivity and efficiency in green practices. For maize, the use of organic amendments can decrease nitrogen loss and increase soil organic matter^[48]. The use of rhizobacteria, which promote plant growth, enhances soil enzyme activities and improves soil physical and chemical properties^[49]. Conservation farming practices, such as no-till or strip-till, can improve soil health and protect arable land quality^[50,51]. These measures can improve soil quality, preserve and provide nutrients, decrease greenhouse gas emissions, and accelerate nutrient transformation, thereby leading to higher crop yields. Additionally, they can enhance crop growth and improve plant defense mechanisms.

4.4 Root zone nutrient regulation technology

The implementation of root zone nutrient regulation technology enhances the biological capabilities of the root system, thereby improving yield and fertilizer use efficiency, while simultaneously lowering greenhouse gas emissions and other detrimental effects. For example, in-season root-zone N management (IRNM) aims to maintain the necessary concentration of inorganic nitrogen supply in the root zone for crop growth, considering factors such as soil nitrogen supply, irrigation water nitrogen and other relevant aspects^[15]. IRNM

matched the total N requirement by crop in application rate, placement and timing, thereby avoiding excessive N use and simultaneously lowering greenhouse gas emissions intensity by 10% to 30%^[52]. The implementation of IRNM in field trials demonstrated a significant increase in maize yields relative to those achieved through standard farmer practices^[53]. Earlier studies have shown that crops with higher yields tend to accumulate a greater percentage of dry matter during the late flowering stage^[54,55]. To improve biomass, we propose coordinating nutrient uptake before and after flowering through nutrient conditioning, intending to achieve higher yields. The integration of IRNM has been shown to enhance post-flowering N accumulation^[56].

In addition, the use of single-application nitrogen fertilizer management in the root zone stimulated root proliferation, resulting in an 8% increase in yield of rainfed maize and decreased nitrogen fertilizer use by 25%^[57]. There are studies recommending the most suitable rates of P and K for rice, wheat and maize in China through monitoring techniques for P and recommending techniques for K in different regions^[58].

4.5 Rhizosphere nutrient regulation technology

Compared to regulating nutrient application in the root zone, techniques for regulating nutrient application in the rhizosphere focus on a smaller, more specific, microscopic and niche-targeted scale^[59,60]. Rhizosphere nutrient regulation technology strengthened biological processes between roots by optimizing external nutrient inputs, improving root uptake efficiency, inter-root connectivity and microbial-root interactions^[61].

Most research on rhizosphere nutrient regulation has focused on studying phosphate fertilizers. Research has shown that phosphorus fertilizer could decrease nutrient availability differences between bulk soil and rhizosphere soil to meet crop nutrient requirements^[62,63]. Many studies have shown that plant nutrient uptake depends largely on root morphology and physiologic properties, such as phosphorus^[64]. Root morphology and spatial distribution are related to crop productivity^[65]. The inter-root environment in which a crop is grown largely determines the efficiency of nutrient use^[66]. The rhizosphere soil acts as a mediator between plants and microorganisms, providing physical support and a variety of nutrients. A recent article similarly noted the great potential of AMF and their associated bacteria in maintaining soil fertility, and plant health and productivity^[67]. Its regulation optimizes the interaction between crop roots, soil and microorganisms.

Compared with broadcasting fertilizers, strip tillage combined with strip-applied controlled-release nitrogen fertilizer increased maize yield by 6% in north-eastern China, and decreased greenhouse gas emissions by 10.4%^[68]. Drip fertigation is an important technique for regulating rhizosphere nutrients. A maize study conducted in the Huang-Huai-Hai region showed that the highest yield using surface drip fertigation was 13.9 t·ha⁻¹, with a water use efficiency of 29.9 kg·m⁻³ and a nitrogen fertilizer agronomic efficiency of 19.0 kg·kg⁻¹^[69]. Also, studies have shown that compared to standard fertilizer application, machine-transplanted rice with deep side-banded fertilizer application can increase yield by 20.2% and still generate profits while decreasing nitrogen application by 20% to 30%^[70].

5 New circumstances, challenges and strategies

5.1 New circumstances

Food security is a challenge for smallholder families in densely populated regions and countries^[16]. To ensure national food security, it is projected that China will need to increase agricultural production by 10% to 20% over the next 30 years^[71]. Particularly, there is a projected increase in grain demand by 15% to 22%, mainly driven by maize demand from the animal production sector^[71,72]. This may necessitate a 30% increase in total maize production, requiring an increase in both planting area and grain yield.

5.2 New challenges

There are several new challenges under the new circumstances in China. First of all, nitrogen and phosphorus surpluses in Chinese farmland are relatively high, posing significant environmental risks. In China, the majority of high nitrogen surplus in farmland are concentrated to the east of the Hu Huanyong Line and in the oasis agricultural areas of the north-west, with an annual nitrogen surplus of 11.3 Mt^[73]. The phosphorus surplus in Chinese farmland is 24 kg·ha⁻¹·yr⁻¹ P, exceeding the planetary boundary threshold of 6.9 kg·ha⁻¹·yr⁻¹ P^[74].

Secondly, China has abundant but inadequately-used and recycled organic resources and nutrients^[75]. The total amount of dry biomass in China is 1.53 Gt·yr⁻¹ and the urine of animal 879 Mt·yr⁻¹^[76]. Improving the use of organic resources is the key of green technology for increasing crop production and

efficiency. However, China use of manure in cropped fields is lower than the global average, so has potential for further improvement.

5.3 New strategies

5.3.1 Precious organic manure management

Organic fertilizer application is regarded as a way to elevate farmland soil organic carbon, decrease the reliance on mineral fertilizers and increase grain yields, contributing to the transition to circular agriculture and sustainable development goals^[77,78]. The scientific application of organic fertilizers is a clear opportunity that has thus far been overlooked. However, the effects of organic fertilizer application are influenced by biophysical background, composting characteristics and environmental factors, resulting in unpredictable bioavailability^[77,79,80]. The current use of organic fertilizers introduces significant uncertainty to grain yields and always leads to higher soil N₂O emissions^[81,82]. Recent studies suggest that implementing a precision composting strategy, which customizes composting and application methods based on specific crops and growing environments, can potentially increase global grain production by 28.8% and raise soil organic carbon content by 2.3% compared to current composting methods^[83]. It is recommended that research on such technologies be advanced and that the government should vigorously promote their application.

5.3.2 Development of enhanced-efficiency fertilizers

More than half of the nitrogen applied in fertilizer to farmland is not used by the crop^[84]. The inefficiency of common fertilizers makes agriculture the largest source of nitrogen pollution worldwide^[85]. Multiple applications of fertilizers during crop growth has been shown to be an effective way to increase fertilizer use efficiency^[86]. However, labor costs for crop production and fertilizer application have increased rapidly in recent years. Multiple applications of fertilizers inevitably come with extra cost. High labor costs can greatly decrease farmer enthusiasm for crop production. At the same time, the decline in rural population has put agricultural development under the pressure of labor shortage^[87]. These issues seriously affect China's food security and are not conducive to green and efficient development of grain crops.

Currently, using enhanced-efficiency fertilizers (EEFs) is one of the effective solutions to the problems given above^[85]. Generally, two types of products are regularly used as EEFs on the three major grain crops. One type includes nitrogen

inhibitors, which delay specific processes in the nitrogen cycle to retain nitrogen in the soil longer^[88,89]. The other type consists of slow- and controlled-release fertilizers, which usually involve coating standard fertilizer granules with a polymer that dissolves during the growing season, delaying the release of nitrogen into the soil^[90]. Studies have found that both nitrification inhibitors and controlled-release fertilizers can decrease N₂O emissions by 35%–40%^[91]. However, nitrification inhibitors used alone tend to increase NH₃ volatilization, which can be mitigated when used in combination with urease inhibitors^[92]. Nitrogen inhibitors and controlled-release fertilizers can increase NUE, with controlled-release fertilizers showing an average increase in NUE by 13%^[93]. Comprehensively, the EEFs can improve nutrient efficiency, decrease fertilizer losses and increase yields^[94,95]. Also, the use of EEFs can decrease the frequency of fertilizer application and labor costs, improve overall economic benefits, and have economic sustainability. Overall, the promotion and popularization of EEFs is an important measure to achieve green development in agriculture.

5.3.3 Strengthen rhizosphere regulation strategies

Rhizosphere nutrient regulation will be important for the balanced nutrition of the major grain crops of the future. This is because the aim of rhizosphere regulation shifts the focus of fertilizer application from enriching the soil to enriching the crops and the rhizosphere. Rhizosphere regulation has significant impacts on carbon sequestration, nutrient cycling and soil biodiversity^[96]. Strengthening rhizosphere regulation involves decreasing external nutrient inputs by regulating the root growth environment, strengthening rhizosphere biological processes and maximizing the biological potential of crops to efficiently obtain nutrient resources^[61]. The core of optimizing external nutrient inputs is to create a suitable rhizosphere nutrient concentration. A recently proposed precision seed and fertilizer co-sowing system can accurately control the relative position of seeds and fertilizers in the soil, which can improve fertilizer use efficiency^[97]. This is important for the application of rhizosphere nutrient regulation techniques.

Regulating the rhizosphere microbial community is an essential part of strengthening rhizosphere regulation, as it is crucial for plant growth, metabolism and stress tolerance^[98,99]. Some scholars believe that the influence of root morphology traits on maize enhances plant soil symbiosis and microbial biomass carbon^[100]. Research on rhizosphere regulation for drought tolerance has shown that abscisic acid regulates crop rhizosphere water scarcity under drought conditions to improve water use efficiency^[101]. This is of great significance

for the study of rhizosphere nutrient regulation in the production of major grain crops in China.

5.3.4 Intelligent nutrient management technology

Intelligent agricultural management technology is the future for achieving high agricultural yield and efficiency. Policies such as the Modern Agriculture Plan, promulgated in 2016, and the “No. 1 Document” in 2019, propose the vigorous development of smart agriculture, making it the future development direction of the agricultural industry. Intelligent agricultural management technology represents a more advanced form of informatization and modernization^[102]. It involves a deep integration of new intelligent technologies with the agricultural industry. This era of rapid development, known as Internet Plus, involves the application of new technologies such as the Internet of Things, big data, cloud computing and remote sensing as the main forms of expression^[103,104]. By deeply integrating these technologies with the agricultural industry, we can monitor and guide agricultural production, thereby promoting agricultural development.

Currently, intelligent agricultural management technology has been applied to varying degrees in different regions. For example, the concept of the Internet of Things has been implemented in the breeding industry in Jiangsu Province, and intelligent sprinkler systems have been installed in winter greenhouses in Shandong Province^[103]. Nevertheless, smart agriculture is still in its infancy in China, and many aspects need to be further explored and deepened.

6 Scenario analysis

Currently, there is growing concern about food security issues^[105]. It is widely recognized that green innovation technologies can enhance crop yields and fertilizer use efficiency^[106]. To meet future development demands, higher requirements have been proposed for green innovation technologies. This study focuses on green innovation technologies, specifically in-season root-zone N management strategy, integrated soil-crop system management, rhizosphere nutrient regulation technology and intelligent nutrient management technology. Based on earlier research, this study analyzes the grain yield of rice, wheat and maize under various technologies. Under the scenario of adopting only one of these technologies across China, the paper predicts the grain yield and total production of China’s major grain crops by the year 2050. This analysis attempts to predict the grain yields and

total production of major grain crops in China by 2050 under the adoption of these four technologies.

By 2050, in-season root-zone N management strategy is projected to deliver yields of 7.9 t·ha⁻¹ for rice, 5.8 t·ha⁻¹ for wheat and 6.5 t·ha⁻¹ for maize. Our findings indicate that in-season root-zone N management strategy has a limited impact on the grain yield of major grain crops. However, this strategy can stabilize the grain yield of major grain crops while simultaneously decreasing nutrient inputs. By 2050, to meet the growing demand for food, the application of integrated soil-crop system management has significantly increased the grain yield of major grain crops. Compared to 2022, the grain yield of major grain crops has increased by 21.4% (rice), 56.1% (wheat), and 86.8% (maize). By using rhizosphere nutrient regulation technology, the yields for rice, wheat and maize is projected to reach 10.1, 9.3 and 9.9 t·ha⁻¹, respectively. In contrast, the yields for rice, wheat and maize using intelligent nutrient management technology are expected to reach 9.7, 9.2 and 8.9 t·ha⁻¹, respectively (Fig. 7). Compared to rhizosphere nutrient regulation technology, intelligent nutrient management technology shows an advantage only in the grain yield of wheat.

According to a study, China’s total demand for rice, wheat and maize by 2050 is expected to reach 187, 141 and 281 Mt, respectively^[71]. This study forecasts the total yields of rice, wheat and maize in China by 2050 under the adoption of in-season root-zone N management strategy, integrated soil-crop system management, rhizosphere nutrient regulation technology and intelligent nutrient management technology. Assuming no change in the current arable land area, the total production for rice, wheat and maize using in-season root-zone N management strategy in 2050 are projected to be 286, 216 and 384 Mt, respectively (Fig. 7). By 2050, the total production under integrated soil-crop system management is projected to experience a substantial increase, with the total production of rice, wheat and maize expected to reach 309, 323 and 708 Mt, respectively. Rhizosphere nutrient regulation technology in 2050 is projected to be 296, 219 and 427 Mt, respectively. The total production for maize, rice and wheat using intelligent nutrient management technology are estimated to be 282, 255 and 408 Mt, respectively (Fig. 8).

We found that integrated soil-crop system management holds significant advantages over other technological approaches in terms of both grain yield and total production of major grain crops. We believe that integrated soil-crop system management is a crucial measure capable of integrating in-season root-zone N management strategy, rhizosphere nutrient regulation

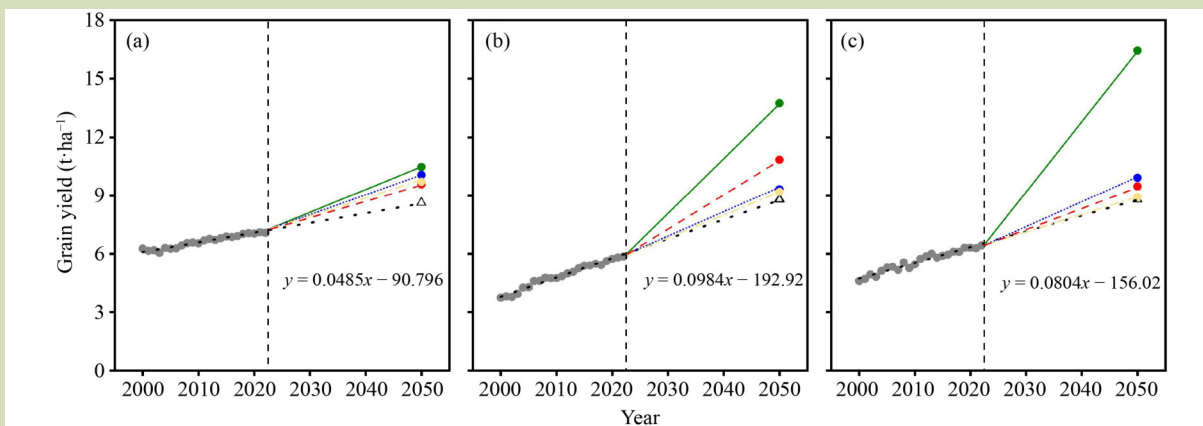


Fig. 7 Predictions for grain yield of major grain crops in China by 2050: (a) rice; (b) wheat; (c) maize. ISSM, integrated soil-crop system management; IRNM, in-season root-zone nitrogen management. Gray circles, grain yield from 2000 to 2022. Black triangles, projected grain yield follow the trend observed from 2000 to 2022. Green circles, projected grain yield under ISSM. Blue circles, projected grain yield under rhizosphere nutrient regulation technology. Yellow circles, projected grain yield under IRNM. Red circles, projected grain yield using under intelligent nutrient management technology.

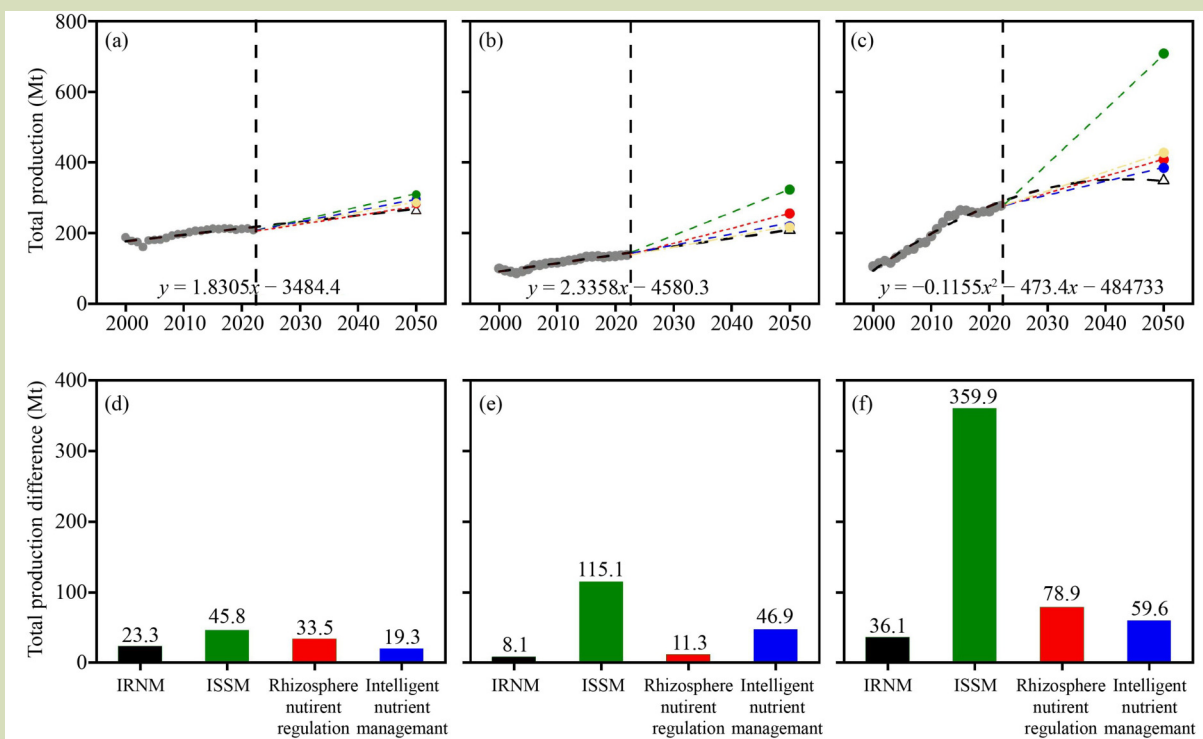


Fig. 8 Predictions for total production of major grain crops in China by 2050: (a) rice; (b) wheat; (c) maize. (d, e and f) The differences between the projected demand for rice, wheat and maize, respectively, in 2050 and the total production achieved after the application of the corresponding technology. ISSM, integrated soil-crop system management; IRNM, in-season root-zone nitrogen management strategy. Gray circles, total production from 2000 to 2022. Black triangles, increasing total production by the trend observed from 2000 to 2022, keeping planting area the same as in 2022. Green circles, projected total production under ISSM. Blue circles, projected total production rhizosphere nutrient regulation technology. Yellow circles, projected total production IRNM. Red circles, projected total production intelligent nutrient management technology.

technology and intelligent nutrient management technology to achieve high yield and efficiency in China's major grain crops. It also represents an essential pathway for China to achieve self-sufficiency in grain production in the future.

7 Conclusions

This study primarily summarizes the production and technological innovation progress in China's major grain crops over the past 20 years. Green theory and technological innovation have been identified as essential for the green production of major grain crops. ISSM, root zone nutrient regulation (in-season root-zone N management) and rhizosphere nutrient regulation technology were found to have excellent potential. Under their impetus, China has witnessed a sustained increase in grain production, a modest increase in total planted area, a lowering in fertilizer use and reactive nitrogen losses, and an optimization of the cropping and

fertilizer structure. However, China's demand for food continues to increase, and there are also problems of excess inorganic nutrients and low utilization of organic resources. To address these issues, we propose effective solutions: (1) precision management of organic resources; (2) promotion of enhanced-efficiency fertilizers; (3) promotion and adoption rhizosphere nutrient regulation technology; and (4) new technologies such as intelligent nutrient management. Additionally, we projected China's demand for 2050. Research indicates that in-season root-zone N management strategy can decrease nutrient inputs without compromising yield, while integrated soil-crop system management have significant advantages in both the grain yield and total production of major grain crops. Also, it is clear that the integration of integrated soil-crop system management with in-season root-zone N management strategy, rhizosphere nutrient regulation technology and intelligent nutrient management technology can meet the future national requirements for food security.

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Compliance with ethics guidelines

Fulin Zhao, Xingbang Wang, Wushuai Zhang, Peng Hou, Qingfeng Meng, Zhenling Cui, and Xiping Chen 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

- Foley J A, Ramankutty N, Brauman K A, Cassidy E S, Gerber J S, Johnston M, Mueller N D, O'Connell C, Ray D K, West P C, Balzer C, Bennett E M, Carpenter S R, Hill J, Monfreda C, Polasky S, Rockström J, Sheehan J, Siebert S, Tilman D, Zaks D P M. Solutions for a cultivated planet. *Nature*, 2011, **478**(7369): 337–342
- Tilman D, Balzer C, Hill J, Befort B L. Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, 2011, **108**(50): 20260–20264
- Yun W. Problems and countermeasures in the development and utilization of cultivated land resource in China. *Bulletin of Chinese Academy of Sciences*, 2015, **30**: 484–491 (in Chinese)
- Zhang F, Chen X, Vitousek P. An experiment for the world. *Nature*, 2013, **497**(7447): 33–35
- Meng T, Fan S G. Transforming Chinese food and agriculture: a systems perspective. *Frontiers of Agricultural Science and Engineering*, 2023, **10**(1): 4–15
- Shen R X, Tian C Y, Liu Z D, Zhang Y H, Li B M, Lu H F, Duan N. Temporal changes in the characteristics of algae in Dianchi lake, Yunnan Province, China. *Frontiers of Agricultural Science and Engineering*, 2015, **2**(3): 266–275
- Guo J H, Liu X J, Zhang Y, Shen J L, Han W X, Zhang W F, Christie P, Goulding K W T, Vitousek P M, Zhang F S. Significant acidification in major Chinese croplands. *Science*, 2010, **327**(5968): 1008–1010
- Shi M, Xiao W, Wang C M, He D W, Hao C, Dang X F. The research progress of agricultural non-point source pollution in the black soil area of Northeast China. *Advanced Materials Research*, 2014, **1010–1012**: 711–716
- Sheldrick W F, Syers J K, Lingard J. Soil nutrient audits for China to estimate nutrient balances and output/input relationships. *Agriculture, Ecosystems & Environment*, 2003, **94**(3): 341–354
- He G, Wang Z H, Shen J B, Cui Z L, Zhang F S.

- Transformation of agriculture on the loess plateau of China toward green development. *Frontiers of Agricultural Science and Engineering*, 2021, **8**(4): 491–500
11. Li C, Shi Y, Khan S U, Zhao M. Research on the impact of agricultural green production on farmers' technical efficiency: evidence from China. *Environmental Science and Pollution Research International*, 2021, **28**(29): 38535–38551
 12. Cui Z, Dou Z, Chen X, Ju X, Zhang F. Managing agricultural nutrients for food security in China: past, present, and future. *Agronomy Journal*, 2014, **106**(1): 191–198
 13. Zhai J, Pu L, Lu Y, Huang S. Is the boom in staple crop production attributed to expanded cropland or improved yield? A comparative analysis between China and India. *Science of the Total Environment*, 2024, **933**: 173151
 14. Zhang J. China's success in increasing per capita food production. *Journal of Experimental Botany*, 2011, **62**(11): 3707–3711
 15. Chen X P, Zhang F S, Cui Z L, Li F, Li J L. Optimizing soil nitrogen supply in the root zone to improve maize management. *Soil Science Society of America Journal*, 2010, **74**(4): 1367–1373
 16. Chen X P, Cui Z L, Vitousek P M, Cassman K G, Matson P A, Bai J S, Meng Q F, Hou P, Yue S C, Römheld V, Zhang F S. Integrated soil-crop system management for food security. *Proceedings of the National Academy of Sciences of the United States of America*, 2011, **108**(16): 6399–6404
 17. Jiao X, He G, Cui Z, Shen J, Zhang F. Agri-environment policy for grain production in China: toward sustainable intensification. *China Agricultural Economic Review*, 2018, **10**(1): 78–92
 18. Yan X, Xia L, Ti C. Temporal and spatial variations in nitrogen use efficiency of crop production in China. *Environmental Pollution*, 2022, **293**: 118496
 19. Qiu B, Jian Z, Yang P, Tang Z, Zhu X, Duan M, Yu Q, Chen X, Zhang M, Tu P, Xu W, Zhao Z. Unveiling grain production patterns in China (2005–2020) towards targeted sustainable intensification. *Agricultural Systems*, 2024, **216**: 103878
 20. Xu K, Zhang Z, Tian W, Zhi L, Yan J, Yan J, Zheng C, Zhang Y, Zhang Y, He Z. Comparative analysis of yield and quality traits in two elite Chinese wheat varieties under varied nitrogen fertilizations and environmental conditions. *Cereal Chemistry*, 2024, **101**(5): 1139–1149
 21. Yang G, Xiang H, Fu Y, Zhou C, Wang X, Yuan S, Yu X, Peng S. Optimal nitrogen management increases nitrogen use efficiency of direct-seeded double-season rice using ultrashort-duration cultivars. *Field Crops Research*, 2024, **316**: 109495
 22. Lam S K, Wille U, Hu H W, Caruso F, Mumford K, Liang X, Pan B, Malcolm B, Roessner U, Suter H, Stevens G, Walker C, Tang C, He J Z, Chen D. Next-generation enhanced-efficiency fertilizers for sustained food security. *Nature Food*, 2022, **3**(8): 575–580
 23. 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
 24. Deng J, Li C, Wang Y. Modeling ammonia emissions from dairy production systems in the United States. *Atmospheric Environment*, 2015, **114**: 8–18
 25. Yang J Y, Drury C F, Jiang R, Worth D E, Bittman S, Grant B B, Smith W N. Reactive nitrogen losses from Canadian agricultural soils over 36 years. *Ecological Modelling*, 2024, **495**: 110809
 26. Shang Z, Zhou F, Smith P, Saikawa E, Ciais P, Chang J, Tian H, Del Grosso S J, Ito A, Chen M, Wang Q, Bo Y, Cui X, Castaldi S, Juszczak R, Kasimir Ā, Magliulo V, Medinets S, Medinets V, Rees R M, Wohlfahrt G, Sabbatini S. Weakened growth of cropland-N₂O emissions in China associated with nationwide policy interventions. *Global Change Biology*, 2019, **25**(11): 3706–3719
 27. Cui X, Shang Z, Xia L, Xu R, Adalibieke W, Zhan X, Smith P, Zhou F. Deceleration of cropland-N₂O emissions in China and future mitigation potentials. *Environmental Science & Technology*, 2022, **56**(7): 4665–4675
 28. Vejan P, Khadiran T, Abdullah R, Ahmad N. Controlled release fertilizer: a review on developments, applications and potential in agriculture. *Journal of Controlled Release*, 2021, **339**: 321–334
 29. Liu L, Zhang X, Xu W, Liu X, Li Y, Wei J, Wang Z, Lu X. Ammonia volatilization as the major nitrogen loss pathway in dryland agro-ecosystems. *Environmental Pollution*, 2020, **265**: 114862
 30. Zheng J, Zhou M, Zhu B, Fan J, Lin H, Ren B, Zhang F. Drip fertigation sustains crop productivity while mitigating reactive nitrogen losses in Chinese agricultural systems: evidence from a meta-analysis. *Science of the Total Environment*, 2023, **886**: 163804
 31. Zhang Y, Wu H, Yao M, Zhou J, Wu K, Hu M, Shen H, Chen D. Estimation of nitrogen runoff loss from croplands in the Yangtze River Basin: a meta-analysis. *Environmental Pollution*, 2021, **272**: 116001
 32. Zhang F, Cui Z, Fan M, Zhang W, Chen X, Jiang R. Integrated soil-crop system management: reducing environmental risk while increasing crop productivity and improving nutrient use efficiency in China. *Journal of Environmental Quality*, 2011, **40**(4): 1051–1057
 33. Chen X, Cui Z, Fan M, Vitousek P, Zhao M, Ma W, Wang Z, Zhang W, Yan X, Yang J, Deng X, Gao Q, Zhang Q, Guo S, Ren J, Li S, Ye Y, Wang Z, Huang J, Tang Q, Sun Y, Peng X, Zhang J, He M, Zhu Y, Xue J, Wang G, Wu L, An N, Wu L, Ma L, Zhang W, Zhang F. Producing more grain with lower environmental costs. *Nature*, 2014, **514**(7523): 486–489
 34. Ruiz A, Trifunovic S, Eudy D M, Sciarresi C S, Baum M, Danalatos G J N, Elli E F, Kalogeropoulos G, King K, dos Santos C, Thies A, Pico L O, Castellano M J, Schnable P S, Topp C, Graham M, Lamkey K R, Vyn T J, Archontoulis S V. Harvest index has increased over the last 50 years of maize breeding. *Field Crops Research*, 2023, **300**: 108991
 35. Hütsch B W, Schubert S. Chapter two—Harvest index of

- maize (*Zea mays* L.): are there possibilities for improvement? In: Sparks D L, ed. *Advances in Agronomy*, Academic Press, 2017, 37–82
36. Ji B, Zhao Y, Mu X, Liu K, Li C. Effects of tillage on soil physical properties and root growth of maize in loam and clay in central China. *Plant, Soil and Environment*, 2013, **59**(7): 295–302
 37. Liu Y, Hou P, Huang G, Zhong X, Li H, Zhao J, Li S, Mei X. Maize grain yield and water use efficiency in relation to climatic factors and plant population in northern China. *Journal of Integrative Agriculture*, 2021, **20**(12): 3156–3169
 38. Hou P, Liu Y, Liu W, Yang H, Xie R, Wang K, Ming B, Liu G, Xue J, Wang Y, Zhao R, Zhang W, Wang Y, Bian S, Ren H, Zhao X, Liu P, Chang J, Zhang G, Liu J, Yuan L, Zhao H, Shi L, Zhang L, Yu L, Gao J, Yu X, Wang Z, Shen L, Ji P, Yang S, Zhang Z, Xue J, Ma X, Wang X, Lu T, Dong B, Li G, Ma B, Li J, Deng X, Liu Y, Yang Q, Jia C, Chen X, Fu H, Li S. Quantifying maize grain yield losses caused by climate change based on extensive field data across China. *Resources, Conservation and Recycling*, 2021, **174**: 105811
 39. Xu W, Liu C, Wang K, Xie R, Ming B, Wang Y, Zhang G, Liu G, Zhao R, Fan P, Li S, Hou P. Adjusting maize plant density to different climatic conditions across a large longitudinal distance in China. *Field Crops Research*, 2017, **212**: 126–134
 40. Zhang G, Cui C, Lv Y, Wang X, Wang X, Zhao D, Hu F, Wen X, Han J, Liao Y. Is it necessary to increase the maize planting density in China. *European Journal of Agronomy*, 2024, **159**: 127235
 41. Lei H, Zhou F, Cai Q, Wang X, Du L, Lan T, Kong F, Yuan J. Effects of planting density and nitrogen management on light and nitrogen resource utilization efficiency and yield of summer maize in the Sichuan hilly region. *Agronomy*, 2024, **14**(7): 1470
 42. Yang W, Wang Z, Ren L, Ye Z, Gao X, Gao J, Lou H, Du B, Chen Z, Zhang S. Effects of population regulation on the source-sink system of hybrid wheat Jingmai 6. *Agronomy*, 2022, **12**(10): 2530
 43. Hou P, Liu Y, Liu W, Liu G, Xie R, Wang K, Ming B, Wang Y, Zhao R, Zhang W, Wang Y, Bian S, Ren H, Zhao X, Liu P, Chang J, Zhang G, Liu J, Yuan L, Zhao H, Shi L, Zhang L, Yu L, Gao J, Yu X, Shen L, Yang S, Zhang Z, Xue J, Ma X, Wang X, Lu T, Dong B, Li G, Ma B, Li J, Deng X, Liu Y, Yang Q, Fu H, Liu X, Chen X, Huang C, Li S. How to increase maize production without extra nitrogen input. *Resources, Conservation and Recycling*, 2020, **160**: 104913
 44. Wang Q, Sun Z, Bai W, Zhang D, Zhang Y, Wang R, van der Werf W, Evers J B, Stomph T J, Guo J P, Zhang L. Light interception and use efficiency differ with maize plant density in maize-peanut intercropping. *Frontiers of Agricultural Science and Engineering*, 2021, **8**(3): 432–446
 45. Qi W, Wang Q, Mak-Mensah E, Zhu J, Zhang D, Zhou X, Zhao X, Xu Y, Sun Y, Liu Q, Li X, Li X. Effects of soil physicochemical properties on maize, wheat, and soybean yields in maize-wheat and maize-soybean intercropping systems in China: a meta-analysis. *Journal of Soil Science and Plant Nutrition*, 2024, **24**(1): 21–29
 46. Wang X, Jia Z, Liang L, Zhao Y, Yang B, Ding R, Wang J, Nie J. Changes in soil characteristics and maize yield under straw returning system in dryland farming. *Field Crops Research*, 2018, **218**: 11–17
 47. Hou S, Ren H, Fan F, Zhao M, Zhou W, Zhou B, Li C. The effects of plant density and nitrogen fertilization on maize yield and soil microbial communities in the black soil region of Northeast China. *Geoderma*, 2023, **430**: 116325
 48. Zhu B, Yao Z Y, Hu D N, Bah H. Effects of substitution of mineral nitrogen with organic amendments on nitrogen loss from sloping cropland of purple soil. *Frontiers of Agricultural Science and Engineering*, 2022, **9**(3): 396–406
 49. Song Q, Deng X, Song R, Song X. Three plant growth-promoting rhizobacteria regulate the soil microbial community and promote the growth of maize seedlings. *Journal of Plant Growth Regulation*, 2023, **42**(12): 7418–7434
 50. Jin H, Hongwen L, Xiaoyan W, McHugh A D, Wenyong L, Huanwen G, Kuhn N J. The adoption of annual subsoiling as conservation tillage in dryland maize and wheat cultivation in northern China. *Soil & Tillage Research*, 2007, **94**(2): 493–502
 51. Shao Y, Xie Y, Wang C, Yue J, Yao Y, Li X, Liu W, Zhu Y, Guo T. Effects of different soil conservation tillage approaches on soil nutrients, water use and wheat-maize yield in rainfed dry-land regions of North China. *European Journal of Agronomy*, 2016, **81**: 37–45
 52. Meng Q, Cui Z, Yang H, Zhang F, Chen X. Chapter three—Establishing high-yielding maize system for sustainable intensification in China. In: Sparks D L, ed. *Advances in Agronomy*. Academic Press, 2018, 85–109
 53. Meng Q F, Chen X P, Zhang F S, Cao M H, Cui Z L, Bai J S, Yue S C, Chen S Y, Müller T. In-season root-zone nitrogen management strategies for improving nitrogen use efficiency in high-yielding maize production in China. *Pedosphere*, 2012, **22**(3): 294–303
 54. Zhiipao R R, Pooniya V, Kumar D, Biswakarma N, Bainsla N K, Saikia N, Duo H, Dorjee L, Govindasamy P, Lakhena K K, Jat R D. Late-sown stress afflict post-anthesis dry matter and nutrient partitioning and their remobilization in aestivum wheat genotypes. *Journal Agronomy & Crop Science*, 2024, **210**(2): e12693
 55. Cheng M, Zhang Y, Lv G, Yu Y, Hao Y, Jiang Y, Han L, Pang H, Jiao F, Qian C. A high amount of straw pellets returning delays maize leaf senescence, improves dry matter accumulation and distribution, and yield increase in northeast China. *Agronomy*, 2025, **15**(3): 711
 56. Yan P, Yue S, Qiu M, Chen X, Cui Z, Chen F. Using maize hybrids and in-season nitrogen management to improve grain yield and grain nitrogen concentrations. *Field Crops Research*, 2014, **166**: 38–45
 57. Jiang C, Lu D, Chen X, Wang H, Zu C, Zhou J. How can urea-N one-time management achieve high yield and high NUE for rainfed and irrigated maize. *Nutrient Cycling in*

- Agroecosystems*, 2022, **122**(3): 241–254
58. Wu L Q. Fertilizer recommendations for three major cereal crops based on regional fertilizer formula and site specific adjustment in China. Dissertation for the Doctoral Degree. Beijing: *China Agricultural University*, 2014
 59. Wang L Y, Liao D, Rengel Z, Shen J B. Soil–plant–microbe interactions in the rhizosphere: incremental amplification induced by localized fertilization. *Frontiers of Agricultural Science and Engineering*, 2025, **12**(1): 57–68
 60. Hao C, Dungait J A J, Wei X, Ge T, Kuzyakov Y, Cui Z, Tian J, Zhang F. Maize root exudate composition alters rhizosphere bacterial community to control hotspots of hydrolase activity in response to nitrogen supply. *Soil Biology & Biochemistry*, 2022, **170**: 108717
 61. Zhang F, Shen J, Zhang J, Zuo Y, Li L, Chen X. Chapter one - rhizosphere processes and management for improving nutrient use efficiency and crop productivity: implications for China. In: Sparks D L, ed. *Advances in Agronomy*, *Academic Press*, 2010, 1–32
 62. Shen J B, Wang L Y, Jiao X Q, Meng F L, Zhang L, Feng G, Zhang J L, Yuan L X, Ma L, Hou Y, Zhang T, Zhang W F, Li G H, Zhang K, Zhang F S. Innovations of phosphorus sustainability: implications for the whole chain. *Frontiers of Agricultural Science and Engineering*, 2019, **6**(4): 321–331
 63. Zhang C, Yu Y, Xu J, Zhou M. Hysteresis modeling and analysis of magnetic shape memory alloy-driven actuator. *IEEE Transactions on Nanotechnology*, 2022, **21**: 390–398
 64. Shen J, Yuan L, Zhang J, Li H, Bai Z, Chen X, Zhang W, Zhang F. Phosphorus dynamics: from soil to plant. *Plant Physiology*, 2011, **156**(3): 997–1005
 65. Zu C, Li Z, Wang C, Wang X X, Ji H, Shen J, Rengel Z, Li H, Yang J. Dissimilarity in root traits and spatial distribution promotes the productivity of *Piper nigrum* L. and tree species in mixture systems. *European Journal of Agronomy*, 2024, **154**: 127094
 66. 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
 67. Duan S, Feng G, Limpens E, Bonfante P, Xie X, Zhang L. Cross-kingdom nutrient exchange in the plant-arbuscular mycorrhizal fungus-bacterium continuum. *Nature Reviews. Microbiology*, 2024, **22**(12): 773–790
 68. Cheng Z, Bai L, Wang Z, Wang F, Wang Y, Liang H, Wang Y, Rong M, Wang Z. Strip-till farming: combining controlled-release blended fertilizer to enhance rainfed maize yield while reducing greenhouse gas emissions. *Agronomy*, 2024, **14**(1): 136
 69. Wu L, Zhang G, Yan Z, Gao S, Xu H, Zhou J, Li D, Liu Y, Xie R, Ming B, Xue J, Hou P, Li S, Wang K. Optimizing maize yield and resource efficiency using surface drip fertilization in Huang-Huai-Hai: impact of increased planting density and reduced nitrogen application rate. *Agronomy*, 2024, **14**(5): 944
 70. Zhong X, Peng J, Kang X, Wu Y, Luo G, Hu W, Zhou X. Optimizing agronomic traits and increasing economic returns of machine-transplanted rice with side-deep fertilization of double-cropping rice system in southern China. *Field Crops Research*, 2021, **270**: 108191
 71. Zhao H, Chang J, Havlík P, van Dijk M, Valin H, Janssens C, Ma L, Bai Z, 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
 72. Ma L H, Li S Y, Fang L F, Chen X J, Xiao R, Su X X, Li Z L, Bai Z H, Ma L, Lakshmanan P, Chen X P. Multiple pollutants from crop and livestock production in the Yangtze River: status and challenges. *Frontiers of Agricultural Science and Engineering*, 2024, **11**(1): 134–139
 73. Zhang Q, Li T, Yin Y, Ying H, Cui Z, Zhang F. Targeting hotspots to achieve sustainable nitrogen management in China's smallholder-dominated cereal production. *Agronomy*, 2021, **11**(3): 557
 74. Zou T, Zhang X, Davidson E A. Global trends of cropland phosphorus use and sustainability challenges. *Nature*, 2022, **611**(7934): 81–87
 75. Yang H S. Resource management, soil fertility and sustainable crop production: experiences of China. *Agriculture, Ecosystems & Environment*, 2006, **116**(1–2): 27–33
 76. Cui X, Guo L, Li C, Liu M, Wu G, Jiang G. The total biomass nitrogen reservoir and its potential of replacing chemical fertilizers in China. *Renewable & Sustainable Energy Reviews*, 2021, **135**: 110215
 77. Bernal M P, Sommer S G, Chadwick D, Qing C, Guoxue L, Michel F C. Chapter three—Current approaches and future trends in compost quality criteria for agronomic, environmental, and human health benefits. In: Sparks, D L, rd. *Advances in Agronomy*. *Academic Press*, 2017, 143–233
 78. Pergola M, Persiani A, Palese A M, Di Meo V, Pastore V, D'Adamo C, Celano G. Composting: the way for a sustainable agriculture. *Applied Soil Ecology*, 2018, **123**: 744–750
 79. Wong J W C, Wang X, Selvam A. Improving compost quality by controlling nitrogen loss during composting. In: Wong J W C, Tyagi R D, Pandey A, eds. *Current Developments in Biotechnology and Bioengineering*, *Elsevier*, 2017, 59–82
 80. Luo G, Li L, Friman V P, Guo J, Guo S, Shen Q, Ling N. Organic amendments increase crop yields by improving microbe-mediated soil functioning of agroecosystems: a meta-analysis. *Soil Biology & Biochemistry*, 2018, **124**: 105–115
 81. Mapanda F, Wuta M, Nyamangara J, Rees R M. Effects of organic and mineral fertilizer nitrogen on greenhouse gas emissions and plant-captured carbon under maize cropping in Zimbabwe. *Plant and Soil*, 2011, **343**(1–2): 67–81
 82. Ribas-Agustí A, Seda M, Sarraga C, Montero J I, Castellari M, Muñoz P. Municipal solid waste composting: application as a tomato fertilizer and its effect on crop yield, fruit quality and phenolic content. *Renewable Agriculture and Food Systems*, 2017, **32**(4): 358–365
 83. Zhao S, Schmidt S, Gao H, Li T, Chen X, Hou Y, Chadwick D,

- Tian J, Dou Z, Zhang W, Zhang F. A precision compost strategy aligning composts and application methods with target crops and growth environments can increase global food production. *Nature Food*, 2022, 3(9): 741–752
84. Zhang X, Davidson E A, Mauzerall D L, Searchinger T D, Dumas P, Shen Y. Managing nitrogen for sustainable development. *Nature*, 2015, 528(7580): 51–59
85. Kanter D R, Searchinger T D. A technology-forcing approach to reduce nitrogen pollution. *Nature Sustainability*, 2018, 1(10): 544–552
86. Robertson G P, Vitousek P M. Nitrogen in agriculture: balancing the cost of an essential resource. *Annual Review of Environment and Resources*, 2009, 34(1): 97–125
87. Lu H, Xie H, Yao G. Impact of land fragmentation on marginal productivity of agricultural labor and non-agricultural labor supply: a case study of Jiangsu, China. *Habitat International*, 2019, 83: 65–72
88. Neels W, Jhala A, Maharjan B, Patel S, Slator G, Iqbal J. Nitrogen source affects in-season nitrogen availability more than nitrification inhibitor and herbicide in a fine-textured soil. *Soil Science Society of America Journal*, 2024, 88(2): 419–433
89. Beeckman F, Annetta L, Corrochano-Monsalve M, Beeckman T, Motte H. Enhancing agroecosystem nitrogen management: microbial insights for improved nitrification inhibition. *Trends in Microbiology*, 2024, 32(6): 590–601
90. Zhang W, Liang Z, He X, Wang X, Shi X, Zou C, Chen X. The effects of controlled release urea on maize productivity and reactive nitrogen losses: a meta-analysis. *Environmental Pollution*, 2019, 246: 559–565
91. Akiyama H, Yan X, Yagi K. Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N₂O and NO emissions from agricultural soils: meta-analysis. *Global Change Biology*, 2010, 16(6): 1837–1846
92. Sanz-Cobena A, Misselbrook T, Camp V, Vallejo A. Effect of water addition and the urease inhibitor NBPT on the abatement of ammonia emission from surface applied urea. *Atmospheric Environment*, 2011, 45(8): 1517–1524
93. Abalos D, Jeffery S, Sanz-Cobena A, Guardia G, Vallejo A. Meta-analysis of the effect of urease and nitrification inhibitors on crop productivity and nitrogen use efficiency. *Agriculture, Ecosystems & Environment*, 2014, 189: 136–144
94. Omonode R A, Halvorson A D, Gagnon B, Vyn T J. Achieving lower nitrogen balance and higher nitrogen recovery efficiency reduces nitrous oxide emissions in North America's maize cropping systems. *Frontiers in Plant Science*, 2017, 8: 1080
95. Li T, Zhang W, Yin J, Chadwick D, Norse D, Lu Y, Liu X, Chen X, Zhang F, Powlson D, Dou Z. Enhanced-efficiency fertilizers are not a panacea for resolving the nitrogen problem. *Global Change Biology*, 2018, 24(2): e511–e521
96. Sokol N W, Slessarev E, Marschmann G L, Nicolas A, Blazewicz S J, Brodie E L, Firestone M K, Foley M M, Hestrin R, Hungate B A, Koch B J, Stone B W, Sullivan M B, Zablocki O, Pett-Ridge J. Life and death in the soil microbiome: how ecological processes influence biogeochemistry. *Nature Reviews. Microbiology*, 2022, 20(7): 415–430
97. Liang J, Pan F, Chen J, Zhang H, Ji C. A precise simultaneous sowed control system for maize seed and fertilizer. *Agriculture*, 2024, 14(2): 192
98. Chang X, Wei D, Zeng Y, Zhao X, Hu Y, Wu X, Song C, Gong G, Chen H, Yang C, Zhang M, Liu T, Chen W, Yang W. Maize-soybean relay strip intercropping reshapes the rhizosphere bacterial community and recruits beneficial bacteria to suppress *Fusarium* root rot of soybean. *Frontiers in Microbiology*, 2022, 13: 1009689
99. Li F, Zhang S, Wang Y, Li Y, Li P, Chen L, Jie X, Hu D, Feng B, Yue K, Han Y. Rare fungus, *Mortierella capitata*, promotes crop growth by stimulating primary metabolisms related genes and reshaping rhizosphere bacterial community. *Soil Biology & Biochemistry*, 2020, 151: 108017
100. Tao D, Gao Y, Revillini D, Yan A, Zhou G, Swanson C S, He Q, Ma H, Yu X, Delgado-Baquerizo M. Root traits regulate the capacity of the rhizosphere to support multiple ecosystem services under intercropping and phosphorus fertilization. *Agriculture, Ecosystems & Environment*, 2024, 374: 109181
101. Kang J, Peng Y, Xu W. Crop root responses to drought stress: molecular mechanisms, nutrient regulations, and interactions with microorganisms in the rhizosphere. *International Journal of Molecular Sciences*, 2022, 23(16): 9310
102. Ray P P. Internet of things for smart agriculture: technologies, practices and future direction. *Journal of Ambient Intelligence and Smart Environments*, 2017, 9(4): 395–420
103. Zhao C, Li J, Feng X, Guo M. Application status and trend of “internet plus” modern agriculture in China and abroad. *Chinese Engineering Science*, 2018, 20(2): 50–56 (in Chinese)
104. Su Y, Wang X. Innovation of agricultural economic management in the process of constructing smart agriculture by big data. *Sustainable Computing: Informatics and Systems*, 2021, 31: 100579
105. Dorward A. The short- and medium-term impacts of rises in staple food prices. *Food Security*, 2012, 4(4): 633–645
106. Yashveer S, Singh V, Kaswan V, Kaushik A, Tokas J. Green biotechnology, nanotechnology and bio-fortification: perspectives on novel environment-friendly crop improvement strategies. *Biotechnology & Genetic Engineering Reviews*, 2014, 30(2): 113–126