Front. Agr. Sci. Eng. 2025, 12(3): 507–518 https://doi.org/10.15302/J-FASE-2025615

RESEARCH ARTICLE

Evaluation and application of sustainable yield and efficiency increasing models in the main maize producing areas of China

Xiaoyu LI[1], Hongguang CAI[2], Yao LIANG[2], Shanchao YUE[3], Shiqing LI[3], Baizhao REN[4], Jiwang ZHANG[4], Wushuai ZHANG[5], Xinping CHEN[5], Qingfeng MENG[6], Peng HOU[7], Jianbo SHEN[6], Wenqi MA[8], Guozhong FENG (✉)[1], Qiang GAO (✉)[1]

1 College of Resources and Environmental Sciences, Jilin Agricultural University, Changchun 130118, China.
2 Jilin Academy of Agricultural Sciences, Changchun 130033, China.
3 College of Natural Resources and Environment, Northwest A&F University, Yangling 712100, China.
4 Shandong Agricultural University, Tai'an 271018, China.
5 College of Resources and Environment, Academy of Agricultural Sciences, Southwest University, Chongqing 400715, China.
6 China Agricultural University, Beijing 100193, China.
7 Institute of Crop Sciences, Chinese Academy of Agricultural Sciences, Beijing 100081, China.
8 College of Resources and Environmental Sciences, Hebei Agricultural University, Baoding 071000, China.

KEYWORDS

Maize, agriculture green development, technical innovations, yield-limiting factors

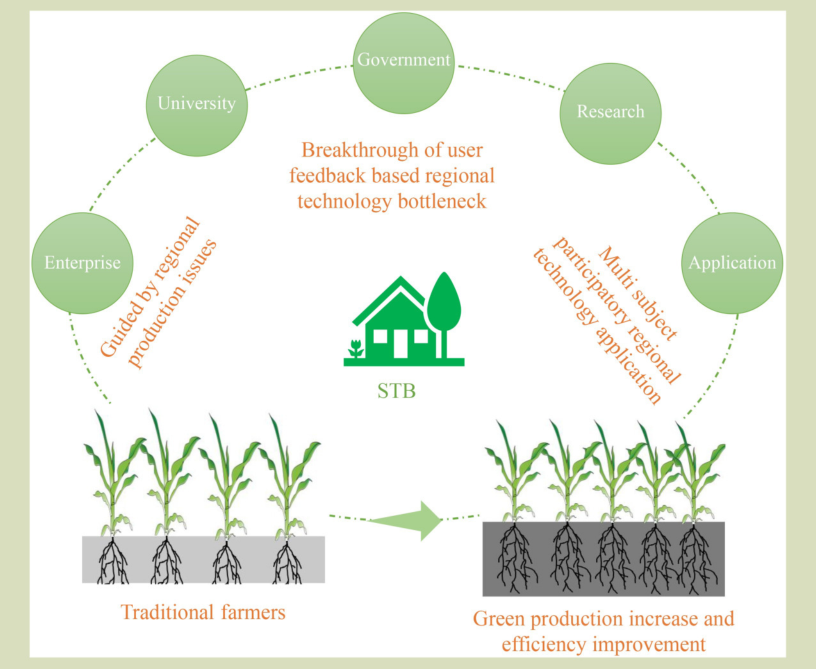
HIGHLIGHTS

- Address limiting factors in corn production across China's regions with tailored planning measures.
- Establish suitable corn planting systems based on climate, soil, and planting density in each region.
- Develop sustainable yield and efficiency models for maize, centered on soil-crop system management.
- Promote high-yield, sustainable corn technologies via the "Government-Enterprise-University-Research-Application" model.

Received August 19, 2024;
Accepted March 19, 2025.

Correspondences: gzf@jlau.edu.cn,
gyt9962@126.com

GRAPHICAL ABSTRACT



ABSTRACT

Maize is a critical grain crop in China, having the largest planting area and highest total yield of all grain crops. In the four-primary maize-producing regions of China (Northeast, North China Plain, Northwest and Southwest), persistent regional production challenges and yield-limiting factors have impeded the realization of efficient maize production. This paper reviews sustainable, yield-enhancing and efficiency-improving practices for maize production in China. By addressing the regional constraints in major maize-producing areas and incorporating strategies, such as high-yield population construction, the establishment of appropriate tillage layers and soil fertility enhancement through precise matching technologies, this study integrates regionalized integrated fertilizer application and a government-enterprise-university-research-application collaborative model, focusing on the Science and Technology Backyards. The goal is to facilitate sustainable, efficient, scaled and modernized development across diverse maize-growing regions in China. This approach is expected to provide a foundation for sustainable and efficient maize production in China.

1 Introduction

Maize is a crucial grain crop in China[1,2], leading in both planted area and total production of the major grain crops, and ranking second globally in maize production, behind only the USA[3]. By 2022, the maize planting area in China has reached 43.1 Mha, being a 4.29% increase over the past decade, indicating a stable growth trend. With the increase in planting area, maize production in China also increased[4], rising to 277 Mt in 2022, an increase of 11.6% over the same period[5]. Despite this growth in total maize production, enhancing yield per unit area remains a significant challenge[6], at present average unit area yield of maize in China is only 6.50 t·ha^{-1}, there is still a great potential for increasing yield. Also, in the increasingly tense situation of arable land resources, expanding the grain area is no longer a viable option, the focus must shift to improving yields[7,8]. Therefore, realizing high maize yield is the basis for ensuring food security in China and an ongoing challenge for agriculture globally.

Maize production in China can be categorized into four principal production regions based on the topography, climate and vegetation, as well as the regional distribution of maize production, namely, spring maize production region of Northeast China, summer maize production region of the North China Plain, spring maize production region of Northwest China and maize production region of Southwest China, which in combination cover about 98% of the total maize planting area in China, with the planting area in these regions being 38%, 30%, 12% and 18%, respectively. The average yield is the highest in Northeast China (9.53 t·ha^{-1}), followed by Southwest China (9.48 t·ha^{-1}), North China Plain (7.50 t·ha^{-1}) and Northwest China (6.49 t·ha^{-1})[9]. However, the impact of climate change on maize production cannot be ignored[10]. These four main maize production regions in China possess natural conditions that are conducive to high yields. For example, Northwest and Northeast China have significant diurnal temperature variation and ample sunlight. Higher solar radiation enhances dry matter accumulation[11,12], supports and prolongs grain fill[13]. Additionally, plants with higher stalk strength are less prone to lodging[14], which is conducive to higher maize yields. Southwest China and the North China Plain have higher temperatures and precipitation, and rain and heat coincide with each other, so maize growth matches light and temperature, which is an important for achieving high yields; regions with higher light radiation can afford larger maize populations, which facilitates higher planting densities and thus higher maize yields[15]. Additionally, higher diurnal temperature difference reduces nighttime respiratory consumption of maize, which improves yields[16,17]. Similarly, the specific climatic and soil conditions of the four regions differ, leading to variations in maize production. Low precipitation in the Northwest and Northeast may result in insufficient moisture availability during the maize growth period, and high temperatures on the North China Plain and in Southwest China, where evaporation can be too high, limit yields. There is potential for yield improvement within each region by developing region-specific production strategies designed for local conditions. The key to enhance maize production in China is requiring a strategic approach that considers these regional differences.

Over the last few decades, agricultural productivity has greatly enhanced, and food production has increased significantly; however, it has also led to a series of problems such as increasing ecological degradation[18,19] and decreasing quality of high-yielding crops[20]. Consequently, future research on high maize yields in China should adopt problem-and goaloriented approaches, specifically targeting the coordinated development of yield improvement, farmer income enhancement and sustainable yield increase in the main maize production regions[21]. Therefore, it is important to start by determining the climate, soil and other natural conditions of each ecological zone in China and then develop region-specific planting strategies. This is especially important in the context of dual priorities of food security and agricultural green development. Therefore, this studied evaluated scientific basis and application of regional models for integration of sustainable efficiencies and yield increase in the main maize production regions of China. This is of great potential significance in the identification of problems preventing high maize yield. By in-depth analysis of these problems, a scientific basis for formulating effective agricultural policies and promoting agricultural green development can be established.

2 Key issues and limiting factors in regional maize production in China

Maize is a C_4 crop originating from the tropics and is best suited to warm and moist growth conditions[22]. However, China is a vast country with complex and diverse climates, a wide range of latitudes, and a large gap between the distance from the ocean, coupled with different terrain elevations and a variety of terrain types and mountain ranges, resulting in a variety of combinations of temperature and precipitation. The mean annual precipitation in each production region of China ranges from 104 to 1240 mm, and the mean annual temperature ranges from 4.1 to 24.2 °C. The highest mean annual precipitation and temperature are in Southwest China, with 1150 mm and 16 °C, followed by the summer maize production region of the North China Plain (697 mm and 12.6 °C). In these regions, rain and heat coincide, so maize growth matches light and temperature, but water stress may occur under particularly high temperature conditions. In contrast, the spring maize production region of Northeast China is characterized by a relatively low temperature but with mean annual of only 290 mm (Table 1) severe drought stress for maize is also possible.

Table 1 details the physicochemical properties of soil tilled layer in the four maize main production regions of China. Black soil is typical of the spring maize production region of Northeast China, with high clay content and fertility. However, continuous cultivation and application of mineral fertilizers has led to the degradation of soil structure and acidification of the soils. The summer maize production region of the North China Plain mostly has brown soil with lower soil organic matter content; the spring maize production region of Northwest China has dark loessal soil with high sand content, loose soil texture, low fertility and alkaline; and the maize growing areas of Southwest China have purple soil with high fertility and weakly acidic soil.

In addition to adequate water and nutrient supply, determining an appropriate planting density is a crucial to optimizing maize yield per unit area[23]. In China, the planting density is typically from 4.99×10^4 to 6.52×10^4 plants ha^{-1}[24,25], which is considerably lower than the USA, the largest maize producer, where densities range from 8.22×10^4 to 9.21×10^4 plants ha^{-1}[26]. This disparity highlights the potential for improving maize planting density in China. Using a quadratic function, it is possible to conclude that the optimal planting density and the peak yield of maize kernel in the four main maize production regions of China varies substantially (Fig. 1). Also, the optimal planting densities in the spring maize production region of Northeast China, summer maize production region of the North China Plain, spring maize production region of

Table 1 Physical and chemical properties of soil tilled layer and climatic condition in four main maize production regions of China

Region	MAP (mm)	MAT (°C)	Clay (%)	Sand (%)	SOM (%)	pH	Alk N ($mg \cdot kg^{-1}$)	Olsen-P ($mg \cdot kg^{-1}$)	Available K ($mg \cdot kg^{-1}$)
NE	570	6.1	43.1	32.8	3.02	6.2	91.4	24.0	203
	(335–755)	(4.1–7.6)	(17–50)	(8–45.5)	(1–4.29)	(5–8.8)	(42.3–144.2)	(3.3–95.8)	(30–257.6)
NCP	697	12.6	16.6	30.8	1.31	7	48	42	168
	(466–1000)	(11.5–16.1)	(13–25)	(20–62)	(0.98–2.73)	(5.25–8.92)	(33.86–120.5)	(9.2–95.5)	(34.66–250)
NW	290	5.9	5.7	80.4	1.37	8.6	41.2	16.2	135.2
	(104–578)	(4.6–12.9)	(4.2–20.5)	(31.6–84.5)	(0.2–1.97)	(7.2–8.76)	(17.28–135)	(2.9–38.7)	(38.7–218)
SW	1150	16	34.8	22.4	1.85	6.9	131	17.3	121
	(600–1240)	(13–24.2)	(16.9–50.4)	(5.3–27.4)	(1.12–4.21)	(4.77–8.3)	(51.34–164)	(2.19–36)	(50.37–230)

Note: The values outside the parentheses are the average values, while the values inside the parentheses are the maximum and minimum values. MAP, mean annual precipitation; MAT, mean annual temperature; SOM, soil organic matter content; and Alk N, alkali hydrolyzed nitrogen. NE, Northeast; NCP, North China Plain; NW, Northwest; SW, South.

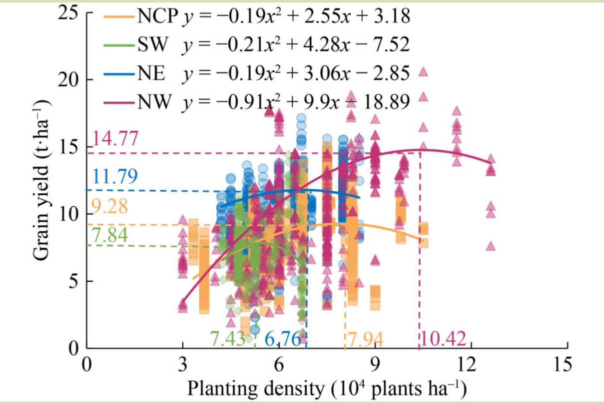


Fig. 1 Optimum planting density and peak grain yield of maize in different main production regions. NCP, North China Plain; SW, Southwest; NE, Northeast; NW, Northwest.

Northwest China and maize production region of Southwest China are respectively, 6.76×10^4, 7.94×10^4, 10.4×10^4 and 5.43×10^4 plants ha^{-1}, at which the peak yields of 11.8, 9.28, 14.8 and 7.84 t·ha^{-1} could be achieved. Therefore, different regions should optimize planting patterns according to their own climatic and soil conditions.

3 Innovation of green technology for increasing maize production and efficiency in China

Achieving sustainable and efficient increase in maize yield, with soil-crop system integrated management as the core, mainly depends on the following aspects (Fig. 2). (1) Increasing photosynthetic products is the foundation for improving yield. Photosynthesis is the entry point for carbon into the terrestrial biosphere, that is, he main pathway for plant carbon absorption. Therefore, any factor that affects the rate of photosynthesis and thus the production of photosynthates will inevitably affect the growth and yield of crops[27]. In plant photosynthesis, ribulose-1,5-diphosphate carboxylase oxygenase is the key enzyme that fixes atmospheric CO_2[28]. This affects the carboxylation efficiency of plant photorespiration, thereby affecting photosynthetic products and ultimately affecting yield. (2) Continuous supply of nutrients is crucial for increasing yield. For example, controlled-release urea-based nitrogen fertilizers have been proposed as an effective nutrient supply strategy[29] to increase crop yield by synchronizing nitrogen supply and crop nitrogen demand[30,31]. This strategy is expected to reduce excessive nitrogen input and nitrogen loss to the environment in crop

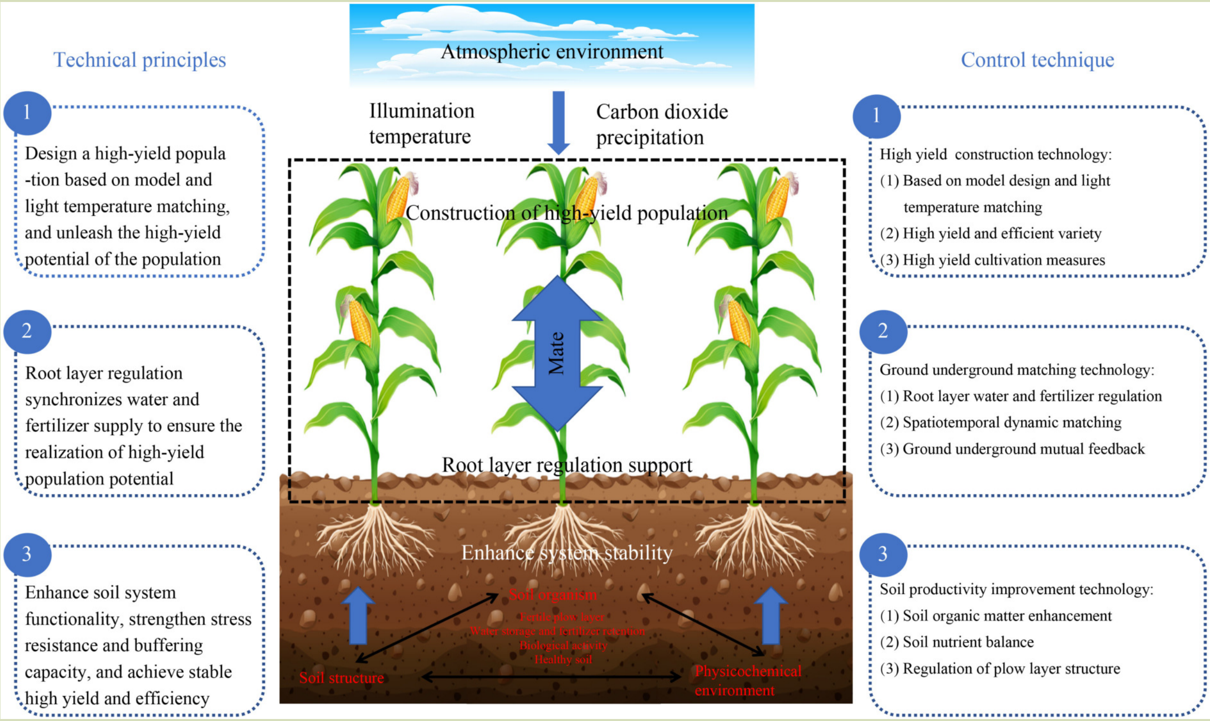


Fig. 2 Principle and technological innovation of sustainable and efficient yield enhancement of maize based on comprehensive management of soil-crop system.

production systems[32]. Studies have shown that using controlled-release fertilizers that can sustainably supply nutrients instead of urea can increase maize yield by 5.3%[33]. (3) Synergistic improvement of yield and efficiency through canopy light nitrogen matching is also essential. The canopy is the fundamental unit of plant photosynthesis in natural ecosystems[34]. Studies have shown that the development of canopy leaves directly affects light interception and photosynthesis[35], with carbohydrates produced by photosynthesis accounting for 90% of crop biomass[36]. Mineral nutrition, especially nitrogen, is crucial in improving crop light resource availability and photosynthetic rate[37]. Nitrogen is an important component of chlorophyll molecules, and its deficiency limits the light energy capture efficiency of chlorophyll, thereby affecting photosynthesis[38]. (4) Soil with higher organic matter can enhance material production capacity and yield. Soil is pivotal for in global carbon sequestration and climate change, as it contains more than twice as much carbon as vegetation and about twice as much carbon as the atmosphere[39]. Most soil carbon exists in the form of organic matter, which is a continuum of organic compounds derived from plants and microorganisms. Its molecular size, decomposition state and binding state with soil mineral particles and aggregates vary. A higher soil organic matter content can promote plant nutrient absorption and serve as a source of activity for soil microorganisms. (5) The application of sustainable plant protection technology can effectively improve the yield of maize seedlings. The seedling stage is more tolerant to drought and afraid of waterlogging. A soil moisture content of 60% to 70% of field capacity is beneficial for root development. Seed treatment should be performed before sowing, such as sun drying and pesticide mixing, to improve germination and emergence rates. (6) Timely, moderately, centrally and efficiently supplying water and nutrients to the root zone of crops, meeting their water and fertilizer needs, and supporting the increase in maize yield is also important[40]. (7) Crop rotation can effectively prevent and control common problems, such as stem rot, ear rot and maize borer. Conservation tillage includes autumn land consolidation, straw retention and deep cultivation operations to maintain soil moisture and reduce compaction, facilitating the development of crop roots[41].

4 Key technological breakthroughs, indicators and considerations

4.1 High yield population construction technology

The design of maize populations is predicated on regional climate and soil conditions, which are variable in humidity and temperature across geographical areas. The performance of maize cultivars also varies regionally. By examining the effective accumulated temperature during the maize growth period in various regions, it is possible to optimize cultivars and enhance their regional adaptability. Additionally, by considering regional climate and soil conditions, and integrating model simulations, optimal sowing dates and planting densities can be determined (Fig. 3). For example, the soil in Northeast China is characterized by high organic matter content and low pH, necessitating an optimized planting density of 6.76 × 10^4 plants ha^{-1}[42,43]. When describing the design of maize population structure, multiple factors need to be considered, including regional climate, soil conditions and cultivar characteristics. However, when it comes to determining the optimal planting density, soil organic matter content and pH are the most important factors to consider. Soil with high organic matter content usually has better fertility, providing a better nutritional environment and supporting plant growth. In soils with high organic matter content, plant growth can be more vigorous, making it a significant factor affecting the choice of planting density. Soil pH has a significant impact on plant growth and nutrient availability. Different crops have different adaptability to differing soil pH, and maize is no exception. Therefore, when considering planting density, it is also necessary to consider whether the soil pH is suitable for the growth of maize.

The soil of the North China Plain has the lowest organic matter content, with a recommended planting density of 7.94 × 10^4 plants ha^{-1}[44]. The Northwest region has high pH soil, with a suitable planting density of 10.4 × 10^4 plants ha^{-1}[45], whereas the Southwest region is best suited to a planting density of 5.43 × 10^4 plants ha^{-1}[46]. Additionally, high-quality maize populations can be achieved through precise sowing, which has been facilitated by technological advancements leading to increased mechanization in maize production. Using a mechanized precision seeder has resulted in a significant improvement in maize emergence rates, from 75% to 98%, a reducing in inter-seedling variability by 9%, and increasing yield by 11% under identical sowing density conditions[47].

4.2 Root layer regulation supporting high-yield and high-efficiency populations

To optimize maize production through root system enhancement, the foundational step is the strategic management of the plow layer. The technology centered on soil tillage enhances the physical and chemical properties of the soil, facilitating root development. This practice has been

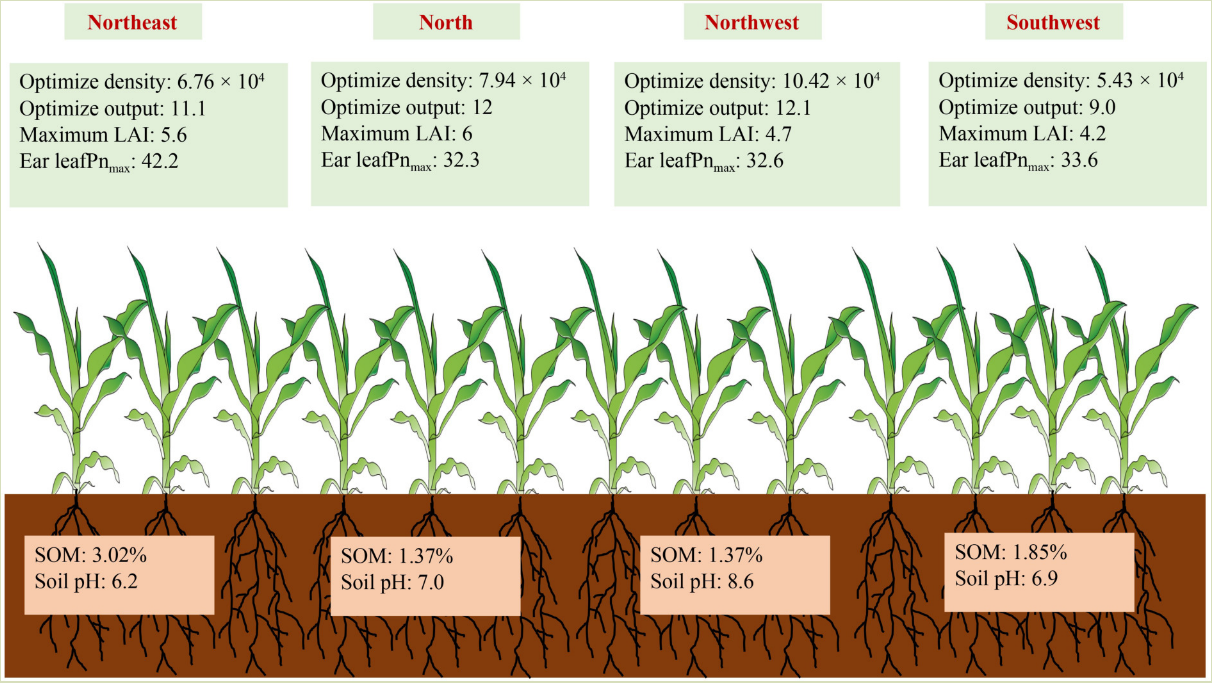


Fig. 3 Performance of high-yield population construction technology in maize. LAI, leaf area index; leafPn$_{max}$, leaf photosynthetic rate net maximum.

shown to improve the growth and development of maize roots in both Northeast and North China, augmenting root quantity and quality, enhancing root function, and facilitating the comprehensive uptake of water and nutrients[48]. Also, fertilizer application techniques that prioritize straw return and increased organic fertilizer application effectively elevate soil organic matter levels. Straw, a significant biomass resource, contributes to soil fertility enhancement, organic matter accumulation and soil quality improvement when mixed into the soil[49]. It contains substantial carbon, which is pivotal for microbial activity in decomposing straw and cycling soil nutrients[50]. The presence of more microorganisms accelerates straw decomposition, with fungi, bacteria and actinomycetes metabolizing cellulose, hemicellulose and lignin into smaller organic compounds and minerals, thereby stabilizing and enhancing soil nutrient content[51,52]. A decade-long practice of straw retention in the field has increased soil organic carbon, reduced greenhouse gas emissions and carbon footprints by 44.4%, enhanced soil carbon sequestration by 17.7%, and increased yield by 38.8%, promoting sustainable maize production[53]. Additionally, the application of organic matter, such as animal manure as an organic fertilizer, slowly releases nutrients to the soil, significantly improving soil fertility and mitigating environmental degradation, thereby decreasing the reliance on mineral fertilizers[54,55]. A combined application of organic and mineral fertilizers is widely recognized as an effective strategy for achieving cleaner and more sustainable crop production[56]. Numerous studies have examined the impact of combined organic and mineral fertilizer application on crop yield, demonstrating that it can maintain or even significantly increase yields[57].

Finally, nutrient management is essential for optimizing maize production. By aligning fertilizer application with the spatiotemporal nutrient demands of maize, in conjunction with improved cultivars and agronomic practices, both yield enhancement and stress tolerance can be achieved. Specifically, nitrogen fertilizer, planting density and cultivar selection influence agronomic traits, such as lodging resistance. The lodging rate its highest level under low (D45) and high (D95) densities[58], while the lowest rate recorded at 7.50 × 10^4 plants ha^{-1}, in the North China plain of China. Under low-density conditions, increasing nitrogen fertilizer decreased lodging whereas high density, high nitrogen levels significantly increased lodging. Appropriate nitrogen and density settings markedly reduced lodging[59]. Cultivar differences in lodging resistance are notable, with Zhongdan 909 has relatively high lodging resistance. The suitable planting areas for Zhongdan 909 mainly include Donghua, Huanghuai River, Heilongjiang and Inner Mongolia. After multiple experiments and field evaluations, the research has shown excellent performance. Overcoming the interaction between intensive planting and lodging resistance in maize, the synergistic improvement of population yields and resistance to intensive production and stress has been achieved. Using precision fertilizer application with a wide gap fertilizer applicator enhances yield and efficiency while minimizing soil mineral nitrogen leaching and environmental risks. Using ammonium sulfate and superphosphate to formulate a specialized starter fertilizer, applied 5 cm lateral and 8 cm below the seed at 230 $kg \cdot ha^{-1}$, effectively promoted root development and resilience to low temperatures[60]. Through appropriate application of potassium fertilizer significantly improved stem puncture strength and node height, with evenly distributed vascular bundles and an increase in small bundles, enhancing overall plant lodging resistance[61].

Appropriate application of medium and trace element fertilizers contributedto maize yield and quality improvement. Sulfur application maize drought resistance and drought stress. Nitrogen and sulfur regulate leaf redox balance via glutathione concentration, influencing photosynthesis. Combined nitrogen and sulfur application also significantly elevates grain cysteine levels, a crucial sulfur-containing amino acid[62]. Additionally, zinc fertilizer reduces maize kernel tip shedding and increases kernel number per ear, thereby improving yield traits in high-density maize populations.

In addition, different regions will have different regional root layer regulation measures to ensure high yield and efficiency of maize. Spring maize areas in the Northeast and along the Great Wall. Mainly use precision irrigation, such as ground drip irrigation and shallow buried drip irrigation, and fertilizer application to ensure that the water and fertilizer needs of maize during the growth period are met[63]. Northwest inland and spring maize irrigation areas along the Yellow River have also widely adopt drip irrigation and integrated water fertilizer technology to support high-density planting and high yield of maize through precise irrigation and fertilizer application. The technical key points include laying drip irrigation pipes, fine soil preparation, applying sufficient base fertilizer, appropriate planting density and wide-narrow row configuration[64]. Summer maize- growing areas on the Huang Huai Fen Wei Plain also attach great importance to the application of integrated water and fertilizer technology, optimizing the growth environment of maize through precise regulation of water and fertilizer, applying appropriate cultivation and straw retention techniques to improve soil structure and enhance soil fertility[65]. Supplementary irrigation in the Southwest maize planting area is a response to the relative scarcity of water resources, with greater emphasis put on the application of water-saving irrigation and precision fertilizer application technologies. By implementing appropriate tillage and straw retention measures, soil water holding capacity and fertility can be improved, thereby supporting high and stable yields of maize[66].

5 Integration and application of regional technology models for maize production in China

For an extended period, the agricultural technology extension system in China has predominantly relied on government channels for the dissemination of agricultural technologies. This approach fails to align with the principles of integrating government, enterprise, university, research and application, and is inadequate for meeting farmers' practical needs. In the context of rural revitalization, it is imperative to explore the establishment of a new model of agricultural technology promotion that integrates government, enterprise, university, research and application, transforms the mode of agricultural development, and meets the technological demands of agricultural production.

The Science and Technology Backyard (STB) has introduced a novel model integrating government, enterprise, university, research and application into agricultural technology promotion, which operates through a framework including university, government, farmer cooperative economic organizations and farmers (Fig. 4). In this model, STB serve as the technological backbone, by connecting government, enterprise, research institutions and field production, it is possible to ensure that technologies and policies are directly implemented at a grassroots level, fostering seamless integration between the upstream and downstream sectors of agricultural production, promoting the sustainable development of sustainable agricultural production, enhancing production and efficiency. Local governments provide a platform for this new model, facilitating changes in farmer production and agricultural management methods. Farmer cooperative organizations are crucial in the transformation system of scientific and technological achievements. Micro-cultivators, in need of cooperative alliances for large-scale land management, boost their farming enthusiasm, improve technology dissemination efficiency and elevate agricultural production and technological levels. Colleges conducts scientific research based on agricultural production needs, continually understanding the technical requirements of farmers from a farmer-centric perspective and conducts targeted scientific experiments to serve agricultural development. Additionally, the STB collaborates closely with

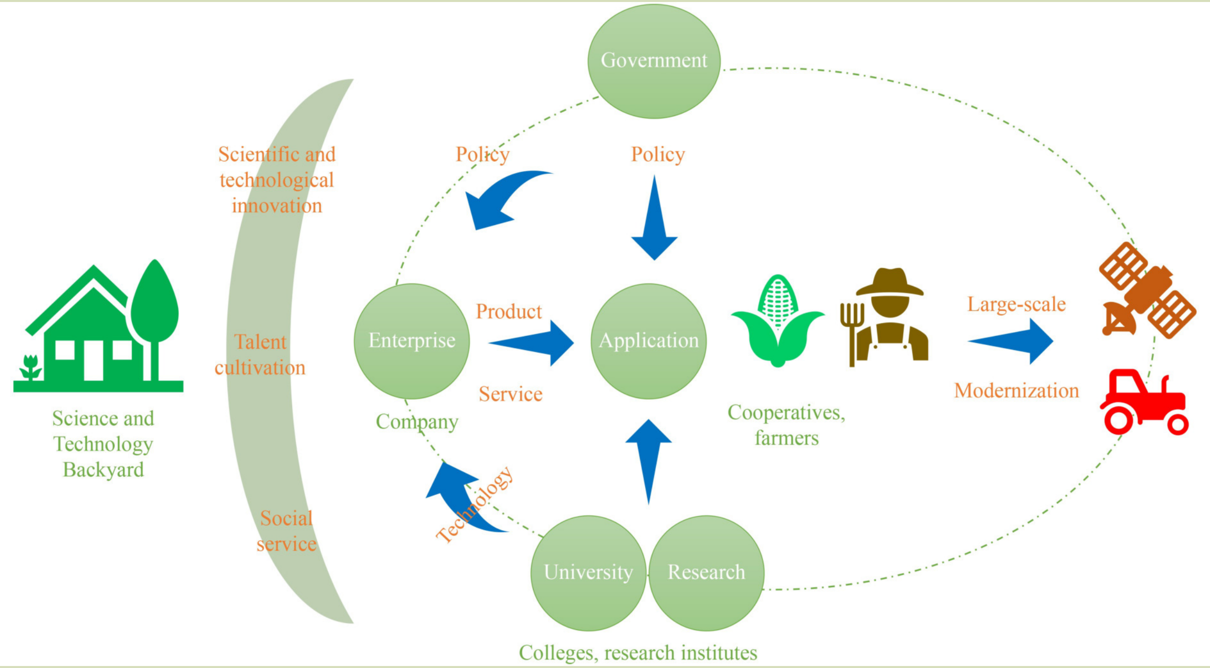
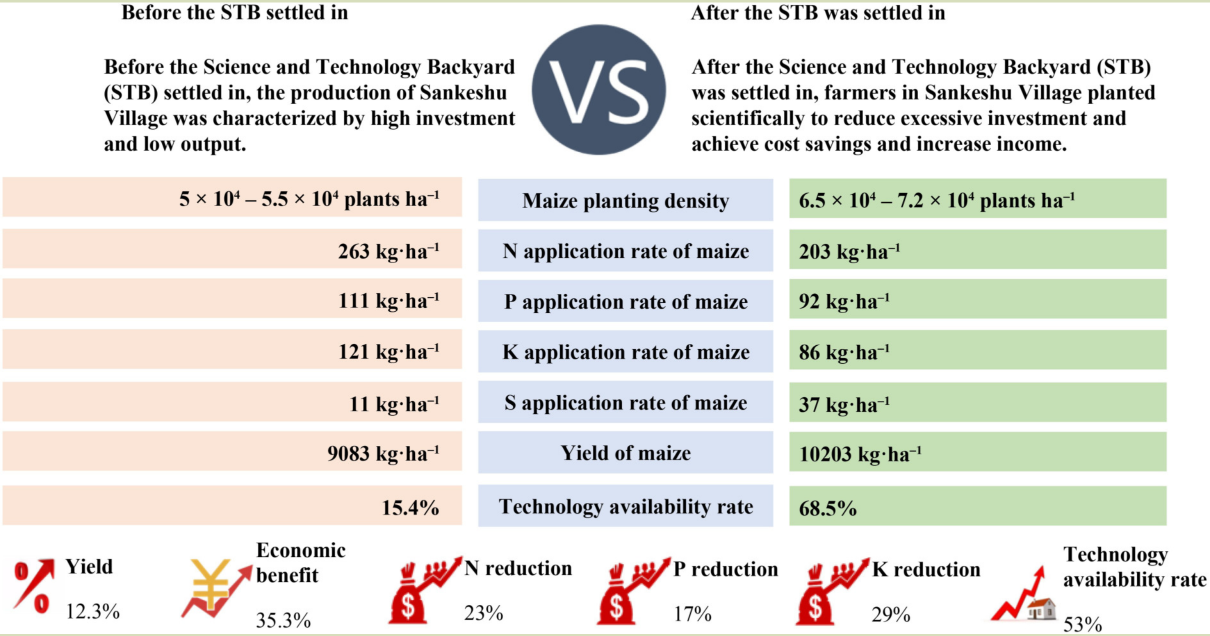


Fig. 4 New model of integrated government, enterprise, university research and application agricultural technology promotion.

local agricultural technology extension stations, leveraging their work system to enhance the overall efficiency of agricultural technology extension. Through synergistic collaboration and complementarity, both entities achieve greater effectiveness and efficiency.

Taking the promotion of sustainable and efficient maize production technology in Lishu County, Jilin Province in Northeast China as an example, the STB for maize in Lishu County has established a four-in-one agricultural technology promotion model of college, government, cooperative organization, farmer integration, effectively extending technology to farmers and creating a three-win outcome through interaction of these stakeholders. In Lishu County, farmers have long faced challenges in maize production, including inappropriate fertilizer application practices, low planting density, and insufficient irrigation. Through the efforts of the STB, optimized water and nutrient management, as well as moderate increases in planting density, have been promoted as effective solutions. With robust support from the Lishu County Agricultural Technology Extension Station, the STB has engaged deeply at a grassroots level, maintaining close contact with agriculture, rural areas and farmers, and addressing the limiting factors for sustainable maize production and efficiency increase through practical, participatory approaches. The Lishu County Agricultural Technology Extension Station has collaborated closely with the STB to enhance the level of agricultural technology extension, and scientific farming knowledge of farmers has improved, transforming them into new-type professional farmers in agricultural management. This has promoted the appropriate reform of local farming land and the development of cooperatives and facilitated the large-scale application of sustainable and efficient maize production technologies, such as soil carbonization and fertilizer application, appropriate group construction, and appropriate nutrient management (Fig. 5). The STB, Agricultural Technology Extension Station, Cooperatives and farmers work closely together, fostering the transformation of agricultural production methods in Lishu County, improving maize production efficiencies and yield, and further promoting local agricultural development.

The establishment of the STB model has made a significant contribution to the transformation of established agricultural practices and advancing the modernization of maize production. However, its current focus remains largely centered on plant nutrition, which limits its broader impact on agricultural development. Looking ahead, the STB should evolve into a multidisciplinary and multidimensional platform. By leveraging a framework including colleges, government, farmer cooperative economic organizations and farmers and incorporating disciplines, including crop and animal production and food sciences, it can foster collaboration to drive sustainable agricultural development.



Before the STB settled in

Before the Science and Technology Backyard (STB) settled in, the production of Sankeshu Village was characterized by high investment and low output.

After the STB was settled in

After the Science and Technology Backyard (STB) was settled in, farmers in Sankeshu Village planted scientifically to reduce excessive investment and achieve cost savings and increase income.

Before the STB settled in		After the STB was settled in
$5 \times 10^4 – 5.5 \times 10^4$ plants ha^{-1}	Maize planting density	$6.5 \times 10^4 – 7.2 \times 10^4$ plants ha^{-1}
263 kg·ha^{-1}	N application rate of maize	203 kg·ha^{-1}
111 kg·ha^{-1}	P application rate of maize	92 kg·ha^{-1}
121 kg·ha^{-1}	K application rate of maize	86 kg·ha^{-1}
11 kg·ha^{-1}	S application rate of maize	37 kg·ha^{-1}
9083 kg·ha^{-1}	Yield of maize	10203 kg·ha^{-1}
15.4%	Technology availability rate	68.5%

Yield	Economic benefit	N reduction	P reduction	K reduction	Technology availability rate
12.3%	35.3%	23%	17%	29%	53%

Fig. 5 Comparison of production status before and after the establishment of the Science and Technology Backyard (STB) for maize in Lishu County, Jilin Province in Northeast China.

6 Conclusions and prospects

The shift toward enhancing sustainable yield and efficiency in maize production in China is a pivotal development. To accomplish this, it is crucial to tackle the specific challenges and constraints in the four primary maize-producing regions of China. By adopting sustainable maize yield enhancement technologies focused on integrated soil-crop system management, through the integration and dissemination of region-specific technical models, comprehensive maize yield has increased by 11.5% nationwide, nitrogen use has decreased by 14.7%, efficiency has improved by 33.4%, and emissions have been reduced by 15%. These achievements provide a strong foundation for sustainable and efficient maize production in major maize-producing regions. The key to achieving sustainable yield enhancement and efficiency in maize production is to tailor strategies to local conditions. This involves aligning regional constraints with precision technologies, constructing high-yielding maize populations through precise canopy-root system matching, and combining precise nutrient supply with soil fertility improvement. Additionally, leveraging the government-enterprise-university-research-application model, centered around the STB, will facilitate the realization of sustainable and efficient maize production, and its development at increasing scale and with more rapid modernization.

Acknowledgements

This research was supported by National Key R&D Programs (2024YFD2300105 and 2022YFD1500700), and National Maize Production System in China and Special Fund for Agriculture Professional (201103003).

Compliance with ethics guidelines

Xiaoyu Li, Hongguang Cai, Yao Liang, Shanchao Yue, Shiqing Li, Baizhao Ren, Jiwang Zhang, Wushuai Zhang, Xinping Chen, Qingfeng Meng, Peng Hou, Jianbo Shen, Wenqi Ma, Guozhong Feng, and Qiang Gao declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

REFERENCES

1. Min H, Chen C, Wei S, Shang X, Sun M, Xia R, Liu X, Hao D, Chen H, Xie Q. Identification of drought tolerant mechanisms in maize seedlings based on transcriptome analysis of recombination inbred lines. *Frontiers in Plant Science*, 2016, **7**: 1080
2. Zhu S, Vivanco J M, Manter D K. Nitrogen fertilizer rate affects root exudation, the rhizosphere microbiome and nitrogen-use-efficiency of maize. *Applied Soil Ecology*, 2016, **107**: 324–333
3. Food and Agriculture Organization of the United Nations (FAO). AQUASTAT—FAO's Global Information System on Water and Agriculture. Rome: *FAO*, 2021. Available at FAO website on April 2, 2025
4. Tian P, Liu J, Zhao Y, Huang Y, Lian Y, Wang Y, Ye Y. Nitrogen rates and plant density interactions enhance radiation interception, yield, and nitrogen use efficiencies of maize. *Frontiers in Plant Science*, 2022, **13**: 974714
5. National Bureau of Statistics of China (NBSC). China Statistical Yearbook 2022. Beijing: *China Statistics Press*, 2022 (in Chinese)
6. Chen X P, Cui Z L, Fan M S, Vitousek P, Zhao M, Ma W Q, Wang Z L, Zhang W J, Yan X Y, Yang J C, Deng X P, Gao Q, Zhang Q, Guo S W, Ren J, Li S Q, Ye Y L, Wang Z H, Huang J L, Tang Q Y, Sun Y X, Peng X L, Zhang J W, He M R, Zhu Y J, Xue J Q, Wang G L, Wu L, An N, Wu L Q, Ma L, Zhang W F, Zhang F S. Producing more grain with lower environmental costs. *Nature*, 2014, **514**(7523): 486–489
7. Pan J X, Zhang L, He X M, Chen X P, Cui Z L. Long-term optimization of crop yield while concurrently improving soil quality. *Land Degradation & Development*, 2019, **30**(8): 897–909
8. Xu X P, He P, Pampolino M F, Johnston A M, Qiu S J, Zhao S C, Chuan L M, Zhou W. Fertilizer recommendation for maize in China based on yield response and agronomic efficiency. *Field Crops Research*, 2014, **157**: 27–34
9. National Bureau of Statistics of China (NBSC). China Statistical Yearbook 2021. Beijing: *China Statistics Press*, 2021 (in Chinese)
10. Brown M E, Funk C C. Food security under climate change. *Science*, 2008, **319**(5863): 580–581
11. Yang Y S, Guo X X, Liu G Z, Liu W M, Xue J, Ming B, Xie R Z, Wang K R, Hou P, Li S K. Solar radiation effects on dry matter accumulations and transfer in maize. *Frontiers in Plant Science*, 2021, **12**: 727134
12. Yang Y S, Guo X X, Liu H F, Liu G Z, Liu W M, Ming B, Xie R Z, Wang K R, Hou P, Li S K. The effect of solar radiation change on the maize yield gap from the perspectives of dry matter accumulation and distribution. *Journal of Integrative Agriculture*, 2021, **20**(2): 482–493
13. Yang Y S, Liu G Z, Guo X X, Liu W M, Xue J, Ming B, Xie R Z, Wang K R, Hou P, Li S K. Quantitative relationship between solar radiation and grain filling parameters of maize. *Frontiers in Plant Science*, 2022, **13**: 906060
14. Yang Y S, Guo X X, Hou P, Xue J, Liu G Z, Liu W M, Wang Y H, Zhao R L, Ming B, Xie R Z, Wang K R, Li S K. Quantitative effects of solar radiation on maize lodging resistance mechanical properties. *Field Crops Research*, 2020, **255**: 107906
15. Yang Y S, Xu W J, Hou P, Liu G Z, Liu W M, Wang Y H, Zhao R L, Ming B, Xie R Z, Wang K R, Li S K. Improving maize grain yield by matching maize growth and solar radiation. *Scientific Reports*, 2019, **9**(1): 3635
16. Liu Y E, Hou P, Xie R Z, Li S K, Zhang H B, Ming B, Ma D L, Liang S M. Spatial adaptabilities of spring maize to variation of climatic conditions. *Crop Science*, 2013, **53**(4): 1693–1703
17. Hou P, Liu Y E, Liu W M, Yang H S, Xie R Z, Wang K R, Ming B, Liu G Z, Xue J, Wang Y H, Zhao R L, Zhang W J, Wang Y J, Bian S F, Ren H, Zhao X Y, Liu P, Chang J Z, Zhang G H, Liu J Y, Yuan L Z, Zhao H Y, Shi L, Zhang L L, Yu L, Gao J L, Yu X F, Wang Z G, Shen L G, Ji P, Yang S Z, Zhang Z D, Xue J Q, Ma X F, Wang X Q, Lu T Q, Dong B C, Li G, Ma B X, Li J Q, Deng X F, Liu Y H, Yang Q, Jia C L, Chen X P, Fu H, Li S K. Quantifying maize grain yield losses caused by climate change based on extensive field data across China. *Resources, Conservation and Recycling*, 2021, **174**: 105811
18. Springmann M, Clark M, Mason-D'croz D, Wiebe K, Bodirsky B L, Lassaletta L, de Vries W, Vermeulen S J, Herrero M, Carlson K M, Jonell M, Troell M, DeClerck F, Gordon L J, Zurayk R, Scarborough P, Rayner M, Loken B, Fanzo J, Godfray H C J, Tilman D, Rockström J, Willett W. Options for keeping the food system within environmental limits. *Nature*, 2018, **562**(7728): 519–525
19. Steffen W, Richardson K, Rockström J, Cornell S E, Fetzer I, Bennett E M, Biggs R, Carpenter S R, de Vries W, de Wit C A, Folke C, Gerten D, Heinke J, Mace G M, Persson L M, Ramanathan V, Reyers B, Sörlin S. Planetary boundaries: Guiding human development on a changing planet. *Science*, 2015, **347**(6223): 1259855
20. Pingali P L. Green revolution: Impacts, limits, and the path ahead. *Proceedings of the National Academy of Sciences of the United States of America*, 2012, **109**(31): 12302–12308
21. Cui Z L, Zhang H Y, Chen X P, Zhang C C, Ma W Q, Huang C D, Zhang W F, Mi G H, Miao Y X, Li X L, Gao Q, Yang J C, Wang Z H, Ye Y L, Guo S W, Lu J W, Huang J L, Lv S H, Sun Y X, Liu Y Y, Peng X L, Ren J, Li S Q, Deng X P, Shi X J, Zhang Q, Yang Z Q, Tang L, Wei C Z, Jia L L, Zhang J W, He M R, Tong Y N, Tang Q Y, Zhong X H, Liu Z H, Cao N, Kou C G, Ying H, Yin Y L, Jiao X Q, Zhang Q S, Fan M S, Jiang R F, Zhang F S, Dou Z X. Pursuing sustainable productivity with millions of smallholder farmers. *Nature*, 2018, **555**(7696): 363–366
22. Schmitt M R, Edwards G E. Photosynthetic capacity and nitrogen use efficiency of maize, wheat, and rice: a comparison

between C_3 and C_4 photosynthesis. *Journal of Experimental Botany*, 1981, **32**(3): 459–466

23. Zhao Y A, Huang Y F, Li S, Chu X, Ye Y L. Improving the growth, lodging and yield of different density resistance maize by optimising planting density and nitrogen fertilisation. *Plant, Soil and Environment*, 2020, **66**(9): 453–460
24. Li J, Wang E, Wang Y, Xing H, Wang D, Wang L, Gao C. Reducing greenhouse gas emissions from a wheat–maize rotation system while still maintaining productivity. *Agricultural Systems*, 2016, **145**: 90–98
25. 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
26. Grassini P, Thorburn J, Burr C, Cassman K G. High-yield irrigated maize in the western US corn belt I. On-farm yield, yield potential, and impact of agronomic practices. *Field Crops Research*, 2011, **120**(1): 142–150
27. Bernacchi C J, Ruiz-Vera U M, Siebers M H, DeLucia N J, Ort D R. Short- and long-term warming events on photosynthetic physiology, growth, and yields of field grown crops. *Biochemical Journal*, 2023, **480**(13): 999–1014
28. Ogren W L. Photorespiration: pathways, regulation, and modification. *Annual Review of Plant Physiology*, 1984, **35**(1): 415–442
29. Dimkpa C O, Fugice J, Singh U, Lewis T D. Development of fertilizers for enhanced nitrogen use efficiency—Trends and perspectives. *Science of the Total Environment*, 2020, **731**: 139113
30. Zhang W S, Liang Z Y, He X M, Wang X B, Shi X J, 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
31. Yao Z, Zhang W, Wang X, Zhang L, Zhang W, Liu D, Chen X. Agronomic, environmental, and ecosystem economic benefits of controlled-release nitrogen fertilizers for maize production in Southwest China. *Journal of Cleaner Production*, 2021, **312**: 127611
32. Zheng W K, Liu Z G, Zhang M, Shi Y F, Zhu Q, Sun Y, Zhou H, Li C, Yang Y, Geng J. Improving crop yields, nitrogen use efficiencies, and profits by using mixtures of coated controlled-released and uncoated urea in a wheat-maize system. *Field Crops Research*, 2017, **205**: 106–115
33. Li T Y, Zhang W F, Cao H B. Region-specific nitrogen management indexes for sustainable cereal production in China. *Environmental Research Communications*, 2020, **2**: 1–12
34. Ort D R, Merchant S S, Alric J, Barkan A, Blankenship R E, Bock R, Croce R, Hanson M R, Hibberd J M, Long S P, Moore T A, Moroney J, Niyogi K K, Parry M A J, Peralta-Yahya P P, Prince R C, Redding K E, Spalding M H, van Wijk K J, Vermaas W F J, von Caemmerer S, Weber A P M, Yeates T O, Yuan J S, Zhu X G. Redesigning photosynthesis to sustainably meet global food and bioenergy demand. *Proceedings of the National Academy of Sciences of the United States of America*, 2015, **112**(28): 8529–8536
35. Barillot R, Escobar-Gutiérrez A J, Fournier C, Huynh P, Combes D. Assessing the effects of architectural variations on light partitioning within virtual wheat-pea mixtures. *Annals of Botany*, 2014, **114**(4): 725–737
36. Makino A. Photosynthesis, grain yield, and nitrogen utilization in rice and wheat. *Plant Physiology*, 2011, **155**(1): 125–129
37. Ye T H, Zhang J L, Li J, Lu J W, Ren T, Cong R, Lu Z, Li X. Nitrogen/potassium interactions increase rice yield by improving canopy performance. *Food and Energy Security*, 2021, **10**(3): e295
38. Schlemmer M R, Francis D D, Shanahan J F, Schepers J S. Remotely measuring chlorophyll content in corn leaves with differing nitrogen levels and relative water content. *Agronomy Journal*, 2005, **97**(1): 106–112
39. Chen S, Xu C, Yan J, Zhang X, Zhang X, Wang D. The influence of the type of crop residue on soil organic carbon fractions: an 11-year field study of rice-based cropping systems in southeast China. *Agriculture, Ecosystems & Environment*, 2016, **223**: 261–269
40. Zhang X J, Bashir M A, Raza Q U. Evaluating the Effects of sustainable chemical and organic fertilizers with water saving practice on corn production and soil characteristics. *Phyton*, 2023, **92**(5): 1349–1360
41. Jiang F, Xue X, Zhang L, Zuo Y, Zhang H, Zheng W, Bian L, Hu L, Hao C, Du J, Ci Y, Cheng R, Dawa C, Biswas M, Islam M U, Meng F, Peng X. Soil wind erosion, nutrients, and crop yield response to conservation tillage in North China: a field study in a semi-arid and wind erosion region after 9 year. *Field Crops Research*, 2024, **316**: 109508
42. Chen Y, Liu S, Li H, Li X F, Song C Y, Cruse R M, Zhang X Y. Effects of conservation tillage on corn and soybean yield in the humid continental climate region of Northeast China. *Soil & Tillage Research*, 2011, **115–116**: 56–61
43. Qing F. Soil properties and corn (*Zea mays* L.) production under manure application combined with deep tillage management in solonetzic soils of Songnen Plain, Northeast China. *Journal of Integrative Agriculture*, 2016, **15**(4): 879–890
44. Quan Q, Yi F, Liu H. Fertilizer response to climate change: evidence from corn production in China. *Science of the Total Environment*, 2024, **928**: 172226
45. Peng Y, Li Z, Sun T, Zhang F, Wu Q, Du M, Sheng T. Modeling long-term water use and economic returns to optimize alfalfa-corn rotation in the corn belt of northeast China. *Field Crops Research*, 2022, **276**: 108379
46. Zheng J Z, Wang W, Wang W, Cui T, Chen S, Xu C, Engel B. Facing climate change: propagation of risks and opportunities for cropping systems in mid-high-latitude regions: a case study between U.S. and China corn belts. *Agricultural Systems*, 2024, **220**: 104087

47. Quan L, Guo Z, Huang L, Xue Y, Sun D, Chen T, Geng T, Shi J, Hou P, He J, Lou Z. Efficient extraction of corn rows in diverse scenarios: a grid-based selection method for intelligent classification. *Computers and Electronics in Agriculture*, 2024, **218**: 108759
48. Yu N, Liu J, Ren B, Zhao B, Liu P, Gao Z, Zhang J. Long-term integrated soil-crop management improves soil microbial community structure to reduce GHG emission and increase yield. *Frontiers in Microbiology*, 2022, **13**: 1024686
49. Lugato E, Berti A, Giardini L. Soil organic carbon (SOC) dynamics with and without residue incorporation in relation to different nitrogen fertilisation rates. *Geoderma*, 2006, **135**: 315–321
50. Zhang Q F. Problems and countermeasures of straw returning. *Science and Technology of West China*. 2014, **13**(3): 73 and 126 (in Chinese)
51. Qin S, Jiao K, Lyu D, Shi L, Liu L. Effects of maize residue and cellulose-decomposing bacteria inocula on soil microbial community, functional diversity, organic fractions, and growth of *Malus hupehensis* Rehd. *Archives of Agronomy and Soil Science*, 2015, **61**(2): 173–184
52. Witt C, Cassman K G, Olk D C, Biker U, Liboon S P, Samson M I, Ottow J C G. Crop rotation and residue management effects on carbon sequestration, nitrogen cycling and productivity of irrigated rice systems. *Plant and Soil*, 2000, **225**(1–2): 263–278
53. Ren H, Cheng Y, Li R, Yang Q, Liu P, Dong S, Zhang J, Zhao B. Integrating density and fertilizer management to optimize the accumulation, remobilization, and distribution of biomass and nutrients in summer maize. *Scientific Reports*, 2020, **10**(1): 11777
54. Laub M, Corbeels M, Ndungu S M, Mucheru-Muna M W, Mugendi D, Necpalova M, Van de Broek M, Waswa W, Vanlauwe B, Six J. Combining manure with mineral N fertilizer maintains maize yields: evidence from four long-term experiments in Kenya. *Field Crops Research*, 2023, **291**: 108788
55. Lazcano C, Zhu-Barker X, Decock C. Effects of organic fertilizers on the soil microorganisms responsible for N_2O emissions: a review. *Microorganisms*, 2021, **9**(5): 983
56. Wu W, Ma B L. Integrated nutrient management (INM) for sustaining crop productivity and reducing environmental impact: a review. *Science of the Total Environment*, 2015, **512–513**: 415–427
57. Wei Q Q, Gou J L, Zhang M, Zhang B X, Rao Y, Xiao H G. Nitrogen reduction combined with organic materials can stabilize crop yield and soil nutrients in winter rapeseed and maize rotation in yellow soil. *Sustainability*, 2022, **14**(12): 7183
58. Miao Y, Stewart B A, Zhang F. Long-term experiments for sustainable nutrient management in China. A review. *Agronomy for Sustainable Development*, 2011, **31**(2): 397–414
59. 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
60. Chen F, Liu X, Mi G. Varietal differences in plant growth, phosphorus uptake and yield formation in two maize inbred lines grown under field conditions. *Journal of Integrative Agriculture*, 2012, **11**(10): 1738–1743
61. Huang J, Wang Q, Qiu Q, Zou L, Shen X, Wan Y, Qu H. Physiological studies on anthocyanin accumulation, quality and yield of purple sweet potato tubers with different forms of potassium fertilizer. *Scientia Horticulturae*, 2025, **343**: 114094
62. Liu S, Cui S, Ying F, Nasar J, Wang Y, Gao Q. Simultaneous improvement of protein concentration and amino acid balance in maize grains by coordination application of nitrogen and sulfur. *Journal of Cereal Science*, 2021, **99**: 103189
63. Song Z, Peng Y, Li Z, Zhang S, Liu X, Tan S. Two irrigation events can achieve relatively high, stable corn yield and water productivity in aeolian sandy soil of Northeast China. *Agricultural Water Management*, 2022, **260**: 107291
64. Han J, Jia Z, Han Q, Zhang J. Application of mulching materials of rainfall harvesting system for improving soil water and corn growth in Northwest of China. *Journal of Integrative Agriculture*, 2013, **12**(10): 1712–1721
65. Pi H, Zhang X, Li S, Webb N P. Influence of crop rotation, irrigation, fertilization, and tillage on the aggregate property and soil wind erosion potential in the floodplain of the Yellow River. *Aeolian Research*, 2024, **67–69**: 100925
66. Zhao L, Fan M, Zhang B, He Y, Jin J, Liu G. A preliminary determination of the plot-scale fertilization tolerance of an Entisol in Southwest China. *Journal of Soil and Water Conservation*, 2021, **76**(4): 369–386