

# Pathways for sustainable production to approach the potential yield of winter wheat and summer maize on the North China Plain

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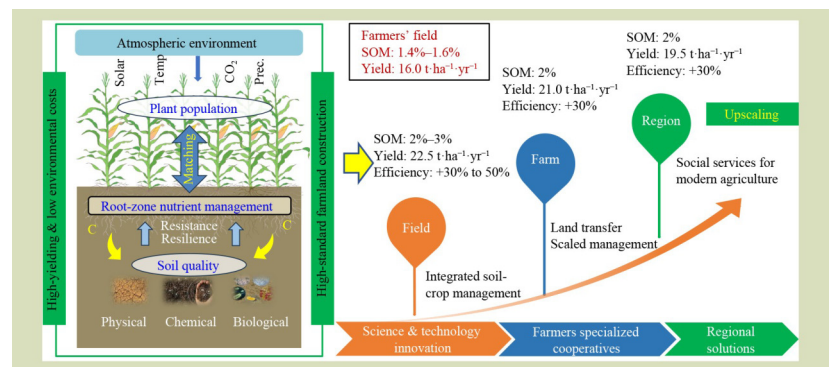
## KEYWORDS

Food security, integrated management, environmental protection, agricultural sustainability

## HIGHLIGHTS

- Sustainable crop production represents a transformative process and a strategic pathway towards achieving sustainable agriculture.
- Pathways for the sustainable production of winter wheat and summer maize rotation on the North China Plain are proposed.
- Sustainable crop production requires a deeper understanding of plant-soil-climate-management interactions.
- Strengthening sustainable crop production involves interdisciplinary research innovation and multistakeholder participation.

## GRAPHICAL ABSTRACT



## ABSTRACT

Pursuing greater crop yields with fewer inputs is a grand challenge under a changing climate, particularly for smallholder farming. Integrated soil and crop management has been proven effective in increasing both crop yield and nutrient use efficiency on a large scale in China. However, there is a lack of multi-objective and integrated technologies aimed at improving soil quality, crop yield, and nutrient and water resource efficiency, which are currently the top priorities of sustainable crop production. This paper proposes pathways for the sustainable production of 22.5 t·ha<sup>-1</sup> yield in a winter wheat and summer maize rotation on the North China Plain. The challenges and constraints of sustainable crop production were reviewed with a focus on extreme climate events, soil quality, resource use efficiency, and socioeconomic factors. There is now increasing attention given to addressing these issues through the selection of superior crop genotypes, precision management of nutrients and irrigation, improvement of soil quality and land management. This can lead to increased yields and reduced resource inputs and can also mitigate greenhouse gas emissions and increase carbon sequestration in soils. Strengthening sustainable crop production requires a deeper understanding of plant–soil–climate–management interactions and involves interdisciplinary

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research innovation and multistakeholder participation, which can help achieve agricultural sustainability.

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## 1 Introduction

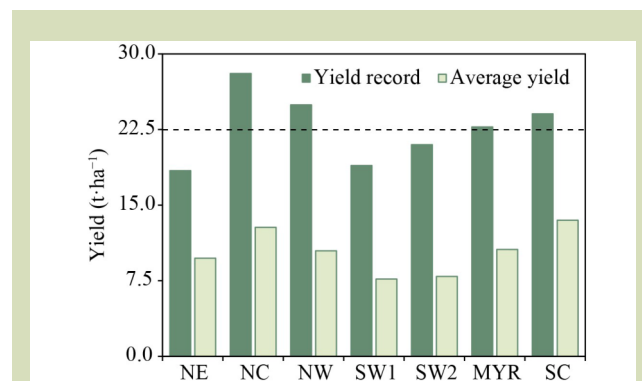
The established strategies for enhancing grain production rely on the increased use of agricultural chemical inputs, which frequently lead to substantial environmental costs<sup>[1]</sup>. In China, the excessive application of mineral fertilizers has increased more than 4-fold over the past four decades, while grain production has increased about 1.2-times, resulting in lower fertilizer use efficiency for the main crops<sup>[2–5]</sup>. The demand for cereals is projected to increase from 420 Mt in 2010 to 530 Mt in 2050, driven mainly by the increase in cereal feed demand<sup>[6]</sup>. Ensuring the national food demand with lower environmental costs is one of the greatest sustainability challenges of the coming decades and has been further exacerbated by global climate change<sup>[7–9]</sup>. To this end, the nation has proposed to the formulation of implementation plans for a new round of action to increase China's grain production capacity by 50 Mt. In addition, China's water management faces significant challenges, such as low efficiency, short supply and uneven geographical distribution<sup>[10]</sup>. Although the food productivity of irrigation water in China has increased from 1.58 to over 1.80 kg·m<sup>-3</sup> over the past decade, it still falls short of the best global level of 2.0 kg·m<sup>-3</sup><sup>[11]</sup>. Currently, agriculture must transform from high-input and low-efficiency intensive farming to a more sustainable model<sup>[5]</sup>. An increase in grain productivity will increasingly depend on the integration of innovative technologies and products rather than the mere augmentation of resource inputs<sup>[4,5]</sup>. This transition is not only an inescapable response to constraints on resources and environmental pressures but also a vital strategy to bolster agricultural competitiveness and drive comprehensive rural revitalization.

Winter wheat and summer maize are the two main grain crops grown on the North China Plain (NCP), and cover 73.6% and 30.6% of the total national wheat and maize production area, respectively<sup>[12]</sup>. These two crops contribute 80.6% and 29.3% of the national total output, respectively, highlighting their crucial role in national food security. However, the yield of wheat and maize in China has reached only 53%–66% of genetic potential<sup>[4,13]</sup>. The average grain yields for the main cereal crops vary across different regions of China; for example, the farmer practices for winter wheat and summer maize production on the NCP yield an average of 12.8 t·ha<sup>-1</sup>, and

spring maize yields in Northeast China of 9.7 t·ha<sup>-1</sup><sup>[12]</sup>. The highest yield of winter wheat and summer maize on the NCP has been 28.1 t·ha<sup>-1</sup>·yr<sup>-1</sup>, followed by 24.9 t·ha<sup>-1</sup>·yr<sup>-1</sup> for spring maize in Northwest China. Notably, the winter wheat and summer maize rotation on the NCP has a distinct advantage and significant potential in terms of annual production (Fig. 1). However, grain production on the NCP faces many challenges and constraints, including frequent extreme climate events, suboptimal soil quality, low resource use efficiency and various socioeconomic factors<sup>[7,14–17]</sup>. Consequently, a profound understanding of the complex interactions among plants, soil, climate and management practices is essential for achieving agricultural sustainability<sup>[5]</sup>. These efforts play pivotal roles in ensuring national food security and offer valuable insights and examples for sustainable agricultural development.

## 2 Current state and potential of grain production on the NCP

Given the scarcity of arable land, increasing crop yields per unit area is imperative for fulfilling escalating food demands. The wheat-maize rotation system on the NCP is notably productive. In particular, certain areas within this region have attained an annual yield target of 22.5 t·ha<sup>-1</sup><sup>[18]</sup>. This target represents 80% of the recorded yield achievable by current farmer



**Fig. 1** Farmer yield averages and the yield records in major food-producing regions. The regions include China's Northeast (NE), North (NC), Northwest (NW), Southwest (SW), South (SC), and middle reaches of the Yangtze River (MYR). SW1, spring maize; SW2, winter wheat and summer maize rotation.

practices<sup>[13,19]</sup>, which corresponds to 80% of the annual yield record of 28.1 t·ha<sup>-1</sup> on the NCP (Fig. 1). However, the majority of areas fall behind, which leaves a substantial gap from the attainable yield target (Table 1). Therefore, achieving the production potential of the winter wheat-summer maize rotation system on the NCP and an annual yield of 22.5 t·ha<sup>-1</sup> on a large scale will have a significant effect on the national grain supply. Agricultural production in this region also faces challenges such as water scarcity and overexploitation of groundwater<sup>[34]</sup>, lower soil quality<sup>[32,33]</sup>, excessive use of mineral fertilizers<sup>[7]</sup> and climate change impacts<sup>[9,16]</sup>. To address these pressing concerns, implementing integrated soil-crop system management, as highlighted in various studies, is essential for driving a shift toward a more sustainable and resilient agricultural framework for the NCP<sup>[7,9,25,35]</sup>.

### 3 Constraints on sustainable crop production on the NCP

#### 3.1 Extreme climate events

The agricultural productivity in this region faces significant challenges due to unpredictable weather patterns and the increasing frequency of climate extremes, including late spring frosts, prolonged droughts and severe flooding, all of which hinder the achievement of high and stable grain yields<sup>[9,36,37]</sup>. Climate change has resulted in more frequent occurrences of extreme weather conditions. Extreme low-temperature events during floral initiation to anthesis and extreme high-temperature events during grain filling are the main extreme climate events causing the loss of wheat yield<sup>[38]</sup>. Under changing environmental conditions, wheat production requires enhanced resilience to climatic variability and extremes, whereas studies have shown that European wheat has experienced a decline in climate resilience across most

countries over the last two decades<sup>[39]</sup>. Nonetheless, strong evidence shows that adopting new breeding technologies and farming practices can increase crop productivity and resilience<sup>[40]</sup>. Genotypes with faster grain-filling rates were more effective at reducing yield losses from delayed sowing<sup>[37]</sup>, indicating a resilience capacity at the reproductive stages.

Owing to climate change, the NCP has had a rising temperature trend, particularly in terms of the winter temperature<sup>[41]</sup>. This has led to a reduction in the growth period for winter wheat and an extension for summer maize, increasing at a rate of 0.21 d·yr<sup>-1</sup> and significantly amplifying the potential for light and temperature-driven productivity gains at a rate of 71.7 kg·ha<sup>-1</sup>·yr<sup>-1</sup><sup>[42]</sup>. In established farming practices, small-scale farmers prioritize wheat production and tend to sow early, typically around early October<sup>[43]</sup>. To facilitate early sowing of winter wheat, farmers often harvest summer maize earlier, which leads to inadequate grain filling of maize and a reduction in yield. Consequently, the annual yield and efficiency of photothermal utilization fail to reach their full potential. This highlights the need to adjust sowing and harvesting schedules to optimize crop maturity and overall productivity<sup>[44]</sup>.

Summer maize has heightened vulnerabilities during its pollination and grain-setting periods due to heat, drought or persistent cloudy and rainy weather<sup>[45]</sup>. The annual precipitation on the NCP is concentrated mainly in the summer maize season. Waterlogging at the stem elongation to flowering stages can significantly inhibit root growth, thereby affecting the ability of plants to take up nutrients. Waterlogging imposed at the jointing stage has the most pronounced effects on maize growth and grain yield. This is followed by waterlogging at the seedling, flowering and grain-filling stages, which mainly influences grain yield through kernel weight and number<sup>[46]</sup>.

**Table 1** Status and target for sustainable production of wheat and maize on the North China Plain (NCP)

Item	Winter wheat		Summer maize		Reference
	Current	Target	Current	Target	
Yield (t·ha <sup>-1</sup> )	4.5–6.5	8.1–9.9	7.3–8.2	15.3–17.6	[20–22]
N input (kg·ha <sup>-1</sup> )	270–330	170–190	250–350	180–225	[3,23,24]
P input (kg·ha <sup>-1</sup> )	39–65	22–41	26–39	11–33	[7,25–27]
K input (kg·ha <sup>-1</sup> )	50–133	50–75	75–125	62–75	[28–30]
Irrigation (mm)	300–400	240–330	45–110	30–90	[26,31]
SOM (g·kg <sup>-1</sup> )	17.2	20.0–30.0	17.2	20.0–30.0	[32,33]

### 3.2 Annual utilization of photothermal resources

On the NCP, the prevalent temperate and subtropical monsoon climates result in markedly uneven annual distributions of rainfall, radiation and thermal resources. The standard annual double-cropping of winter wheat and summer maize rotation on the NCP suffers from the irrational allocation of resources throughout the year. The mismatch between crop cultivars, sowing dates and growth cycles with changing radiation, temperature and water resources has further suppressed increases in the annual yield and efficiency of resource use<sup>[16,41]</sup>. Based on 45 field experiments, researchers have reported that yield variation across different sites on the NCP are influenced primarily by disparities in the distribution of photothermal resources and precipitation<sup>[47]</sup>. However, the distribution rates of these resources between the wheat and maize growing seasons remain relatively consistent across various locations. Specifically, the accumulated temperature distribution rate was 43% during the wheat season and 57% during the maize season, resulting in an accumulated temperature ratio of 0.7 between the two seasons. This ratio is regarded as an optimal distribution of resources for the growth cycles of winter wheat and summer maize<sup>[47]</sup>.

Sowing time and seeding rate are crucial practices that significantly influence wheat yield. Achieving the optimal window for sowing and calibrating the seed quantity correctly are essential for coordinating the yield components. Only through this precise approach can these indicators be optimized to achieve the highest yield<sup>[48]</sup>. Studies have indicated that postponing the sowing date of winter wheat minimally impacts yield, whereas delaying the harvest of summer maize can substantially increase yields by 8%, consequently increasing the annual output<sup>[47,49]</sup>. This strategy optimizes the utilization and seasonal alignment of light and thermal resources throughout the year. Given the close correlation between maize growth and photothermal resources, timely early sowing can increase the effective accumulated temperature during the maize growth phase and prolong the grain filling, thereby potentially increasing yields<sup>[47,50]</sup>.

The summer maize season is characterized by a shorter growing period and thus has relatively constrained heat resources. On the NCP, enhancing light resource use is crucial for increasing summer maize yields. One effective approach is increasing the maize planting density to maximize photothermal resource use<sup>[51]</sup>. Optimizing the planting density can more effectively harness available light, thereby increasing biomass production and, ultimately, grain yield. Studies have demonstrated that moderate increases in planting density can efficiently capture additional sunlight and transform it into

chemical energy through photosynthesis, thus increasing grain yields<sup>[52]</sup>. Increasing the planting density enhances the grain yield primarily by efficiently utilizing light resources during the vegetative stage, thereby increasing pre-silking dry matter production at the population level and its subsequent remobilization to the grain<sup>[52]</sup>. Studies have shown that achieving a maize yield exceeding 22.5 t·ha<sup>-1</sup> under high-density conditions has a small source and strong biomass productivity, along with rapid initiation of grain filling, a relatively high maximum grain-filling rate and an extended maturation drying period<sup>[53]</sup>. However, the implementation of this strategy must consider a range of factors, including the particular maize hybrid, soil conditions and regional climate profile.

### 3.3 Soil conditions

Better soil quality is imperative for the attainment of robust crop yields. However, the persistent pursuit of high-intensity cultivation has led to a significant depletion of soil carbon reserves<sup>[54]</sup>. This decline underscores the need for more sustainable agricultural practices that prioritize soil health and aim to regenerate these vital carbon stores<sup>[32,55]</sup>. Soil organic carbon is crucial for maintaining soil water and nutrient retention capacity<sup>[56]</sup> and promotes soil aggregation<sup>[57]</sup>. Research has established a positive link between crop yields and increasing soil organic carbon (SOC) levels, with the contribution of SOC to yield enhancement being roughly one-fifth that of nitrogen fertilizers<sup>[33]</sup>. For both maize and wheat, the positive impact of SOC on yield plateaus when the SOC concentration exceeds 43.2–43.9 and 12.7–13.4 g·kg<sup>-1</sup>, respectively<sup>[33]</sup>. This indicates the importance of striking a balance in SOC levels to maximize agricultural output.

The SOC content of agricultural soil in China to a depth of 20 cm ranges from about 26.6–32.5 t·ha<sup>-1</sup> C, with a mean value of 14.5 t·ha<sup>-1</sup> C on the NCP. This value is considerably lower than the average level of 43.7 t·ha<sup>-1</sup> C found in agricultural soils in the USA<sup>[58]</sup>, indicating the potential for improved carbon sequestration in NCP soils. In particular, about two-thirds of the global maize and wheat production area currently have SOC content of less than 2%<sup>[59]</sup>. It is crucial to implement prudent management practices to safeguard and increase soil carbon reserves. The long-term application of organic fertilizer can significantly improve the soil carbon sequestration rate, as well as the content and quality of SOC. Conservation tillage practices can effectively increase SOC content, with an average annual carbon sequestration rate ranging from 0.22 to 0.52 g·kg<sup>-1</sup><sup>[60]</sup>. These strategies are effective for improving SOC levels and ensuring the long-term fertility and productivity of croplands.

As agricultural mechanization has advanced, soil compaction has emerged as a major factor impacting soil quality and crop growth, with an average compacted layer thickness of 12.4 cm<sup>[61]</sup>. Strategic deep plowing effectively penetrates the hard pan layer of the soil, increasing its permeability and water retention capabilities, which in turn increases crop yields. The application of organic fertilizers is effective for increasing soil nutrient levels, refining soil structure and improving soil physical properties<sup>[55]</sup>, particularly in terms of permeability and the formation of aggregates<sup>[62]</sup>. These practices are instrumental in improving soil health and sustaining agricultural productivity.

Notably, numerous soil-related limiting factors constrain the yield increase of wheat and maize, and these factors often interact with each other, creating compound effects. A recent study conducted in Quzhou County, an intensive agricultural region on the NCP, revealed that the average obstacle degrees of soil bulk density, soil organic matter, irrigation guarantee rate and soil profile constitution all exceeded 20%. The maximum obstacle degrees of field slope, groundwater depth, soil bulk density, irrigation guarantee rate, soil profile constitution, field road accessibility, soil salinization and drainage conditions are all above 60%, indicating that these indicators pose significant limitations for certain cropping fields<sup>[63]</sup>. The impacts of these indicators on soil quality vary, depending on the extent to which they are influenced by natural environmental factors and human activities<sup>[64]</sup>.

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### 3.4 Nutrient and water resources and their utilization

The NCP is one of the most intensive agricultural areas in China. The nutrient application rates commonly used by farmers significantly surpass the actual nutritional requirements of crops, as opposed to what optimized nutrient management would dictate<sup>[7]</sup>. This misconception has led farmers to erroneously believe that high yields are solely attainable through high (actually excessive) nutrient applications<sup>[65,66]</sup>. Currently, a range of approaches are adopted to increase crop yields while mitigating environmental impacts, including integrated soil-crop system management, and novel and efficient fertilizers<sup>[7,67]</sup>. By integrating digital technology with non-destructive diagnostic methods, a precision management system for crop nutrition has been developed. This system enables the identification of crop nutritional stress in terms of both type and severity, allowing the precise adjustment of fertilizer application strategies, particularly for topdressing. This approach ensures that nutrient applications are tailored to the specific needs of the

crops, optimizing yield potential while minimizing environmental impact<sup>[68]</sup>. Research has shown that adhering to integrated soil-crop system management guidelines leads to significantly higher crop yields, ranging from 18% to 35%. Concurrently, there was an 8.5%–15.6% reduction in the nitrogen rate, which was complemented by a 26.0%–33.1% increase in nitrogen productivity. Additionally, losses of reactive nitrogen have decreased by 22.9%–4.9%, and greenhouse gas emissions have been reduced by 18.6%–29.1%<sup>[7]</sup>. These findings underscore the value of integrated soil and crop management practices in advancing sustainable agriculture on the NCP.

The prevailing irrigation techniques in north China have fallen short of efficiency standards, with established flood irrigation methods, such as furrow, ridge, and border irrigation, still most commonly used. This has resulted in a problematic loss of nearly 60% of agricultural water to inefficiencies during its conveyance, highlighting an urgent need for modernization in irrigation practices to conserve this vital resource<sup>[11,34]</sup>. The north China region has only 3.7% of total national water resources, with per capita availability at about 16% of the national average. This situation is further strained by the annual consumption of water resources, which outpaces the replenishable supply four times<sup>[69]</sup>. The average precipitation received during the wheat growing season on the NCP is less than 200 mm, which is significantly short of the crop's water requirement by an additional 450 mm<sup>[70]</sup>. Substantial extraction of groundwater is undertaken to fill this gap, resulting in continuous and concerning depletion of the aquifer. In recent years, intensive agricultural practices coupled with the widespread adoption of efficient water-saving irrigation technologies, such as sprinklers and micro-irrigation systems, have significantly increased the effective irrigation water use coefficient in north China. This coefficient has increased from 0.573 in 2000 to 0.647 in 2020, surpassing the national average by 14.5%<sup>[11]</sup>. Drip irrigation has been promoted to markedly increase both crop yields and water use efficiency while precisely controlling irrigation volume and frequency<sup>[71]</sup>.

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### 3.5 Integration of agricultural machinery, agronomic practices and informatics

Further enhancement of the use efficiency of radiation, temperature, water and fertilizer resources is crucial for achieving high grain yields on the NCP. The integration of agricultural machinery, agronomic practices and informatics offers a comprehensive solution to this challenge<sup>[50]</sup>. The fusion of these three disciplines allows for precision planting,

the efficient use of resources such as water and fertilizers, and the implementation of data-driven decision-making processes. This integration not only increases crop yields but also contributes to the overall resilience of the agricultural system against various biotic and abiotic stresses. On the NCP, standard winter wheat cultivation has incorporated rotary tillage. However, shallow tillage fails to mix crop residues thoroughly in the soil layer<sup>[72]</sup>. Improper management of crop residues can lead to missed sowing opportunities, thereby reducing crop establishment, the efficiency of land use and the availability of photothermal resources. No-till sowing for maize encounters challenges due to excessive wheat straw, which compromises the needed contact between seeds and soil. This separation reduces the effective establishment of maize plants<sup>[73]</sup>. At present, several constraints hinder optimal agricultural outcomes, including subpar maize seeding quality attributed to no-tillage planting following wheat harvest, challenges in providing adequate irrigation from sowing to seed emergence, the timing of irrigation and fertilizer application and the implementation of inferior farming techniques<sup>[50]</sup>. It is through this holistic and integrated approach that the agricultural sector can achieve its goals of productivity, profitability and environmental stewardship.

In recent years, the swift advancement of agricultural machinery and information technology has led to the widespread adoption of navigation driving systems and agricultural machinery monitoring technologies. These

innovations have significantly increased the precision and accuracy of farming operations. As a result, work efficiency has increased and operational costs have substantially decreased<sup>[50]</sup>. Researchers have developed an integrated solution that harnesses a suite of innovative technologies on the NCP, including a four-to-one narrow-wide strip-planting method for winter wheat (Fig. 2), satellite-guided precision planting and annual shallow subsoil drip irrigation for the synchronized management of water, fertilizers and agrochemicals. This solution is complemented by state-of-the-art agricultural machinery and information technology. The new technology has outperformed existing farming regimes, resulting in a 9%–17% increase in grain yield for winter wheat and a 12%–14% increase for summer maize, all while reducing both fertilizer and water usage<sup>[50]</sup> (Fig. 2).

### 3.6 Socioeconomic constraints

The magnitude of yield gaps is particularly large in developing countries where smallholder farming dominates the agricultural landscape. Many factors and constraints interact to limit yields, involving agronomic, infrastructural and socioeconomic conditions<sup>[74]</sup>. Globally, much effort has been made to provide smallholders with advanced management technologies; although some are successful, many fail to scale up or to produce consistent and sustained results<sup>[75]</sup>. With the aging of the population, the adoption of recommended modern technologies has become a critical challenge that cannot be

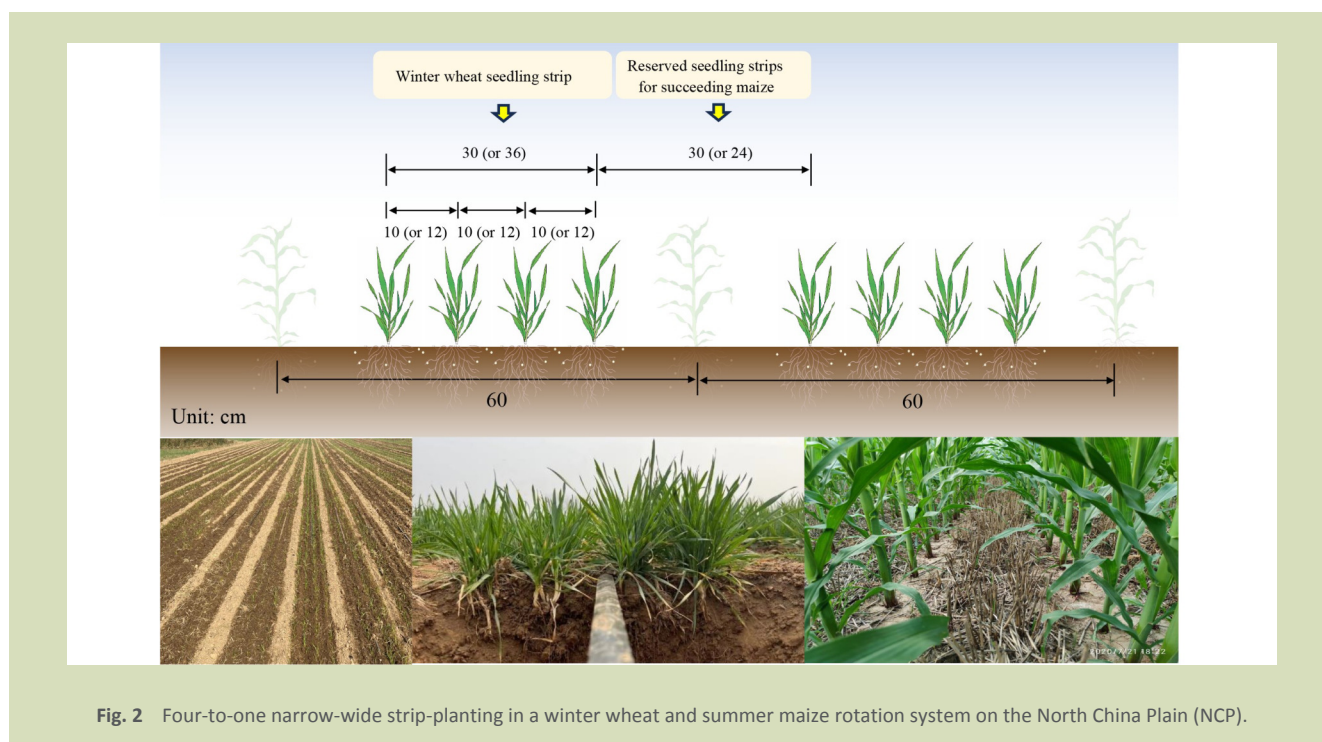


Fig. 2 Four-to-one narrow-wide strip-planting in a winter wheat and summer maize rotation system on the North China Plain (NCP).

ignored in pursuit of high grain yields. The emergence of agricultural socialized services offers a potential solution to this dilemma. A recent survey of 18 counties in five provinces of China revealed that the demand for socialized services and the age of the workforce have an inverted U-shaped relationship<sup>[17]</sup>. The land size is negatively and linearly correlated with the age of the labor force; as the age of the labor force increases, the resistance of land transfer also increases. This results in a lack of economies of scale for the main operation entities. Consequently, there is a need to replace the aging labor force to compensate for efficiency losses, which in turn increases the demand for socialized services<sup>[17]</sup>.

In addition, the limited availability of technical support and training hampers the adoption of cutting-edge technologies and modern management practices. Addressing the complexities of the agricultural product processing industry in the NCP and devising effective strategies to increase the value of agricultural products are of paramount importance. These efforts are crucial for the expansion of the agricultural industry chain and the stimulation of regional economic growth. Enhancing the technological capabilities of industry and investing in human resources are essential steps toward realizing the industry's full potential and ensuring its enduring viability. The grain industry chain propels the innovation of planting technologies by creating a demand for higher efficiency, quality and sustainability. As downstream sectors such as processing, storage and distribution evolve, they require more consistent and superior raw materials. This demand incentivizes farmers to adopt advanced agricultural practices, including precision farming, genetically improved crops and eco-friendly methods, to increase productivity and meet the stringent standards of the market.

## 4 Framework and solutions for sustainable crop production on the NCP

In farmers' practices, management is typically small-plot-based, often resulting in the excessive application of fertilizers beyond the crop's needs. This excess led to environmental pollution as the surplus nutrients leached away. Conversely, there are also instances where the application was insufficient, thereby lowering crop yield potential. This imbalance underscores the need for a more refined approach of precise nutrient management in crop and soil systems, minimizing waste and environmental impact while maximizing productivity. Precision management in wheat and maize production calls for a sophisticated approach that leverages

advanced technologies to optimize crop production. By utilizing data-driven insights and real-time monitoring, farmers can make informed decisions that enhance both yield and quality. Model-based designs of cropping systems, satellite imagery, drones and soil sensors provide detailed information on field conditions, allowing for variable rates of planting, targeted fertilizer application, and precise irrigation.

### 4.1 Eliminating soil constraint factors and building resilient soils for sustainable agriculture

Key soil amelioration strategies include deep plowing, organic fertilizer application, straw return to the fields and the use of soil conditioners. Deep plowing effectively breaks up the compacted layer, which restricts root growth and water infiltration<sup>[76]</sup>. By breaking this layer, deep plowing increases soil permeability, allowing for better root penetration and improved water and nutrient uptake by plants. Based on 1830 yield comparisons in 202 studies conducted globally, a recent meta-analysis demonstrated that 35 cm is an optimum depth of deep tillage for wheat and maize yield on a global scale; however, the optimal depth is affected by climate<sup>[76]</sup>. For expanding the soil layer, increasing the soil organic matter content is the cornerstone for increasing and stabilizing crop yields<sup>[33,35]</sup>. Soil quality both increases crop production and improves resilience to climate change<sup>[35,56]</sup>. The application of organic fertilizers enriches the soil with essential nutrients and organic matter, which can improve soil structure, water retention and nutrient holding capacity. However, cereal farmers perceive greater barriers than cash crop growers do. The key barriers to manure use include the perceived high economic costs of manure use, lack of suitable application technology, and unknown manure quality and availability<sup>[77]</sup>. Organic matter is particularly important because it provides carbon and energy sources for soil microorganisms, which in turn contribute to nutrient cycling and soil fertility. These practices are designed to address specific limitations in the soil profile and enhance its overall health and productivity.

### 4.2 Data-driven design of high-yielding cropping systems

Data-driven approaches are revolutionizing the design of high-yielding cropping systems for winter wheat and summer maize. By mining large data sets, including historical yield data, soil conditions and climate patterns, we can develop tailored management strategies that optimize crop performance. The integration of remote sensing technology allows real-time monitoring of crop growth and yield, providing invaluable insights for precision agriculture practices. Climate change

considerations are also critical and data analytics can help assess the potential impact of climate change on crop productivity, enabling the development of resilient cropping systems. Sustainability is a key factor in these systems, with data-driven methods identifying practices that balance yield increases with minimal environmental impact. In summary, data-driven design offers a powerful tool for optimizing high-yielding wheat and maize cropping systems, considering environmental sustainability while enhancing productivity.

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### 4.3 Precision fertilizer and water management

Fertilizers should be applied precisely in response to soil testing to avoid excessive or insufficient application. Efficient water-saving irrigation technologies such as drip and sprinkler irrigation can be used to improve the efficiency of water resource use<sup>[50]</sup>. In addition, by integrating data-driven approaches and advanced agricultural technologies, these practices can significantly improve efficiency and sustainability. For example, the application of decision support systems facilitates the simulation of crop growth under various management practices, including different irrigation and fertilizer application schedules<sup>[7,24,26,65]</sup>. This helps in identifying the most effective strategies for resource application, thereby maximizing yields and minimizing waste. In summary, precision agriculture techniques, supported by data analytics and modeling, provide a viable approach to increase wheat and maize yields while promoting the efficient use of water and fertilizers.

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### 4.4 Integration of agricultural machinery and agronomy

Modern agricultural machinery has great potential for improving work efficiency and reducing labor costs. In wheat and maize production, achieving the integration of agronomic information involves leveraging advanced technologies to optimize farming practices. This can be accomplished by using precision agriculture tools such as GPS-guided machinery, drones, and sensors to monitor crop health, soil conditions, and weather patterns in real-time. Data collected from these technologies can be analyzed via artificial intelligence and machine learning algorithms to provide actionable insights, enabling farmers to make informed decisions on planting, irrigation, fertilizer application and pest/weed control. Additionally, the use of farm management software can help in planning and tracking agricultural activities, ensuring efficient resource use and maximizing yield. By integrating these digital tools with existing agronomic knowledge, farmers can increase

their productivity, reduce environmental impact, and ensure sustainable crop production.

## 5 Pathways for large-scale sustainable crop production on the NCP

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### 5.1 Interdisciplinary and transdisciplinary research and innovations

China has recognized the urgent need to transform its agriculture to sustainable development<sup>[5]</sup>. The primary goals are to increase the supply of healthy, safe and nutritious food; increase resource use efficiency, farm income and environmental protection; and strengthen biodiversity conservation<sup>[5]</sup>. To achieve these goals, there needs to be a greater focus on the interactions and coupling mechanisms within food systems. Research must focus more on the interfaces between subsystems, connecting belowground rhizosphere research to aboveground crop production and the atmospheric interface (Fig. 3). This interlinking and integration may contribute to the generation of new insights that lead to a more efficient production system and greater resource use efficiency, thereby achieving a greater understanding of key variables that may not be developed by single disciplinary research. Therefore, interdisciplinary and transdisciplinary research innovations are crucial<sup>[5]</sup>.

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### 5.2 Building transformative partnerships to realize agriculture for green development

Realizing AGD in practice requires building transformative partnerships to link knowledge and action and to integrate the interests of multiple stakeholders<sup>[5]</sup>. Concurrently, research initiatives have built stakeholder collaborative innovation platforms, such as Science and Technology Backyards (STBs) (Fig. 4). STBs connect multiple actors to co-innovate, build bridges between stakeholders, complement each other and find innovative solutions to specific problems via a bottom-up approach<sup>[74]</sup>. In promoting these technologies more broadly, STBs created a one-stop multistakeholder program<sup>[78]</sup>. The program was shown to be much more effective than the normal extension methods applied at the STB and has increased crop yields and nitrogen factor productivity by 7.2%–11.4% and 27.0%–28.1%, respectively, yielding substantial environmental and economic benefits<sup>[78]</sup>.

Currently, farmers are faced with narrowing profit margins; the

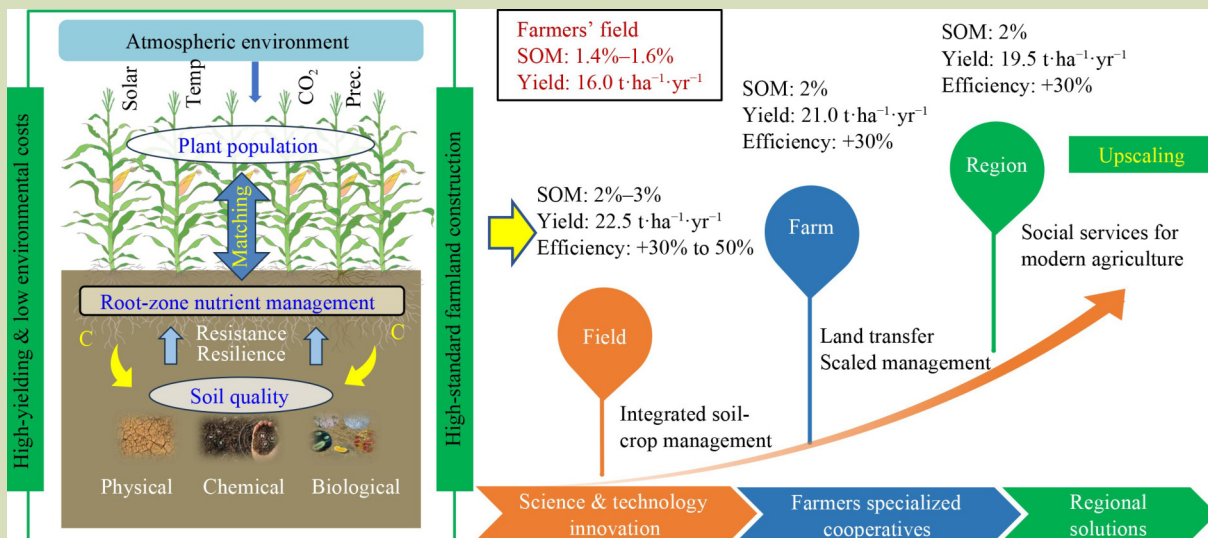


Fig. 3 A new paradigm for sustainable production: a case study of winter wheat and summer maize rotation on the North China Plain (NCP). C, carbon; Prec., precipitation; SOM, soil organic matter; Temp, temperature.

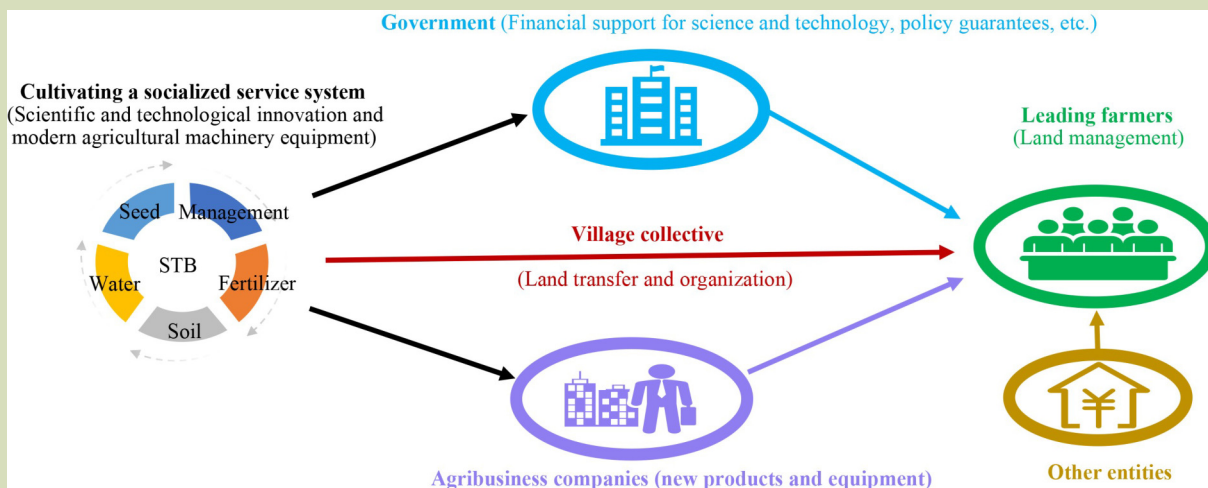


Fig. 4 Schematic diagram depicting the role of Science and Technology Backyard (STB) in promoting agricultural socialized services supporting sustainable crop production.

costs of many production inputs have increased, whereas product prices have remained fairly constant or even decreased. In recent decades, the agricultural sector has undergone a profound transformation. Normally, agriculture has been driven primarily by supply, but it has shifted to be demand driven. The future of agriculture is poised to be information-centric. Timely dissemination of new information to end users is crucial for seizing potential opportunities and reaping benefits. For example, in the realms of precision farming and livestock management, information and

communication technologies enable more efficient decision-making processes. This advancement not only benefits the managers of agricultural enterprises but also informs policymakers, enhancing overall sector performance and strategic planning.

### 5.3 Strengthening sustainable crop production by empowering smallholder farmers

Strengthening the sustainable production of crops is pivotal for

sustainably feeding the growing global population. Smallholders grapple with a plethora of socioeconomic challenges beyond mere knowledge gaps and tackling these issues requires a multistakeholder network<sup>[78]</sup>. The STB model has demonstrated efficacy, especially in propagating comprehensive technology practices<sup>[74,79]</sup>. The STB staffs reside within the villages, collaborate with farmers and conduct research-education extension activities focused on technology transfer, empowering smallholders to attain greater yields with enhanced environmental stewardship.

Notably, the influence of STB intervention extends to adjacent villages, which outperform control villages because of facilitated access to STB events and information<sup>[74]</sup>. Based on 288 site-year field trials on the NCP spanning five years, researchers found that involving farmers through equitable dialog and integrating their feedback into the technology design process enhances the adoptability of technologies<sup>[78]</sup>. Through close and long-term collaboration with farmers, technologies co-developed through the STB framework are more readily embraced, increasing crop yields and nitrogen factor productivity by 7.2% and 28.1% in wheat production, and by 11.4% and 27.0% in maize production, respectively<sup>[78]</sup>. Consequently, the STB model emerges as a promising approach to empower smallholders, taking into account their concerns and interests, and advocating for multistakeholder collaboration and sustained investment in the promotion of sustainable smallholder agriculture (Fig. 4).

#### 5.4 Developing agricultural management entities and socialized agricultural services

Agricultural enterprises and farmer cooperatives, as innovative agricultural management entities, are pivotal in the evolution of modern agriculture. They make a significant contribution to connecting farmers, advocating for sustainable practices, and actualizing the value of sustainable and high-quality agricultural outputs. Their influence in these areas is becoming more pronounced. Small-scale farmers are progressively transitioning toward family farms, cooperatives and diverse agricultural socialized service organizations, which are effectively driving down costs and enhancing efficiency<sup>[80]</sup>.

Since the beginning of the century, China's agricultural economic status has contracted, and the service system has increased due to the movement of labor from rural to urban areas and the restructuring of economic and social systems<sup>[80]</sup>. This situation demands better technology and services, which are crucial for enhancing the efficiency of crops and food. The results indicate a greater role of service provision in moderate-

to-high-scale development, leading to land productivity and thereby improving agricultural production efficiency. The results also imply a greater demand for socialized agricultural services among farmers considering the value-added potential of such an integrated system with greater spillover options for achieving self-sufficiency in agriculture and ensuring food security<sup>[81]</sup>.

## 6 Outlooks

The endeavor of sustainable production of winter wheat and summer maize rotation on the NCP is highly important for national food security and ecological environment safety, supporting the transformation toward sustainable agriculture. In addition, it serves as a broad reference for other developing nations with a prevalence of smallholders<sup>[7,74,78]</sup>. Such transformation is not only an inevitable choice in response to resource constraints and environmental pressures but also a key measure to enhance agricultural competitiveness and promote the comprehensive revitalization of rural areas.

Sustainable crop production represents a transformative process and a strategic pathway toward achieving agriculture that is productive, highly efficient, resilient, and sustainable. While foundational strengths and critical measures are instrumental in this journey, the sustainable production of the yield target of 22.5 t·ha<sup>-1</sup> still faces certain limitations. To this end, it is necessary to further strengthen efforts in the following areas in the future.

(1) Enhancing infrastructure and upgrading the soil quality of arable land should be prioritized. It is essential to increase the fertility of these high-yielding fields by enhancing their physical, chemical and biological properties. Increasing the soil organic matter content and improving its overall fertility are crucial steps. Additionally, cultivating a resilient soil environment that is conducive to crop growth is necessary to ensure yield sustainability and productivity.

(2) The breeding and selection of superior crop cultivars should be expedited to fully realize high yield-potential<sup>[82]</sup>. Future wheat and maize breeding efforts will increasingly focus on interdisciplinary approaches, leveraging cutting-edge technologies for precision breeding. By developing high-yielding, high-quality, stress-tolerant and resource-efficient cultivars, it should be possible to ensure food security and promote green, smart and sustainable agriculture. Specifically, it is increasingly urgent to develop cultivars resistant to drought, salinity, high temperatures and cold to cope with

extreme environmental conditions caused by climate change; cultivars with efficient nitrogen, phosphorus and potassium utilization to reduce fertilizer input and environmental pollution; cultivars with increased pest and disease resistance; cultivars with improved nutritional value and processing quality; and cultivars suitable for mechanized planting, management and harvesting to improve agricultural efficiency.

(3) Striving for the interconnection and synthesis of research methodologies, the focus should be on the integration of superior cultivars, effective methods and advanced techniques. This approach should emphasize the promotion of breeding for high-quality and high-yielding cultivars, precision seeding, balanced and rational fertilizer application practices, water-efficient irrigation systems, and comprehensive disease and pest management. Additionally, the synergy between agricultural machinery and agronomic practices necessitates the enhancement of modern agricultural machinery equipment. There is a need to upgrade substantial quantities of

power machinery and combined operation machinery to meet the demands of advanced agricultural machinery for the evolution of contemporary agriculture. This upgrade aims to improve the capacity to mechanize grain production. By implementing professional training programs, we can increase the standardization of machine operation and the adaptability of operators, thereby increasing the efficiency of agricultural machinery operations.

(4) Aligning national policy with social action is critical. It is needed to fortify the construction of agricultural technology promotion service capabilities and innovate in technology service methods. It is essential to intensify technical guidance and training for grain farmers and new agricultural entities, thereby increasing the adoption rates of green, high-yielding, and efficient grain production technologies. This comprehensive approach will facilitate the realization of scientific farming practices across the board.

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### Compliance with ethics guidelines

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