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RESEARCH ARTICLE

Innovation and application of technology models for wheat green production in China

Gang HE[1,2,3], Wanyi XIE[1], Lei FAN[1], Xiaotian MI[1], Zhaohui WANG (✉)[1,2]

1 College of Natural Resources and Environment, Northwest A&F University, Yangling 712100, China.
2 State Key Laboratory for Crop Stress Resistance and High-Efficiency Production, Northwest A&F University, Yangling 712100, China.
3 Key Laboratory of Low-carbon Green Agriculture in Northwestern China, Ministry of Agriculture and Rural Affairs, Yangling 712100, China.

KEYWORDS

Framework for wheat green production, crop management techniques, year-round plastic film mulching, technology diffusion model, food security

HIGHLIGHTS

- Framework for wheat production was developed from soil, root layer, and canopy systems.
- Single technologies based on the framework effectively improved wheat yield and NUE.
- Technology models developed based on a single technology provided greater benefits.
- The establishment of a multi-subject joint extension model helped to promote technology.
- Innovation and application of technology models for wheat green production in China.

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Correspondence: w-zhaohui@263.net

GRAPHICAL ABSTRACT

ABSTRACT

In the face of rising food demand and declining wheat acreage, improving wheat yield and resource use efficiency will be key to sustainable wheat production. To address the challenge, this study proposed a framework for wheat green production, quantified the benefits of key technologies and technology models based on the framework in wheat yield and nitrogen use efficiency (NUE), and developed a new model for the promotion of technology. The framework included soil, root layer and canopy systems, where the adoption of single technologies based on the framework could increase wheat yield and NUE by improving soil fertility, managing soil nutrient supply and building high-yielding systems. Through combining specific single technologies, a year-round plastic film mulching model in dryland cropping, and an efficient nutrient and water management technique model for irrigated cropping were established, providing benefits in wheat yield and NUE. A multi-subject joint innovation technology model was also developed to serve as a bridge to transform agricultural technology into agricultural productivity. In the future, a sustainable increase in wheat production in China will require innovation in key technologies and technology models, the development of new technology promotion models, and the combined efforts of the whole community.

1 Introduction

Wheat is a critical food crop, but global wheat yields have only increased slowly in recent decades and have even stagnated in some regions and countries. China is the largest wheat producer globally (with an annual production of 136 Mt)[1], and its wheat production is crucial to the global supply-demand balance. Wheat imports to China have grown rapidly in recent years and peaking at 9.96 Mt in 2022[2], and continued high levels of imports could increase volatility in future global grain markets. Further growth in wheat production in China is key to maintaining global food security and stabilizing grain markets. In recent decades, the heavy use of mineral fertilizers has improved wheat yields, but at a high environmental cost[3]. Faced with the dual pressures of food and environmental security, the innovation and development of agronomic management techniques and technology models will be at the heart of the way forward.

In recent years, many crop management techniques have been developed and applied that could reconcile crop production and environmental issues. For example, deep fertilizer application increased wheat grain production by 7% and reduced N_2O emission by 15%[4]; the use of slow-release fertilizer and/or topdressing increased cereal crop yield by 3% to 8% and reduced reactive N losses by 24% to 50%[5,6]. These crop management techniques are more effective for improving wheat yield and nitrogen use efficiency (NUE). For a long time, field trials of single-factor treatments have been preferred because they provide a good explanation of what causes variability, but this is of limited value in terms of yield and efficiency gains. For example, reducing the N application rate was the main practical technique to increase NUE, but this risks of reducing crop yield[7]. Combining reduced N application rate with slow-release fertilizer or animal manure increased wheat yield by 12% to 17% and NUE by 33% to 56%[8,9]. Technology models (a combination of individual crop management techniques) appear to provide to be more appropriate[7–9]. Given the complexity and diversity of these crop management techniques, establishing a new framework will be key for further innovation in technology models that can help improve yield and nutrient use efficiency.

Promotion of agricultural technology is a fundamental to accelerating the transformation of agricultural technology into crop productivity, both domestically and internationally[10]. For a long time, agricultural technology promotion departments at all levels of government have undertaken the main task of agricultural technology promotion in China. In the past, agricultural technology promotion mainly consisted of field extension and demonstrations, technical training, and publicity through mass media such as newspaper and television[11]. In recent years, increasingly new agricultural promotional models have been developed and applied[12]. Of these, the Science and Technology Backyard (STB) is a successful example[13]. The STB members have long been engaged in the front line of agricultural production and have established close partnerships with smallholders through zero-distance service, stimulating the willingness of farmers to actively adopt green production technologies[14]. This model of smallholder-led scientist-farmer partnership could directly promote the application of new technologies[15]. Recently, with the diversification and refinement of agricultural production, and a steady transfer of agricultural land, wheat production in China are undergoing a major transformation. As a direct result, the number of large-scale farmers is gradually increasing and their demand for new technologies is more urgent, placing higher demands on a diversified and new media channel technology extension model.

Faced with the double pressures of food and environmental security, wheat green development must meet the challenge of increasing grain production at minimal environmental cost. Innovation and widespread application of high-yielding, high-nutrient use efficiency agronomic management techniques is a golden key to addressing the challenge. In this study, we developed the framework for wheat green production, quantified the effect of agronomic management techniques based on the framework on wheat yield and NUE, developed the typical-case technology model in wheat production, and explored new techniques promotion models. This study will be an important starting point for further innovation and application of technology models for wheat green production.

2 Materials and methods

2.1 Effect of key technologies on wheat production

2.1.1 Data collection

To quantify the effect of management practices on wheat production, a data set on management practices and wheat yield was constructed based on peer-reviewed literature published before December 2021 using the Web of Science and China National Knowledge Infrastructure database. Specific search terms included crop management practices [fertilizer application rate, topdressing, deep fertilizer application, enhanced-efficiency fertilizers (EEFs), animal manure, irrigation, straw incorporation, cultivar, soil tillage and crop cultivation], wheat productivity (grain yield, plant N uptake and NUE) and soil organic carbon (SOC) stock. To control data quality and minimize publication bias, the study applied the following criteria: (1) the trial must be conducted in the field; (2) at least one of the crop management practices was included; and (3) at least one index of wheat productivity and SOC stock was provided. Finally, 1481 peer-reviewed studies were selected including 14273 observations for further analysis.

2.1.2 Data calculation

SOCstock ($\mathrm{Mg{\cdot}ha^{-1}\ C}$)[16] was calculated as:

$$\mathrm{SOCstock} = \mathrm{SOC} \times b \times d \times 10^{-3} \tag{1}$$

where, SOC is the concentration of SOC ($\mathrm{g{\cdot}kg^{-1}\ C}$), b is soil bulk density ($\mathrm{g{\cdot}cm^{-3}}$) and d is the depth of soil (cm).

SOCsequestration rate ($\mathrm{Mg{\cdot}ha^{-1}{\cdot}yr^{-1}\ C}$) was calculated as:

$$\mathrm{SOCsequestration\ rate} = \frac{\mathrm{SOC}_e - \mathrm{SOC}_s}{n} \tag{2}$$

where, SOC_e is the SOCstock at the end year, SOC_s is the SOCstock at the start year, and n is the number of years the experiment.

SOCsequestration efficiency (%) was calculated as:

$$\mathrm{SOCsequestration\ efficiency} = \frac{\mathrm{SOC}_e - \mathrm{SOC}_s}{\mathrm{Accumulative\ crop\ residue\text{-}C\ input}} \tag{3}$$

where, SOC_e is the SOCstock at the end year, SOC_s is the SOCstock at the start year, and accumulative crop residue-C input is the sum of crop straw and root C input.

NUE (%) was calculated as:

$$\mathrm{NUE} = \frac{\mathrm{plant\ N\ uptake}}{N} \times 100\% \tag{4}$$

where, plant N uptake is the amount of aboveground N taken up by the plant ($\mathrm{kg{\cdot}ha^{-1}\ N}$), and N is the amount of N fertilizer applied ($\mathrm{kg{\cdot}ha^{-1}\ N}$).

2.1.3 Data analysis

The effects of crop management practices on the X-variables were evaluated using the treatment against the pairwise control. The natural logarithm of the response ratio (lnRR) was calculated as:

$$\ln\mathrm{RR} = \ln\frac{Xt}{Xc}, \tag{5}$$

where, lnRR is the effect size for each paired observation, and Xt and Xc are the average of the treatment and control, respectively. The confidence intervals were calculated by bootstrapping resampling procedures (4999 iterations) in R (version 4.3.1). Result was considered significantly different if the 95% confidence intervals did not overlap zero.

2.2 Field experiment for establishing typical technology models

2.2.1 Typical technology model in dryland cropping

In 2018–2022, the technology model in dryland cropping was designed and verified in Changwu County (35.20° N, 107.75° E), located in the central Loess Plateau. The technology model is named YPM for year-round plastic film mulching cultivation. For the YPM model, covering the soil surface using transparent plastic film in the wheat growing season and summer fallow after the harvest of wheat; its application rates of N fertilizer were 150 $\mathrm{kg{\cdot}ha^{-1}}$ N in all years and the application method was strip-trenching. For farmer practice, no mulch was used, N fertilizer rates were 195 $\mathrm{kg{\cdot}ha^{-1}}$ N and the application method was broadcasting. In all years for farmer practice and YPM model, the P fertilizer rate was 105 $\mathrm{kg{\cdot}ha^{-1}}$ $\mathrm{P_2O_5}$, and K fertilizer was not applied because there was sufficient K available in the soil. N and P fertilizers were applied before sowing. More detail is given in previous papers[17,18].

2.2.2 Typical technology models in the irrigation area

In 2023–2024, the technology model was designed and verified in Fengxiang (34.46° N, 107.43° E), located in the central Guanzhong plain in Northwest China, a typical irrigation area. The typical technology model is named ENWM for the efficient nutrient and water management. For the ENWM model, the main optimization steps included optimizing mineral N fertilizer application rates based on monitoring $\mathrm{NO_3^-}$-N in the 1.0 m soil layer[19], optimizing irrigation water application rates based on plant water requirements and precipitation, and matching crop nutrient and water requirements by drip irrigation.

For the farmer practices and the ENWM model, the amount of irrigation water was 2475 and 1650 $\mathrm{m^3{\cdot}ha^{-1}}$, and the N fertilizer application rate was 300 and 210 $\mathrm{kg{\cdot}ha^{-1}}$ N, respectively. For the farmer practices, 50% of the mineral fertilizer was used as basal fertilizer at sowing and the remaining as topdressing at the post-winter greening stage; 1500 $\mathrm{m^3{\cdot}ha^{-1}}$ of irrigation water was used during the overwintering period and 975 $\mathrm{m^3{\cdot}ha^{-1}}$ during the greening period of winter wheat. For the ENWM model, the 30%

mineral fertilizer was used as basal fertilizer in sowing, and zero, 30%, 30% and 10% were used as topdressing in overwintering, greening, elongation and flowering stages of winter wheat, respectively. With 30%, 30%, 30% and 10% of the irrigation water applied during the overwintering, greening, elongation and flowering stages of winter wheat, respectively. For two treatments, the P and K fertilizers were applied at the same rates of 90 kg·ha^{-1} P_2O_5 and 60 kg·ha^{-1} K_2O, respectively.

2.2.3 Sampling and measurement

At maturity for winter wheat, the fresh grain for each plot was harvested and weighed to obtain a fresh weight. One kg of fresh grain was collected from each plot and used to calculate the water content and the dry weight of the grain yield. After air-drying and weighing, subsamples of 100 g grain and 100 g stems were dried in an oven to determine plant N concentration and plant N uptake. The leaf area index and SPAD were tested at the anthesis period. Soil samples were taken annually before sowing and after harvest of winter wheat to a depth of 2 m to determine soil water content and soil nitrate-N concentration. The procedure is described in a previous paper[20].

2.2.4 Data calculation

Soil water storage (SWS, mm) was calculated as:

$$\text{SWS} = \sum_{i}^{n} b_i \times d_i \times w_i \times 10/100 \tag{6}$$

where, b (g·cm^{-3}) is soil bulk density, d (cm) is the depth of soil, w (%) is soil water content on a gravimetric basis, n is the number of soil layers and i is 20, 40, …, 200.

Soil nitrite-N accumulation (SNS, kg·ha^{-1} N) was calculated as:

$$\text{SNS} = \sum_{i}^{n} b_i \times d_i \times c_i \times 10/100 \tag{7}$$

where, c (g·kg^{-1}) is the concentration of soil nitrate-N.

Soil water storage during summer fallow (mm) was calculated as:

$$\text{Soil water storage during summer fallow} = \text{SWS}_2 - \text{SWS}_1 \tag{8}$$

where, SWS_2 (mm) and SWS_1 (mm) are the soil water storage to 2 m deep at the time of winter wheat sowing for the following growing season and at the time of winter wheat harvest of the previous growing season, respectively.

Evapotranspiration (ET, mm) of winter wheat was calculated as:

$$\text{ET} = \text{SWS}_2 - \text{SWS}_3 + P \tag{9}$$

where, SWS_3 (mm) is the soil water storage to 2 m deep at winter wheat harvest of the following wheat growing season, respectively, and P is the effective precipitation (mm) during the winter wheat growing season.

Water use efficiency (WUE, $\text{kg·ha}^{-1}\text{·mm}^{-1}$) was calculated as:

$$\text{WUE} = \text{Wheat yield} \div \text{ET} \tag{10}$$

Partial factor productivity of N fertilizer (PFP_N, kg·kg^{-1}) was calculated as:

$$\text{PFP}_\text{N} = \text{Wheat yield} \div N \tag{11}$$

where, N is the N fertilizer application rate (kg·ha^{-1} N).

2.2.5 Data analysis

Statistical analyses were performed using the SAS 9.0 software, and the means were evaluated using a one-way analysis of variance with the least significant difference test at a significance level of $P < 0.05$.

3 Results and discussion

3.1 Framework of wheat green production

The goal of wheat green production is to transform wheat production from a system with high resource consumption and high environmental costs to one with high crop productivity and high resource use efficiency. Therefore, the framework of wheat green production mainly focused on two key standards: high yield and high NUE. Wheat production is a complex process, and integrated soil-crop management systems are the basis for achieving the objectives[21]. On this basis, this study divided wheat production into three subsystems: soil, root layer and canopy systems (Graphical Abstract).

For the soil system, the core goal is to improve stress tolerance and the supply ability of water and nutrients; the key pathway is to improve soil fertility and structure by increasing the input of exogenous organic materials. The main techniques included adding animal manure, straw return, the adoption of biochar and green manure incorporation.

For the root layer system, the goal is to maximize use and minimize losses of nutrients, and water by regulating the supply of soil nutrients and water to match the needs of the plants as closely as possible. In addition, increasing soil water storage, reducing soil water evaporation, using soil water throughout the season, and optimizing root morphology were also key pathways to achieving the system goals for the root layer. Currently, the main techniques are optimized fertilizer management, optimized tillage and adoption of fertigation.

For the canopy system, the goal was to improve the resistance to stress and efficient use of light, ambient heat and water resources by building light-heat-matched high-yielding populations. The main techniques included optimizing the time and rate of sowing, wide spaced precision sowing and updating cultivars. For a long time, many techniques have been developed and innovated based on the framework, thanks to unwavering political support and substantial investment, offering an excellent opportunity for the transformation of wheat green production. For this study, we summarized the technology from the soil, root layer and canopy systems, which is the basis for clarifying the effects of these technologies and developing the wheat green production models. In the future, more innovative studies would be beneficial to provide new insights into the framework of wheat green production.

3.2 Key technologies based on the framework of wheat green production

Based on the framework of wheat green production, many corresponding techniques have been developed. One of the main constraints to wheat productivity is the weakening of resistance and indigenous soil nutrient supply[22]. The adoption of organic matter to improve soil fertility is the main way to address this challenge. The results showed that adding animal manure based on the equivalent mineral fertilizer raised the SOC sequestration efficiency to 26%, and increased the SOC sequestration rate by 205% (by 356 kg·ha^{-1}·yr^{-1} C) and wheat yield by 15.1% (Fig. 1(a,b)). Straw return increased SOC sequestration efficiency to 11.7%, SOC sequestration rate by 150% (by 302 kg·ha^{-1}·yr^{-1} C), and wheat yield by 6.6%. The adoption of organic matter improved the physical properties, fertility and nutrient availability in soil, as well as its hydrothermal properties, which were increasingly recognized as essential for improving crop yields[23,24]. Conservation tillage, including zero and reduced tillage, also increased the SOC sequestration rate by 38% (by 203 kg·ha^{-1}·yr^{-1} C) without significantly reducing wheat yield. This was mainly due to an increase in the proportion of macro-aggregates, an improvement in the health of the soil microbial community, and a decrease in the rate of SOC mineralization[25,26].

Facing the excessive use of mineral fertilizer in China[27], optimized mineral fertilizer management is a key means of improving NUE and reducing environmental costs. In recent decades, many new fertilizer management technologies have been developed. Results showed that optimized topdressing and deep fertilizer application increased wheat yield by 7.3% and 7.1%, and NUE by 5.5% and 8.3%, respectively (Fig. 1(c)). This was mainly due to improved synchronization between soil nutrient supply and crop nutrient demand, thus promoting plant nutrient uptake[28]. The adoption of EEFs (including nitrification inhibitors and urease inhibitors) increased wheat yield by 4.7% and NUE by 16.6%, mainly due to improved synchronicity between fertilizer N release and plant N uptake, reducing reactive N losses and improving NUE[29].

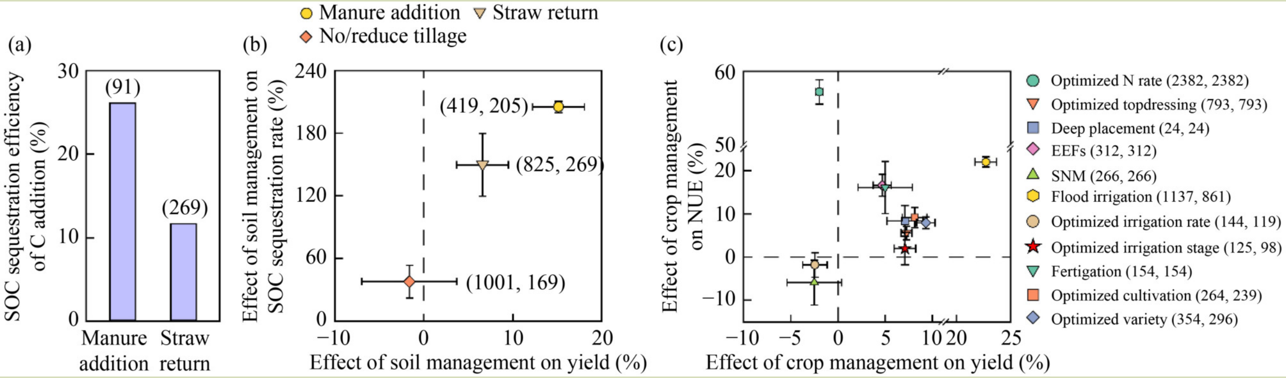

Fig. 1 Effects of soil and crop management techniques on soil organic carbon (SOC) sequestration, wheat yield and N use efficiency (NUE): manure addition and straw return on SOC sequestration efficiency (a), soil management practice on wheat yield and SOC sequestration rate (b), and crop management practice on wheat yield and NUE (c). Error bars are 95% confidence intervals. Differences are considered significant if confidence intervals do not include zero. Numbers in parentheses are sample sizes, and when there are two values in parentheses, these are sample sizes of the horizontal and vertical indicators, respectively. EEFs, enhanced-efficiency fertilizers; and SNM, substitution of partial mineral N fertilizer by animal manure at the same total N input.

Substitution of partial mineral N fertilizer by animal manure at the same total N input reduced wheat yield and NUE, since the low nutrient release rate of manure could not meet the nutrient requirements for wheat growth[30].

In addition, due to the mismatch between precipitation and plant water requirements, wheat usually requires irrigation, with flood irrigation being the most common method. Studies have shown that flood irrigation increased wheat yield and NUE by 22.7% and 22.0% (Fig. 1(c)), respectively, due to improved soil water supply[31]. However, flood irrigation was associated with considerable water wastage and low irrigation WUE, and our study showed that optimized irrigation rate did not result in yield losses when irrigation water use was reduced by 41%. And, optimized irrigation stage increased wheat yield by 7.1% at the same irrigation water volume, due to increasing plant transpiration and reducing soil evaporation. Further, the application of drip irrigation increased wheat yield by 5% and NUE by 16%, compared to flood irrigation. This was mainly due to reducing soil evaporation by partial root zone irrigation and accelerating water uptake and utilization of water from deeper soil layers by promoting root distribution in deeper soil layers[28].

Breeding new cultivars with higher yield potential was an important path for increasing wheat yield. Our study showed that optimized cultivar also showed good benefits for wheat yield (9.3%) and NUE (7.9%) (Fig. 1(c)) because new cultivar usually enhanced the absorption of nutrients by the plant root system[32]. Between 2000 and 2023, more than six hundred new wheat cultivars were approved by the Chinese Government, and sufficient genetic resources ensured that farmers could choose and update cultivars suitable for local production. Our study showed that optimized cultivation also resulted in 8.1% and 9.1% increases in wheat yield and NUE, respectively. Optimized cultivation was more conducive to the formation of high-yielding populations, improved the use of light and heat resources, and increased the nutrient and water uptake capacity[21]. Based on the framework, we summarized the effects of key technologies from the soil, root layer and canopy systems on wheat yield and NUE, and obtained promising results that should provide a basis for the development of typical technology models.

3.3 Typical technology models for improving wheat productivity

Compared with single key technology, the technology models improved more key steps of crop production, thus providing greater benefits in yield improvement and environmental protection[7]. Given the great difference in key limiting factors in dryland and irrigated cropping, typical cases were developed separately and verified by field experiments. For wheat production in dryland contexts, soil water deficiency is the most limiting factor, plastic film mulching could improve soil water condition, so has been widely used. For dryland cropping, we developed the YPM model, with the main improvement being the covering of ridges with transparent plastic film during the wheat growing season and summer fallow, rather than just during the growing period. In addition, considering the overuse of N fertilizer, the N fertilizer application rate was optimized based on plant nutrient needs[18]. Compared to farmer practice, the YPM model increased soil water storage at wheat sowing by 7%, due to increased rainfall infiltration and reduced soil water evaporation (Fig. 2). Improved soil water conditions before sowing are the foundation for high yields[33].

The adoption of the YPM model enhanced wheat growth and development and increased the leaf area index by 69% and the net photosynthetic rate by 12% at the anthesis stage. As expected, the YPM model increased mean yield by 11%, evapotranspiration by 4%, water use efficiency by 8% and $\mathrm{PFP_N}$ by 19%, respectively. As a result, the YPM model increased plant N uptake by 5%, resulting in a 34% decrease in soil nitrate-N residues at the wheat harvest, which also decreased the soil nitrate-N leaching by 63%. However, studies reported that mean plastic film residue has reached 34 $\mathrm{kg \cdot ha^{-1}}$ in China due to the long-term use of plastic film mulching technologies[34]. As a result, the YPM model was a better choice for increasing yields, but it also had environmental risks that needed to be considered.

For wheat production in the irrigation area, we developed an ENWM model. The key optimized steps had optimized mineral N fertilizer application rate based on monitoring $\mathrm{NO_3^-}$-N in the 1.0 m soil layer[19], optimized irrigation water application rate based on crop water demand and precipitation, and matched crop nutrient and water demand by drip irrigation. Our results showed that the ENWM model could reduce irrigation water consumption and mineral fertilizer use by 33% and 30%, respectively, and increase leaf area index by 24% at the anthesis stage (Fig. 3). The reason being that drip irrigation provides improved water conditions at the roots, promotes nutrient movement to the roots by mass flow or diffusion, and improves nutrient uptake and use by the plants through a synchronous supply of water and fertilizer[35]. As a result, the ENWM model increased wheat yield, NUE and irrigation water use efficiency by 10%, 57%, and 65%, respectively. In conclusion, we developed two typical technology models,

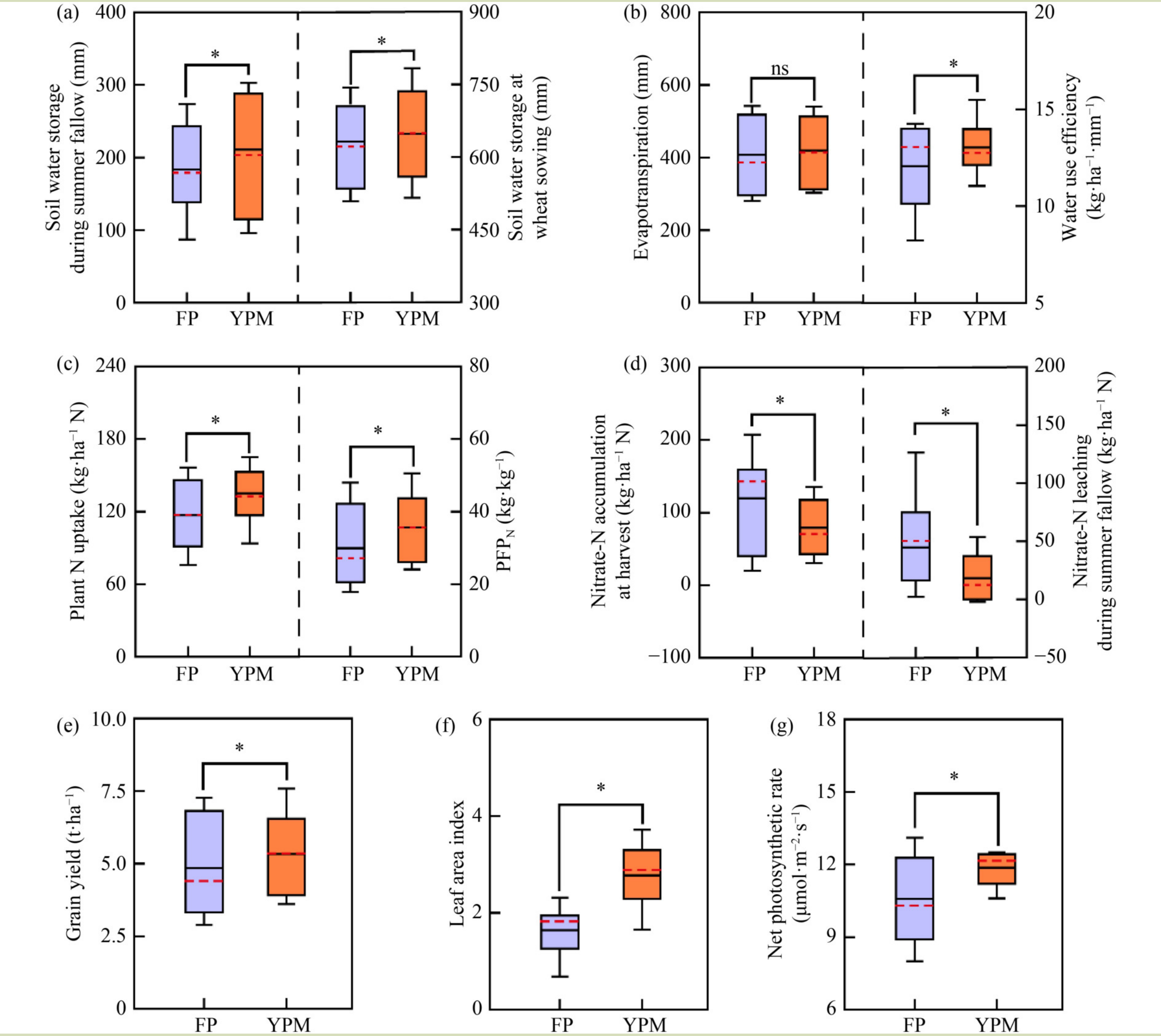

Fig. 2 Typical technology models of wheat production in dryland cropping: effects of year-round plastic film mulching (YPM) cultivation model on soil water storage during summer fallow and at wheat sowing (a), evapotranspiration and water use efficiency (b), plant N uptake and PFP_N (c), nitrate-N accumulation at wheat harvest and nitrate-N leaching during summer fallow (d), wheat grain yield (e), leaf area index (f), and net photosynthetic rate (g). FP, farmer practice; *, significant differences; and ns, not significant at $P < 0.05$.

providing substantive benefits for improving yield and NUE. In the future, developing new technologies adapted to local climates, soils and cropping systems is one of the key ways to further increase production and efficiency in the future.

3.4 New model for technology promotion

In recent years, with on-going transfer of agricultural land, there has been a major shift in the operators of wheat production in China and a gradual increase in the number of large-scale farmers in need of new technologies[36]. Exploring new technology support models is a way to transform agricultural technology into crop productivity. In generally, the greater the geographical distance of technology adoption, the greater the time and transport costs, which are not conducive to technology diffusion and thus delay the adoption of new technologies by farmers[37]. After considerable refinement, we developed a new model of technology application that integrates multiple subjects, named as the Multi-subject Joint Innovation Technology (MJIT) model (Fig. 4). Specifically, it is policy-oriented, with higher education institutions and research mechanisms as the source of technology, with crop technology promoters and production enterprises as the core, with the core area of regional wheat production as the object, and with service production in close proximity.

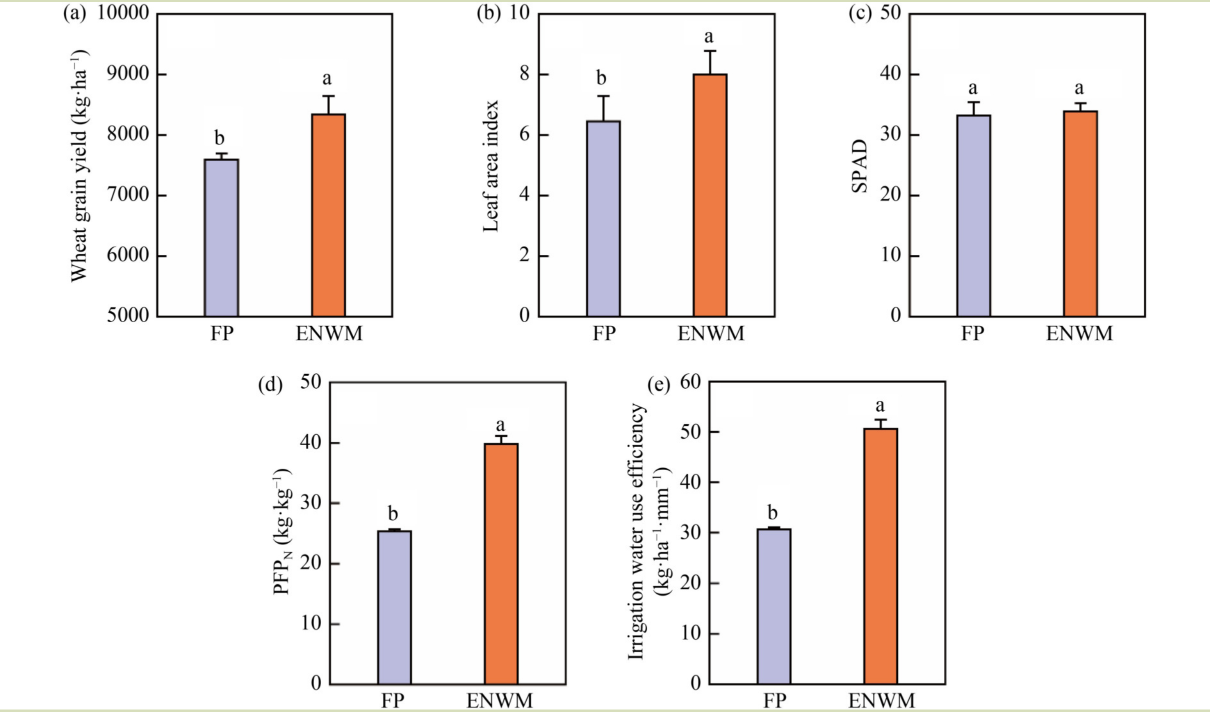

Fig. 3 Typical technology model of wheat production in the irrigation are: effects of efficient nutrient and water management (ENWM) technology model on wheat grain yield (a), leaf area index at wheat anthesis (b), SPAD at wheat anthesis (c), PFP$_N$ (d), and irrigation water use efficiency (e). FP, farmer practice. Treatments with the same letters are not significantly different at $P < 0.05$.

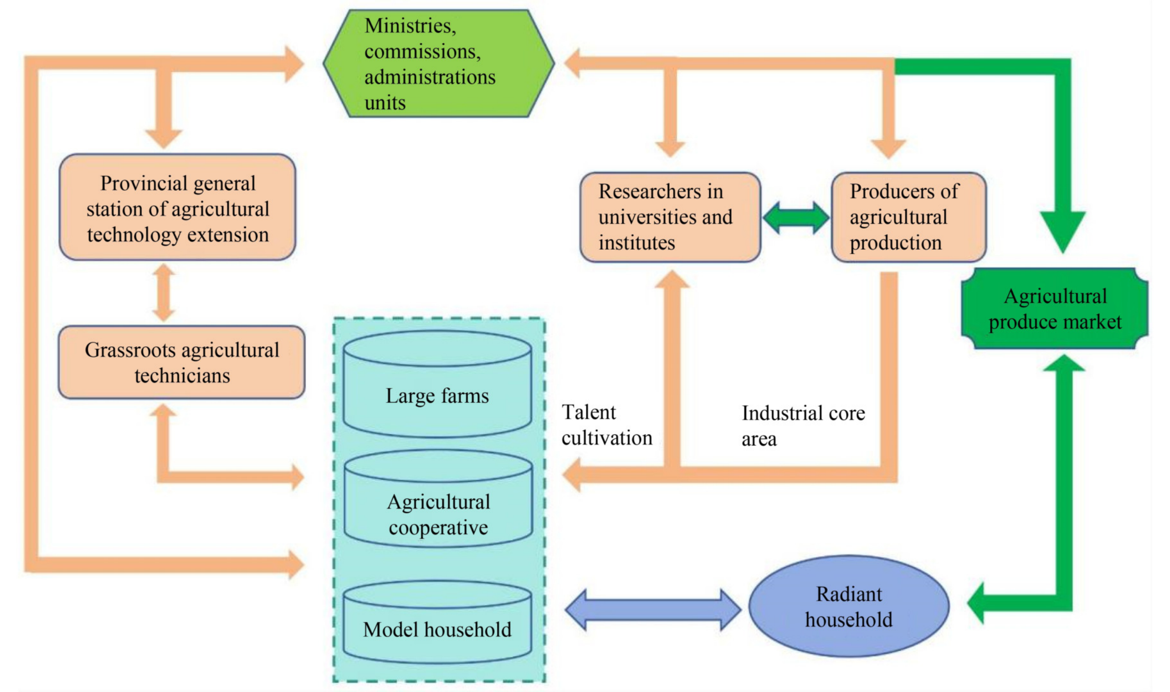

Fig. 4 Framework and implementation of a technology diffusion model for wheat production in Northwest China. Entities are shown in shaded boxes and arrows indicate specific processes and information flows.

The innovations of the MJIT model are mainly evident in three aspects. First, policy-oriented, aims at solving the major scientific and technological problems of regional wheat production, and capturing the main contradiction is the basis of the new model. Second, it organizes multi-disciplinary participation, including institutions, research experts, production enterprises and agricultural extension workers. In contrast to the previous models, the MJIT model integrates technical advisors at the grassroots level into the main body of technological innovation, because they have been involved directly in the production process for a long time and are the practitioners of technology application, which is conducive to accelerating technological innovation. Third, it focuses on the core area of regional wheat production, relying on large farms, agricultural cooperatives and demonstration farming households to undertake application and demonstration work, and it provides a platform for technology deliver.

Based on the benefits of this research model, it has been applied to more than 100 kha of farmland in Northwest China, achieving greater benefits in terms of higher yields and savings in fertilizer and irrigation water. The STB model has given us an excellent example of how technology promotion and application can be achieved[38]. The wheat production area in China is widely dispersed, and there are great economic and cultural differences between regions, which means that new locally-focused models for technology promotion are increasingly needed. Their development will provide technical services for the development of modern agriculture.

4 Conclusions

Faced with the continuing rise in food demand as wheat production growth slows and the area harvested for wheat continues to decline, improving wheat yield and resource use efficiency will be key to achieving sustainable wheat production. In this study, we developed frameworks for wheat green production from building high-yielding systems, managing soil nutrient supply and improving soil fertility, which provided a guide for technological innovation and development. We summarized and quantified the benefits of key technologies and technology models in improving yield and NUE, and technology models showed provided greater benefits. Through this, we propose a new model of technology application to transform agricultural technology into crop productivity. In the future, innovative key technologies and technology models, and the development of new technology promotion models will be the key to the sustainable growth of wheat production in China.

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Compliance with ethics guidelines

Gang He, Wanyi Xie, Lei Fan, Xiaotian Mi, and Zhaohui Wang declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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