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Adaptation Strategy Can Ensure Seed and Food Production With Improving Water and Nitrogen Use Efficiency Under Climate Change

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Key Points:

- High yield and high resource use efficiency in the Hexi Corridor can be achieved through an adaptation strategy under climate change
- An adaptation irrigation and nitrogen strategy can ensure future seed and food production
- The maize seed production under the adaptation strategy in Hexi Corridor can ensure 67% of China's field maize planting area

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Adaptation strategies can reduce the negative impacts of climate change on food security. As an important part of food security, more attention should be paid to seed security, as it determines the crop planting area and ultimately affects food production, especially in major seed production locations, such as the Hexi Corridor in China. This region is an important production base of grain (including field maize and wheat) and maize seed, but the shortage of water resources and low use efficiency of water and nitrogen (N) seriously constrain the sustainable development of agriculture. Formulating an adaptation strategy to balance the seed and food production and resource use efficiency is an important way to maintain regional as well as national food production. We established an optimization-simulation framework, which consists of a novel crop production function and a grid-based crop model, APSIM. This framework was used to optimize agricultural management and evaluate its performance considering the spatio-temporal variability of climate and soil properties, actual crop water consumption and N uptake during each growth stage, and interactive sensitivity coefficients of water and N at different growth stages under climate change. We show that the proposed adaptation strategy could save 0.31 km³ of irrigation water and 22 thousand tonnes of N fertilizer, and increase seed and food production by 33 thousand tonnes, compared with traditional practices. Significant increases in irrigation water productivity and N use efficiency can be expected by using the adaptation supporting the sustainable development of agriculture.

Plain Language Summary

Food security is negatively affected by climate change, while adaptive strategies can change this situation. Grain crop production is generally used to evaluate food security. However, seed yield is often ignored and affects crop planting area and yield. To ensure food security, the government and farmers should pay more attention to the high-yield, high-efficiency, and sustainable development of agriculture. Hexi Corridor is a major seed- and grain-producing area in China. We established an optimization-simulation framework in Hexi Corridor for seed crop (seed maize) and grain crops (field maize), which consists of a novel crop production function and a grid-based crop model. Considering the spatio-temporal variability of climate and soil properties, actual crop water consumption and N uptake during each growth stage, and interactive sensitivity coefficients of water and N in growth stages under climate change, we thereby formulate an adaptive management strategy to balance the seed and food production and resource use efficiency. Our findings show that the adaptive distributed irrigation and nitrogen fertilization strategy in Hexi Corridor can ensure seed production for China's 67% field maize cultivation and adequate food production in 2021–2050, with a significant improvement in irrigation water productivity and nitrogen use efficiency.

1. Introduction

Securing food production is one of the important measures to ensure food security, and has become a critical issue worldwide with the growth of population and increasing food demand, while global crop production could be less stable and more uncertain under future climate change (Agnolucci et al., 2020; Iizumi et al., 2017), mainly due to changes in temperature and precipitation (Aihaiti et al., 2021; Stevanović et al., 2016). Since the Green Revolution in the 1960s, the increase in crop yield was mainly achieved by intensive land management with increasing fertilizer and irrigation water inputs to meet the growing food demand (Tilman et al., 2001).

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However, increasing agricultural inputs led to low use efficiency and substantial environmental pressure due to the imbalance between input and output (Liu, Yang, Ciais, et al., 2018), which is contrary to the Sustainable Development Goals (SDGs) of the United Nations. Hence, finding an adaptation strategy to balance food production and resource use efficiency is a pressing target in the agricultural production system under climate change.

Previous studies predominantly focused on grain production for evaluating regional food security (Du et al., 2014; Jägermeyr et al., 2016; Najafi et al., 2018). Crop production, especially for cereals, would be threatened by heatwaves, drought, and water availability on global, national, and subnational scales during the historical period (Zampieri et al., 2017) and under different climate change scenarios (Jägermeyr et al., 2021) by multi-model simulations. On the other hand, seed security, which determines the crop planting area and production, receives less attention. The Hexi Corridor is a major seed- and grain-producing area in China with favorable sun and temperature conditions. Seed maize production in the Hexi Corridor provides seed for more than 56% of field maize cultivation in China. However, the shortage of water resources due to the little precipitation and strong evaporation has largely restricted the development of agriculture in the region (Chen et al., 2021; Li et al., 2015). Since climate change could reduce cereal yields in this region, adaptation strategies need to be planned to ensure food production (Fu et al., 2019). Therefore, formulating adaptation strategies to cope with climate change is essential to achieve a double-win for seed/food production and resource utilization.

Adaptation strategies have been proven to be effective to increase both crop yield and resource use efficiency in changing environments (Lee et al., 2014; Xu et al., 2021). Previous studies, based on statistics, field experiments, and modelling, have shown that regulated deficit irrigation could achieve the win-win of crop yield and irrigation water productivity (WP_I) (Du et al., 2015; Kang et al., 2017; Mansouri-Far et al., 2010). In addition, precise nitrogen (N) application according to crop N uptake could significantly improve N use efficiency (NUE) and crop yield (Jiang et al., 2019; Srivastava et al., 2018). For cereals, the sensitivity of different crop growth stages to water and N eventually affects crop yield. This provides an incentive for optimizing irrigation water and N fertilization input by determining the time and amount of water and N input to achieve the optimal interplays of yield, utilization efficiency, and environmental health. Establishing an optimization-simulation framework of distributed irrigation and N fertilization strategy (DINS) has been an effective method to optimize management and evaluate performance. However, the spatio-temporal variability of climate and soil properties and their effects on crop yield are difficult to quantify under climate change on the regional scale (García-Vila & Fereres, 2012; Li et al., 2018), which increases the difficulty of establishing the optimization-simulation framework.

In this study, we established an optimization-simulation framework, which includes a water-N production function and a grid-based crop model. Three major cereal crops (seed maize, field maize, and wheat) were considered in the analysis. The new proposed water-N production function consists of the water-N Jensen (WN-Jensen) function and genetic algorithm for optimizing trade-off strategies, which integrated the spatio-temporal variability of climate and soil properties, actual water and N uptake during each growth stage, and interactive sensitivity coefficient of water and N in growth stages under climate change on the regional scale. The performance of trade-off strategies was evaluated by using the Agricultural Production Systems sIMulator (APSIM), to explore the crop yield, WP_I, and NUE under different management strategies under future climate scenarios. Ultimately, the best DINS was determined to balance the seed and food production, WP_I, and NUE in Hexi Corridor under climate change.

2. Materials and Methods

2.1. Study Area

The Hexi Corridor is located in the inland arid area of Northwest China (37°17′–42°48′N, 92°12′–104°20′E), with a length of about 1,000 km from east to west, covering an area of 2.7×10^5 km^2 (Figure 1). From east to west, the Hexi Corridor is composed of the Shiyang River basin, the Heihe River basin, and the Shule River basin. In this area, annual average temperature is 5.8°C–9.3°C (standard deviation (SD) = 0.8°C), annual sunshine hours around 2,550–3,500 hr (SD = 438 hr), annual average precipitation only 50–200 mm (SD = 32 mm), and annual mean pan evaporation 1,500–2,000 mm (SD = 86 mm) calculated based on the daily climate data during 1979–2018.

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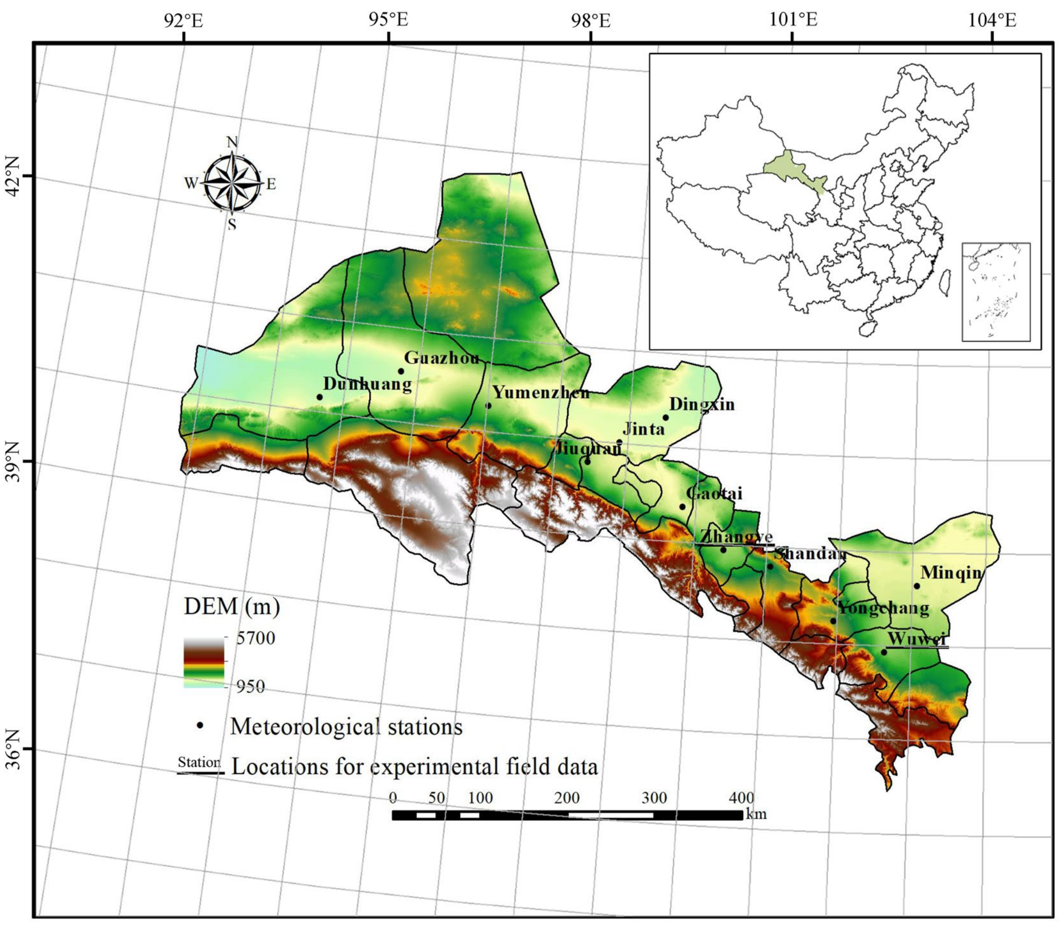

Figure 1. Elevation of the Hexi Corridor and the spatial distribution of meteorology stations and locations for experimental field data.

2.2. Methods

2.2.1. Sowing Date and Crop Growth Stage Division

In this study, the sowing dates and growth stages of seed maize, field maize, and wheat were determined by using a 5-day moving-average (Zhao et al., 2015) and accumulating growing degree days (GDD) (Qureshi & Neibling, 2009). The sowing date of each crop was selected as the first day when the 5-day moving average temperature exceeded the critical temperature. The growth stages of crops were divided based on the critical GDDs. Taking seed maize as an example, GDDs of 520, 1,068, 1,454, 1,936, and 2,242 are the ends of seedling, jointing, heading, filling, and maturity stages, respectively. Critical values of 5-day moving-average temperature, lower and upper growing temperatures, and GDDs for seed maize, field maize, and wheat are shown in Table S1 in Supporting Information S1.

2.2.2. Regional Crop Evapotranspiration and Nitrogen Uptake Prediction Models

The regional crop evapotranspiration (ET_c) prediction module under standard conditions consisted of the single crop coefficient approach (Allen et al., 1998) and temperature effect function (TEF) (Huang et al., 2004; van Delden et al., 2001) to simulate the standard ET_c without any stress. TEF is a Gaussian function to calculate the daily crop coefficient based on critical temperatures of crops and daily temperature. The regional maximum crop N uptake (NU_m) prediction module consisted of the logistic function (Wu et al., 2002) and the N dilution curve (Yin et al., 2017) to simulate the standard NU_m without any stress. In the regional NU_m prediction module, the logistic function was one of the frequently-used methods that could characterize the universal laws in biology based on GDDs of crops, while the N dilution curve could characterize the relationship between plant N content and growth process on the temporal scale. Detailed information can be found in Supporting Information S1. The prediction values obtained from ET_c and NU_m prediction modules were taken as the maximum ET_{ci} and NU_{mi} in each growth stage for different crops in the WN-Jensen production function, which would be used in the following section.

2.2.3. Optimization of Distributed Irrigation and Fertilization Strategy

Climate data, such as ET_0 and precipitation, varied in spatial and temporal scales, which would influence the optimization of irrigation and N fertilization strategy. Therefore, we developed a spatially- and temporally-distributed irrigation and fertilization optimization framework.

2.2.3.1. *Water-Nitrogen Production* ***Function***

The Jensen function is a static model that describes the macro relationship between yield and water (Jensen, 1968) without considering the physiological processes of crop growth and development. In practice, not only water but also N are important factors. In this study, a new WN-Jensen function was developed by considering water, N, and the interaction of these two factors for seed maize, field maize, and wheat:

$$\frac{Y_a}{Y_m} = \prod_{i=1}^{n} \left(\frac{ET_{ai}}{ET_{ci}} \cdot \frac{NU_{ai}}{NU_{mi}} \right)^{\lambda_i} \tag{1}$$

where Y_a and Y_m are actual and maximum crop yield, respectively, kg/ha; i is the growth stage of crops; ET_{ai} and ET_{ci} are the actual and maximum water consumption in stage i, mm; NU_{ai} and NU_{mi} are the actual and maximum N uptake of in stage i, kgN/ha; λ_i is the interactive sensitivity coefficient of water and N in stage i. The least squares method and sequential quadratic programming were used for calculating λ_i of each crop in SPSS (version 20, IBM Corp, Armonk, NY) based on the experimental data from 17 peer-reviewed published papers in this region (Table S2 in Supporting Information S1).

For optimizing the irrigation and N fertilization strategy, ET_{ai} and NU_{ai} could be expressed as irrigation (I_i) and N fertilization (N_{fi}) amounts in stage i. Initial available soil water content (TAW_{ini}) before planting was taken as 18 mm in the tillage layer (0–30 cm) based on measurements from Li, Du, et al. (2019), which was one of the main sources of crop water uptake at the seedling stage instead of the later stages after seedling. Since the purpose of water-saving irrigation was to minimize runoff and percolation, we assumed that ET_a was equal to the sum of irrigation and precipitation during the growth stages after seedling in the optimization algorithm. The sources of crop N included soil initial N and applied N fertilization. Soil N and fertilizer N were used to represent crop N uptake by using N source proportion and utilization coefficients. Based on the regional ET_c and NU_m prediction model (Section 2.2.2), the WN-Jensen used in this study can be expressed as:

$$\frac{Y_a}{Y_m} = \left(\frac{I_1 + P_1 + TAW_{ini}}{ET_{c1}} \cdot \frac{\mu N_{f1} + \varphi N_0}{NU_{m1}} \right)^{\lambda_1} \cdot \prod_{i=2}^{n} \left(\frac{I_i + P_i}{ET_{ci}} \cdot \frac{\mu N_{fi} + \varphi (1-\varphi)^{i-1} N_0}{NU_{mi}} \right)^{\lambda_i} \tag{2}$$

where I_i and P_i are the irrigation water and precipitation in stage i, respectively, mm; N_{fi} is the N fertilization amount in stage i, kgN/ha; N_0 is the soil initial N, kgN/ha; μ is the utilization rate of N_{fi}; φ is the utilization rate of N_0. Based on the results from Kalembasa et al. (2020), Mihalache et al. (2019), and Zhang, Liu, and Qi (2020), μ and φ were taken as 0.75 and 0.2, respectively. In this study, five growth stages were considered: seedling, jointing, heading, filling, and maturity for seed maize, seedling, jointing, tasseling, filling, and maturity stages for field maize, and seedling, tiller-jointing, heading, filling, and maturity stages for wheat. These five stages were represented by S1 to S5 respectively. Estimated values of λ_i of three crops are shown in Table S3 in Supporting Information S1.

2.2.3.2. *Optimization Framework of Irrigation and Nitrogen Fertilization Strategy*

In this study, a DINS was optimized based on two goals: high water and N use efficiency (HWNE) and high seed and food production (HSFP). Three objectives were considered: maximum total crop production (TP), irrigation water productivity (WP_I), and partial factor productivity from applied N (PFP_N) as follows:

$$\begin{cases} \max \mathrm{TP_a} = \max \sum_{m=1}^{s} Y_m \cdot \prod_{i=1}^{n} \left(\frac{\mathrm{ET}_{ai}}{\mathrm{ET}_{ci}} \cdot \frac{\mathrm{NU}_{ai}}{\mathrm{NU}_{mi}} \right)^{\lambda i} \times A_m \times 10^{-7} \geq \mathrm{TP_{min}} \\ \max \mathrm{WP_I} = \mathrm{TP_a} / \sum_{m=1}^{s} \left(\sum_{i=1}^{n} I_i \times 10 \times A_m \right) \\ \max \mathrm{PFP_N} = \mathrm{TP_a} / \sum_{m=1}^{s} \left(\sum_{i=1}^{n} N_{fi} \times A_m \right) \end{cases} \quad (3)$$

where TP_a and TP_{min} are actual and minimum total production, respectively, 10^4 tonnes; the units of WP_I and PFP_N are kg/m³ and kg/kg, respectively; I_i and N_{fi} are irrigation water and N fertilizer in stage *i*, units are mm and kgN/ha, respectively; A_m is the crop planting in grid m, ha, from the SPAM2010 data set (cited from Yu et al., 2020 and the detailed information is shown in Section 2.4). PFP_N was used to evaluate NUE. A genetic algorithm was chosen, while constraints and weights of objectives for HWNE and HSFP (Table S6) are shown in Supporting Information S1.

The purpose of the optimizing strategy is to determine the trade-off point between the potential of improving water and NUE and improving crop production on the premise of ensuring the lower limit of crop production. Therefore, minimum total production constraints (TP_{min}) for field maize, seed maize, and wheat in HWNE and HSFP scenarios were set in the optimization algorithm. For the HWNE scenario, the crop production would be kept at the level of the reference year 2010 (seed maize production supported 56% of national field maize planting area, and production of field maize and wheat were 0.36% of national demand). For the HSFP scenario, seed maize production supported above 60% of national the field maize planting area, and production of field maize and wheat was above 0.40% of national demand. Values of TP_{min} for different crops are calculated based on different satisfaction levels of future food demand (Table S5 in Supporting Information S1) and detailed information of the optimization framework (Figure S1 in Supporting Information S1) can be found in Supporting Information. The traditional management scenario (TMS) was also considered, using historical irrigation water and N fertilization application rates (data from Gansu Development Yearbook with 2010 as the reference year). Therefore, there are three simulation scenarios in this study: TMS, HWNE, and HSFP.

DINS would be obtained by the optimization framework and could provide irrigation and N fertilization at growth stages in each grid for crops, which could then be used as inputs for APSIM modeling. APSIM (Keating et al., 2003) was used to simulate crop yield, WP_I, and PFP_N of different scenarios, and was calibrated by using the CroptimizR package (Buis et al., 2021) and run by gridded climate, soil, CO_2 concentration, and irrigation and N fertilization strategies. Coefficient of variation (CV, obtained from statistical analysis) (Warrick & Nielsen, 1980), *z*- and *p*-values (obtained from Mann-Kendall test) (Pohlert, 2020), and random variation (RV, obtained from geostatistical analyses) (Tesfahunegn et al., 2011) were used for quantifying the characteristics of spatio-temporal variation of yield for the different crops. We calculated the *N* surplus (N_{sur}) is based on the *N* inputs and outputs to evaluate the nitrogen budget:

$$N_{sur} = N_{fer} + N_{man} + N_{min} + N_{dep} - N_Y \quad (4)$$

where N_{fer}, N_{man}, N_{min}, N_{dep}, and N_Y are *N* from fertilizer application, manure application, mineralization in the soil, atmospheric deposition, and the any part of the crop yield to be removed from the field. N_Y was calculated by multiplying crop aboveground biomass by crop *N* concentration, where aboveground biomass was obtained by dividing the simulated grain yields by the harvest index. Harvest index was obtained from Ran et al. (2017), Xiao et al. (2021) and Li et al. (2018), and *N* concentration data was obtained from Chen et al. (2022). N_{fer}, N_{man}, N_{min}, N_{dep}, and were obtained from different data sets, shown in Supporting Information S1 with the detailed information regarding APSIM, model performance, and the analysis methods.

2.3. Data Description

2.3.1. Crop Planting Distribution and Area

The harvested areas of wheat and maize (including seed maize and field maize) were obtained from spatial production allocation model 2010 (SPAM2010) data (IFPRI, 2019; Yu et al., 2020) with a spatial resolution of 5 × 5′. For verifying the accuracy of SPAM2010, we used the crop planting area data derived from the Gansu Development Yearbook (https://data.cnki.net/Yearbook/Single/N2022010251) and compared it with SPAM2010

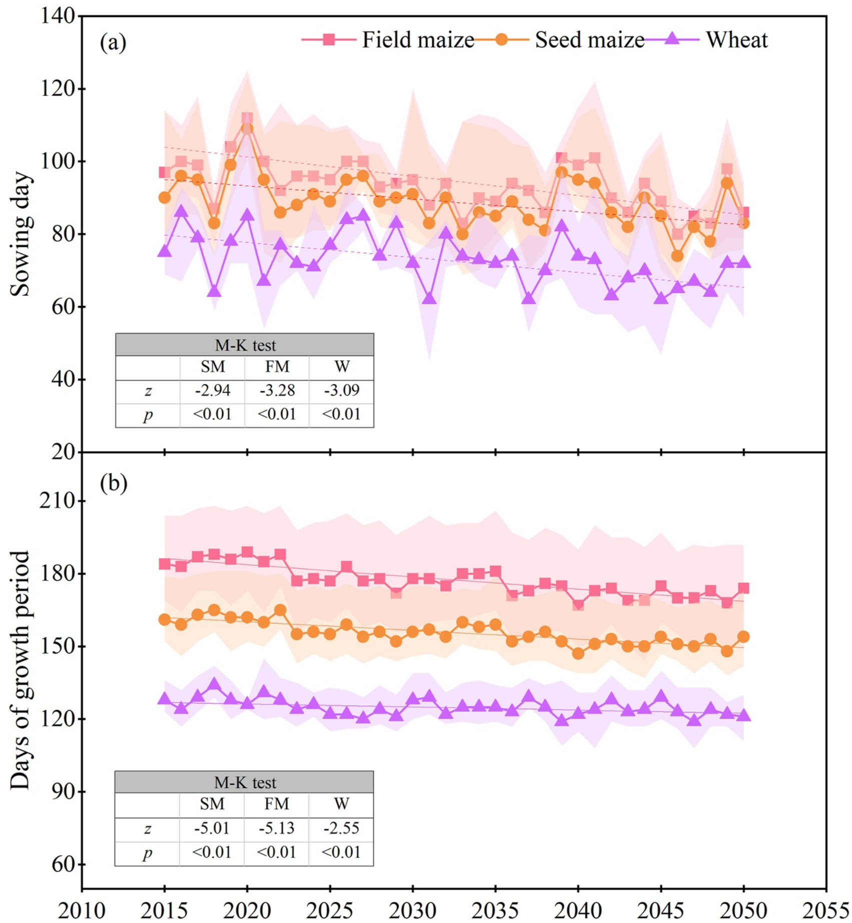

Figure 2. Sowing dates and days to harvest for field maize (FM), seed maize (SM), and wheat (W) from 2015 to 2050 under future climate change. Mann-Kendall test (M-K test) was used to quantitatively evaluate changing trends on the temporal scale. *Z*-value represents the change trend (for $z > 0$, $z = 0$, $z < 0$ means increase, no change, and decrease), and *p*-value represents whether this trend is significant ($p < 0.01$ means the trend is significant). Shadows are the range between the maximum and minimum values.

at the county-level. Results showed good consistency between the two data sets (Figure 2). The area of seed maize as a proportion of the total planting area of maize was obtained based on the statistical data of five cities located in the Hexi Corridor (Wuwei, Zhangye, Jinchang, Jiayuguan, and Jiuquan, data was reported by http://nync.gansu.gov.cn/), which was applied to grids.

2.3.2. Climate, Soil, Crop Yield, and Agricultural Resource Input Data

Soil data were obtained from the China Data set of Soil Hydraulic Parameters Using Pedotransfer Functions for Land Surface Modeling (Dai et al., 2013; Shangguan and Dai, 2013) and the Soil Database of China for Land Surface Modeling (Shangguan et al., 2013) with 138.3-cm depth (0–4.5, 4.5–9.1, 9.1–16.6, 16.6–28.9, 28.9–49.3, 49.3–82.9, and 82.9–138.3 cm) on a 30 × 30″ global grid, including bulk density, field capacity, wilting point, saturated water content, saturated hydraulic conductivity, alkali-hydrolyzable N (N_0 in this study), and soil organic matter.

The daily climate input data used in this study included precipitation, minimum and maximum air temperature, surface pressure, specific humidity, wind speed, and downwelling shortwave radiation. The China Meteorological Forcing Data set (He et al., 2020; Yang et al., 2010; Yang & He, 2019) on a 0.1° × 0.1° global grid was used in this study as the historical climate data (1979–2018), which was retrieved from the National Tibetan Plateau Data Center (TPDC, https://data.tpdc.ac.cn/en/data/8028b944-daaa-4511-8769-965612652c49). Five bias-adjusted global circulation model data sets (CanESM5, CNRM-CM6-1, CNRM-ESM2-1, EC-Earth3, and GFDL-ESM4) and three SSP scenarios (SSP126, SSP370, and SSP585) with a spatial resolution of 0.5° × 0.5°

and a research period of 2015–2050 (Lange & Büchner, 2022) were used in this study, accessed through the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP, https://data.isimip.org/search/query/CanESM5/) bias-adjusted and downscaled from the Coupled Model Intercomparison Project Phase 6 (CMIP6) climate model outputs. CO_2 concentrations were collected from ISIMIP3a atmospheric composition input data (Matthias & Christopher, 2022), which was 400 ppm during 1979–2015, and ranged from 400 to 469, 400 to 541, and 400 to 563 ppm in SSP126, SSP370, and SSP585, respectively, during 2015–2050.

The soil and climate input data were resampled to a resolution of 5′ using a first-order conservative remapping procedure in Climate Data Operators (CDO: https://code.mpimet.mpg.de/projects/cdo). Measured data of crop yield (wheat and maize), irrigation water and chemical fertilizer inputs were obtained from field investigation and statistical data from the Gansu Development Yearbook (1984–2017).

2.3.3. Population and Food Demand

Annual population data in the Hexi Corridor and China were derived from the Gansu Development Yearbook and the National Bureau of Statistics (http://www.stats.gov.cn/), respectively. Future annual population data until 2050 in China were collected from FAOSTAT (https://www.fao.org/aquastat/en/), and the data in Hexi Corridor were obtained by multiplying China's population by a specific proportion (0.335% based on historical data during 1984–2017). The evaluation of seed maize production was only for field maize cultivation that could be supported by seed maize production, without considering the usage and storage in the next or several years due to data limitations.

Future maize and wheat demand were extracted from Luo et al. (2014), which included the requirements of food, feed, and industry. In this study, future demand was used as one of the optimization objectives, while the number of people that can be satisfied by the grain production (expect industrial consumption) under each scenario was calculated by human dietary needs. The recommended diet plan referred to the Scientific Research Report on Dietary Guidelines for Chinese Residents 2021 (NNS, 2021) and the healthy reference diet (Willett et al., 2019), which included the demand for grains (field maize and wheat) and consumption by feed (poultry, livestock, fish, eggs, and dairy food). Field maize and wheat consumed by feed was calculated based on feed conversion ratio (Luo et al., 2014). The proportion of industrial consumption of field maize and wheat referred to Liu et al. (2018).

3. Results

3.1. Impact of Climate Change on Sowing Date and Phenology

Sowing dates were significantly advanced and the days of the growth period were significantly shortened ($z < 0$ and $p < 0.01$ based on the M-K test) for field maize, seed maize, and wheat in the Hexi corridor under future climate change (Figure 2, Figure S3 in Supporting Information S1). For field maize, average sowing dates were day 100, 92, and 89 in 2020s, 2030s, and 2040s, respectively, while total days to harvest were 186, 176, and 172 days for the three periods. Average sowing dates of seed maize were day 95, 87, and 85 in 2020s, 2030s, and 2040s, respectively, while 162, 155, and 151 days for the whole growing season in the three periods. As for wheat, average sowing dates were day 78, 72, and 68 in 2020s, 2030s, and 2040s, respectively, with 128, 125, and 123 days of the growing growth season in the three periods.

3.2. Distributed Irrigation and N Fertilization Strategy for Climate Change Adaptation

DINSs were determined for HWNE and HSFP scenarios (Figure 3). The interactive sensitivity coefficient of water and N for seed maize, field maize and wheat at seedling and maturity stages were 0.001–0.059 (Table S3 in Supporting Information S1), indicating that these two stages are not sensitive to water and N stress and do not have to use additional irrigation and N fertilization inputs. HWNE could lead to 40.3%, 26.5%, and 37.8% less irrigation than TMS for seed maize, field maize, and wheat, respectively, while HSFP could lead to 18.5%, 13.0%, and 26.3% less irrigation than TMS for these three crops. In contrast, HWNE could reduce N fertilizer by 51.0%, 40.3%, and 26.7% relative to the TMS scenario for seed maize, field maize, and wheat, respectively, while HSFP could lead to 44.5%, 37.5%, and 21.3% lower N fertilizer than TMS for these three crops.

Spatial distribution of DINS under HWNE and HSFP varied across the Hexi Corridor (Figure 4). Under the HWNE scenario, 276–420 mm irrigation water and 121–255 kgN/ha fertilization for field maize were applied,

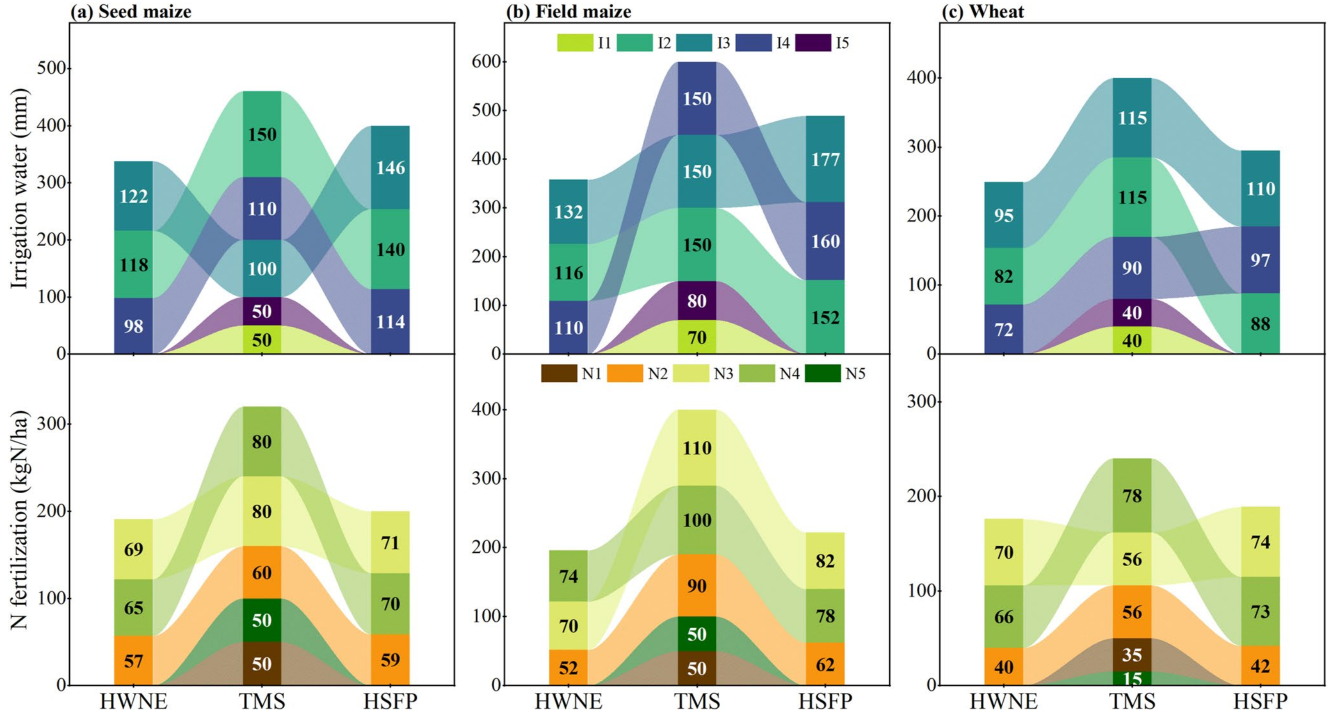

Figure 3. Future irrigation and N fertilization strategy for different crops under TMS (traditional management), HWNE (high water and N use efficiency), HSFP (high seed and food production) scenarios during 2021–2050. I1 to I5 and N1 to N5 represent irrigation water and N fertilization application during stage 1 to stage 5 for seed maize, field maize, and wheat, and are mean values for 2021–2050. Five growth stages were divided into seedling, jointing, heading, filling, and maturity stages for seed maize, seedling, jointing, tasseling, filling, and maturity stages for field maize, seedling, tiller-jointing, heading, filling, and maturity stages for wheat.

259–376 mm and 122–250 kgN/ha for seed maize, and 204–278 mm and 124–222 kgN/ha for wheat. Under the HSFP scenario, 389–564 mm irrigation water and 134–286 kgN/ha fertilization for field maize were applied, 317–457 mm and 128–266 kgN/ha for seed maize, and 244–333 mm and 132–236 kgN/ha for wheat. Irrigation and N fertilization application of HWNE and HSFP increased from southeast to northwest.

3.3. Response of Crop Performance to Climate Change Under Different DINS Strategies

The calibrated APSIM model could accurately simulate LAI, grain yield and biomass ($0.67 < R^2 < 0.98$, 7.5% < nRMSE < 23.2%) based on the historical experimental data collected from 17 published papers (Figure S4, Table S2 in Supporting Information S1). The calibrated APSIM model was then used to simulate future crop yield under climate change at the regional scale.

Yield of seed maize, field maize, and wheat showed a decreasing trend at the temporal scale (based on significance obtained from the M-K test) in some regions (like Wuwei, Yongchang, Jiuquan, etc) and a strong spatial variability (based on RV values) across the Hexi Corridor, and the temporal stability of crop yield was poor under TMS (Figure 5). Especially for wheat, yield reduction trend appeared in many regions ($z < 0$ and $p < 0.01$), with high temporal variance (12.2% < CV < 65.2%) and strong spatial variability (4.2% < RV < 22.2%). Yields of the three crops showed moderate to strong variability (12.1% < RV < 27.7%) and an increased temporal stability (6.9% < CV < 28.6%) under HWNE and HSFP compared to TMS, while the weakest and most temporally stable variance appeared in HSFP (21.1% < RV < 31.4%, 5.0% < CV < 25.0%). The simulated yield of seed maize, field maize, and wheat under SSP126, SSP370, and SSP585 are shown in Figures S5, S6, and S7, respectively in Supporting Information S1. Yields of seed maize, field maize, and wheat simulated based on CanESM5, CNRM-CM6-1, CNRM-ESM2-1, EC-Earth3, and GFDL-ESM4, are shown in Figure S8 in Supporting Information S1.

The total production of the three crops decreased by 20.3×10^4 tonnes from 2035 to 2050 under TMS, decreased by 6.8×10^4 tonnes under HWNE and increased by 3.3×10^4 tonnes under HSFP (Table 1). Field

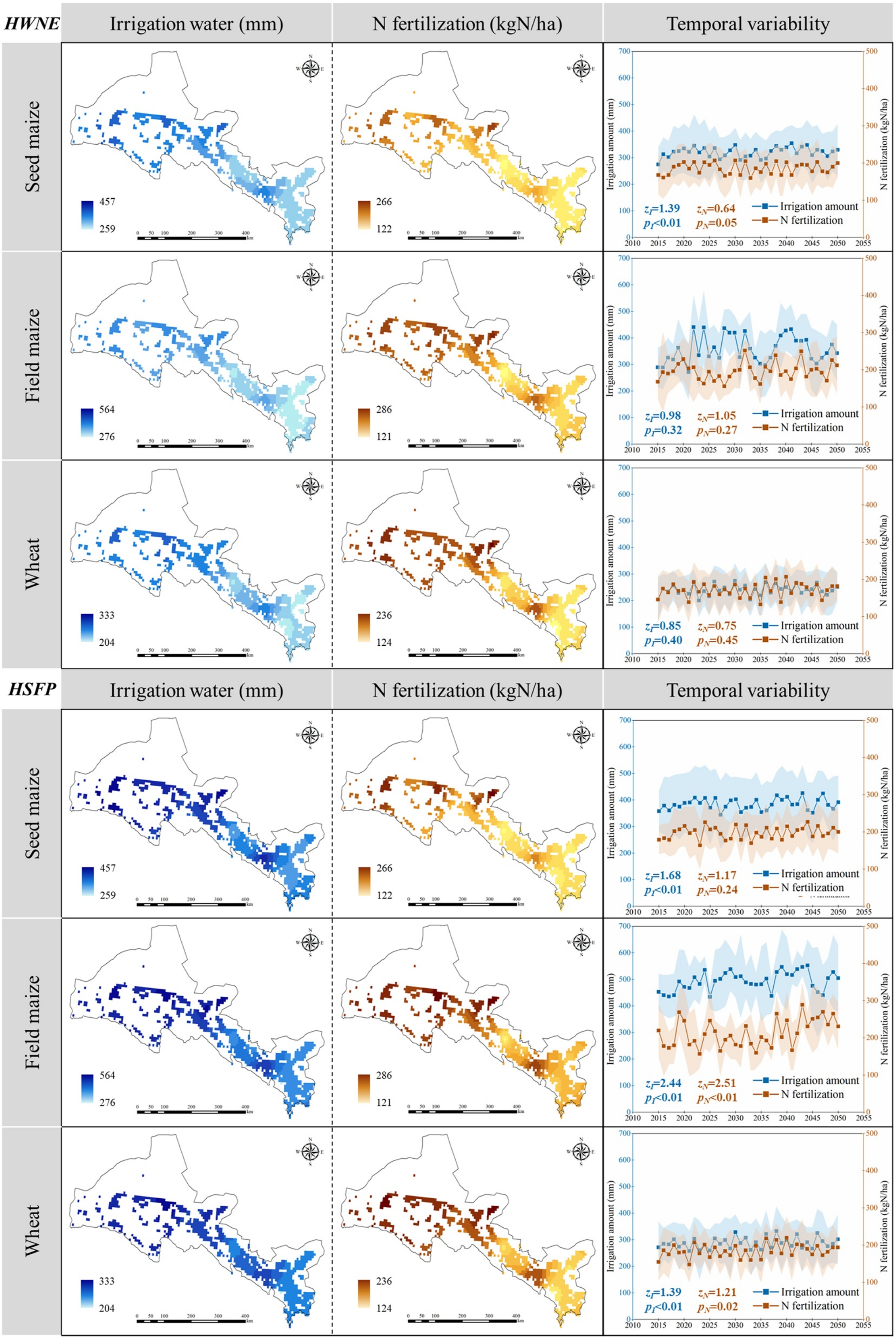

Figure 4. Spatio-temporal variability of distributed irrigation and N fertilization strategy (DINS) for seed maize, field maize, and wheat under high water and N use efficiency (HWNE) and high seed and food production (HSFP) scenarios in the Hexi Corridor during 2021–2050. Data in the spatial distribution maps are mean values for 2021–2050. Irrigation water for seed maize, field maize, and wheat were 460, 600, and 400 mm under TMS, respectively, while N fertilization for the three crops were 320, 400, and 240 kgN/ha under TMS, respectively.

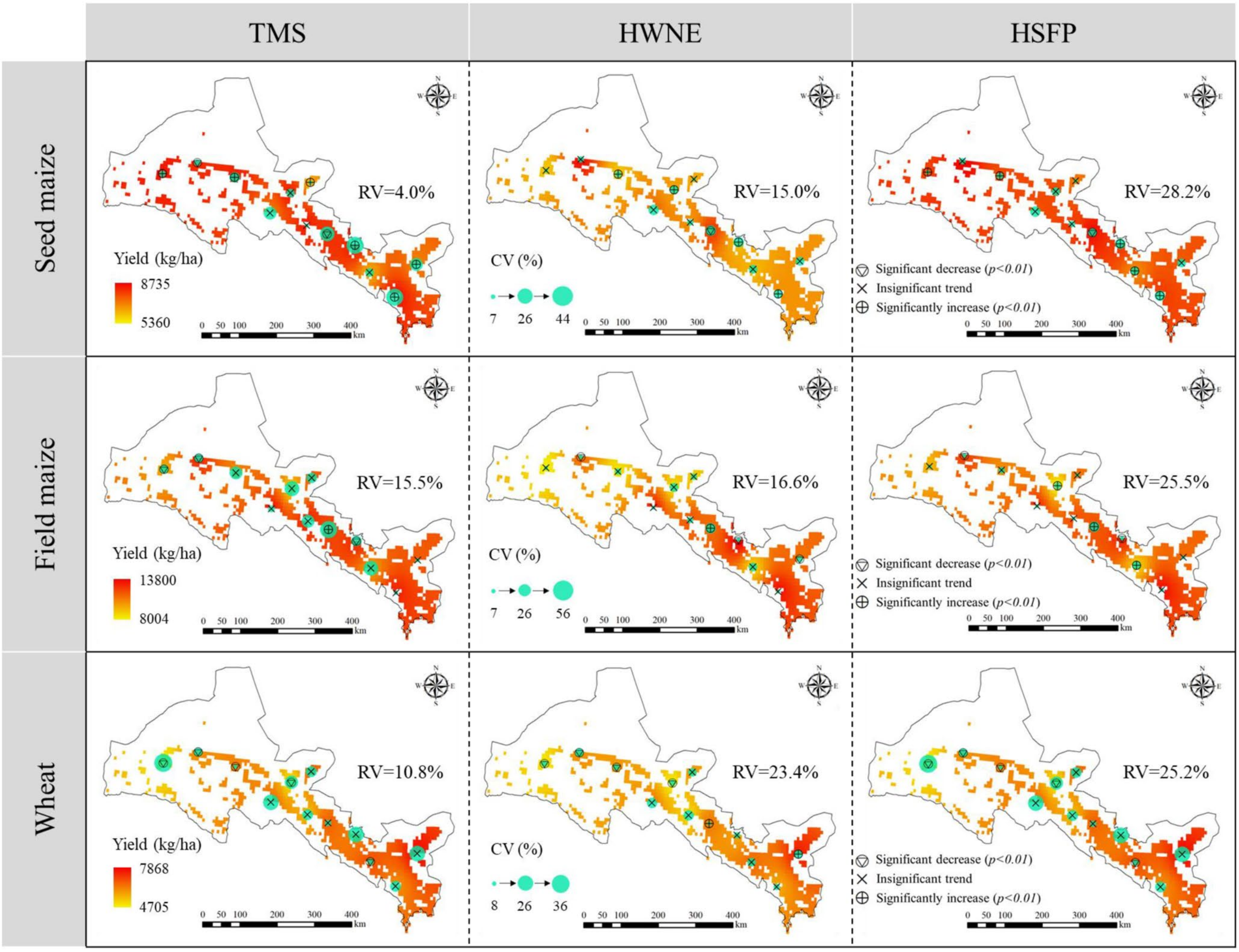

Figure 5. Spatial distribution, temporal variance, and spatial variability of seed maize, field maize, and wheat yield in the Hexi Corridor under traditional management (TMS), high water and N use efficiency (HWNE), and high seed and food production (HSFP) scenarios, which were obtained from the mean values based on simulated yield during 2021–2050 under SSP126, SSP370, and SSP585. CV and RV represent the coefficient of variation and random variation, while the significance level is determined by the M-K test.

maize and wheat production under HSFP could satisfy healthy reference diet the food requirements of 11.9 million and 11.6 million people, respectively, which is equivalent to 46% of the population of Gansu Province. Seed maize production could be increased by −39 to 53 thousand tonnes and 56–173 thousand tonnes under HWNE and HSFP, respectively, which could support 56%–61% and 64%–70% of China's field maize planting area.

Total irrigation water and N fertilizer application in the Hexi Corridor under HSFP could be decreased by 0.31 km³ and 2.2×10^4 tonnesN per year, respectively, and could be decreased by 0.53 km³ and 3.5×10^4 tonnesN under HWNE per year. Under HWNE and HSFP scenarios, WP_I and PFP_N could be significantly improved by 0.35–1.12 kg/m^3 and 4.2–17.4 kg/kg ($p < 0.001$) (Figure S10 in Supporting Information S1), respectively, by increasing crop production and saving water and N. WP_I and PFP_N under HWNE were significantly higher than those under HSFP, but with lower crop production. Compared with TMS, the overall WP_I and PFP_N under HWNE were increased by 50.8% and 53.8%, respectively, and under HSFP were increased by 42.3% and 46.7%, respectively. More stable spatial variability appeared in HWNE and HSFP, with RV values reduced by 9.8%–16.5% and 12.1%–23.1%, respectively, compared with TMS.

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Table 1
Crop Production, Total Irrigation Water and N Fertilizer Application, Seed and Food Supply Amount in the Hexi Corridor Under Three Management Scenarios (T, HWNE, HSFP) in 2021, 2035 and 2050

	TMS			HWNE			HSFP		
Variables	2021	2035	2050	2021	2035	2050	2021	2035	2050
Seed maize (10^4 tonnes)	70.4	71.1	67.0	66.7	67.2	72.2	75.6	76.7	84.3
Field maize (10^4 tonnes)	70.6	71.3	66.3	75.2	76.0	73.4	77.1	77.9	83.2
Wheat (10^4 tonnes)	90.8	91.8	80.6	78.3	79.2	70.0	95.5	96.8	87.2
Total irrigation water (km^3)	1.51	1.49	1.49	0.92	0.96	0.97	1.19	1.17	1.20
Total N application (10^4 tonnes N)	9.62	9.68	9.68	6.06	6.12	6.20	7.34	7.39	7.55
WP_I-overall (kg/m^3)	1.54	1.57	1.44	2.39	2.31	2.21	2.09	2.14	2.12
PFP_N-overall (kg/kg)	24.10	24.19	22.10	36.34	36.34	34.77	33.81	34.02	33.74
N surplus (10^4 tonnes N)	6.68	6.66	7.38	3.65	3.63	3.93	3.85	3.78	3.88
Support the field maize planting area (10^6 ha)	23.4	23.7	22.3	22.1	22.4	24.1	25.3	25.6	28.1
Population satisfied with maize as food (10^6)	10.4	10.5	9.8	11.1	11.2	10.8	11.4	11.5	12.2
Population satisfied with wheat as food (10^6)	11.5	11.6	10.2	9.9	10.0	8.8	12.1	12.2	11.0

Note. TMS, HWNE, HSFP were traditional management, high water and N use efficiency, and high seed and food production scenarios, respectively. WP_I-overall and PFP_N-overall were the overall mean values of irrigation water productivity and partial factor productivity from applied N, respectively, based on the data from the sum of seed maize, field maize, and wheat.

4. Discussion

4.1. Influence of Climate Change and Strategy on Crop Yield

Warming is a universal trend in most of the major cereal cropping regions around the world, which generally leads to crop production reduction (Asseng et al., 2015; Qiao et al., 2021). With the rising temperatures, the challenge of securing adequate food production is enormous in Northwest China (Wu et al., 2019). Higher temperature accelerates the phenological development of crops and decreases the required growing days, which reduces photosynthesis and biomass accumulation, and thereby decreases the crop yield (Lizaso et al., 2018; Zabel et al., 2021). The phenology and filling rate of the seed crops are sensitive to temperature changes, which ultimately affect the seed yield (Singh et al., 2013). However, the effect of annual warming on crop yield reduction is not certain, and the yield changes caused by warming in different stages are quite different (Asseng et al., 2015). The maximum yield often appears near the optimum growing temperature (T_0) obtained based on TEF (Table S3, Figure S11 in Supporting Information S1) and a clear decreasing tendency for yields occurs for temperatures warmer than the optimum growing temperature (Lobell & Gourdji, 2012). The optimum temperatures in phenological stages are distinct, while the sensitivity of temperature is also different among stages based on our estimation. Research based on field experiment and modeling have indicated that the reproductive stage is highly temperature sensitive for maize (Sanchez et al., 2014), whereas flowering and grain-filling stages are most sensitive for wheat (Zampieri et al., 2017). In this study, future temperature rising caused crop yield reduction with a shortened growth period in the Hexi Corridor (Figure 2 and Figure S12 in Supporting Information S1).

Precipitation during crop growth season in the Hexi Corridor increased by 5.4%–30.5% under climate change (Figure S12 in Supporting Information S1), which might not be the main reason for yield reduction due to the arid climate, the low precipitation (84–323 mm during 2021–2050), and widely distributed irrigated agriculture. However, it does not mean that future precipitation events do not need too much attention. The probability of extreme precipitation events is increasing under climate change (Aihaiti et al., 2021), resulting in increased crop production damages (Li, Zhao, et al., 2019; Rosenzweig et al., 2002). Generally in cold regions, temperature plays a more relevant role than precipitation in crop production, while crop reduction effects caused by excessive precipitation events are more significant than that in warm regions due to the possibility of waterlogging (Li, Guan, et al., 2019; Shaw & Meyer, 2015). The increased probability of concentrated precipitation (Figure S12 in Supporting Information S1) affected crop yield and optimization results of DINS (Figure 4) to an extent in our study.

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The effects of CO_2 and its combination with other factors (e.g., climate factors and agricultural management) on yields of different crops are complex and highly uncertain globally (Müller et al., 2015). Increasing CO_2 concentration promotes the increase of vegetation water use efficiency, which is constrained by N status (He et al., 2017). Although there are differences in the CO_2 fertilization effect on the yield of different crop types, it is positive for maize and wheat yields in Northwestern and Northern China (Qu et al., 2019; Saddique et al., 2020). In this study, the interaction of CO_2 concentration, climate change, and management scenarios on crop production in the Hexi Corridor was not explored, however, the guidance for future agricultural adaptation strategies were provided (Figures 3 and 4).

4.2. Feasible Strategies to Ensure Regional Seed and Food Production

Results in this study showed that crop yield would be more stable on spatial and temporal scales under HSFP than under TMS, reducing water and N inputs. The persistent yield gap between potential and actual yield is an important issue to be solved for global food production, especially in low- and middle-inputs regions (Ray et al., 2012). Adaptation strategies, like optimized irrigation and N fertilization strategies, determine the potential for closing yield gaps, increasing yield and resource use efficiency, and reducing agricultural pollution (Horton et al., 2021; Liu, Yang, Folberth, et al., 2018; Xu et al., 2021).

Adaptation strategies can reduce the yield reduction caused by climate change, and can also improve WP_I and NUE (Li et al., 2022; Liu, Ying, et al., 2021). Based on a large-scale survey, only the top 10% of crop yields in each county showed a good balance between high yield and high resource use efficiency due to the limitations of agricultural intensification, resource supply, and climate variability in most areas of China (Liu, Ying, et al., 2021). Large N_{sur} has negative impacts on the environment, which is a problem that deserves attention in China (Zhang et al., 2015). N surplus in maize and wheat planting area of the Northwest China exceed 150 kgN/ha (Sapkota et al., 2022), which is similar to the results of TMS but much higher than HSFP and HWNE in our study. Optimizing water and N input at sensitive growth stages, and allowing an appropriate deficit in non-sensitive periods can achieve the trade-off between water and N saving and high yield (Du et al., 2015; Kang et al., 2017). Results from field experimental data suggest optimized irrigation and N fertilization rates (irrigation + N) of 433 mm + 180 kgN/ha for field maize (Xiao et al., 2021), 298 mm + 175 kgN/ha for seed maize (Ran et al., 2017), and 323 mm + 150 kgN/ha for wheat (Wen et al., 2019) in the Hexi Corridor. These results consider crop yield, WP_I, and NUE, which provides good guidance for actual field management and targets a trade-off between saving water and N input and maintaining yield. However, the popularization of these recommended management strategies is limited due to the spatio-temporal variability of climate and soil, and production of seed crops is usually not considered. Previous studies on high-efficient and high-yield strategies for seed maize production have only been conducted on the field or farmland (Chen et al., 2020; Ran et al., 2017), while emphasizing seed maize production in the Hexi Corridor on the regional scale focused on economics rather than the adaptation management and resource utilization (Hong et al., 2019). In this study, the WN-Jensen function was established for seed maize, field maize, and wheat, considering the soil N concentration, interactive sensitivity coefficient of water and N in different growth stages, and water consumption and N uptake during each stage, which was the basis of the formulating DINS for different management scenarios. In our study, HSFP was the best strategy that could save 0.31 km³ of irrigation water and 22 thousand tonnes of N fertilizer and reduce 3.1 thousand tonnes of N_{sur} every year under climate change.

Facing rising population and food demand, finding synergies to ensure seed and food production rather than focusing only on the grain crop production is a new strategy to ensure food security. Seed maize production could be increased by optimizing irrigation and N fertilization and agricultural strategies (Ma et al., 2021; Shi et al., 2020). However, these results were only proved in field experiments and did not evaluate seed production under climate change. Our results showed that formulating DINS for the adjusted agricultural pattern is a powerful strategy for seed and food security and saving agricultural resources. To ensure the stable supply of water and nitrogen under DINS in the future, agricultural infrastructure should be developed, especially by building agricultural reservoirs and upgrading machinery (Wheeler & Lobley, 2021).

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5. Conclusions

With the growing population and food demand throughout the world, food security faces a huge challenge, and sufficient seed supply is essential for crop planting. Seed maize production in the Hexi Corridor maintains more than half of China's field maize cultivation and production, which plays an irreplaceable role in safeguarding national food production in China. This study formulated the DINS for the Hexi Corridor under future climate change based on a combination of a novel irrigation and N fertilization optimization and the APSIM simulation framework. The approach considered spatio-temporal variability of climate and soil properties, actual crop water consumption and N uptake in each growth stage, and interactive sensitivity coefficient of water and N in different growth stages. Based on the optimization results, HSFP scenario is the best strategy, which could save 0.31 km³ irrigation water and 22 thousand tonnes N fertilizer and increase 173 thousand tonnes seed and food production compared with traditional practices per year with a 42.3% increase in WP_I and a 46.7% increase in NUE. WP_I and NUE improving potential under HSFP comes from the phased input ratio during the growth period, that is, sufficient supply in the sensitive stages and appropriate stress in the non-sensitive stages. The optimization-simulation framework developed in this study can be further applied to other crops and other regions around the world facing similar problems.

Data Availability Statement

The China meteorological forcing data set (1979–2018) is provided by National Tibetan Plateau Data Center (https://data.tpdc.ac.cn/en/data/8028b944-daaa-4511-8769-965612652c49).

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