Agricultural Water Management 290 (2023) 108577

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Improving yield, quality, and environmental co-benefits through optimized irrigation and nitrogen management of hybrid maize in Northwest China

Shichao Chen [a,b,c], Wenfeng Liu [a,b,c], Julien Morel [d,e], David Parsons [d], Taisheng Du [a,b,c,*]

[a] State Key Laboratory of Efficient Utilization of Agricultural Water Resources, Beijing 100083, China
[b] National Field Scientiffc Observation and Research Station on Efffcient Water Use of Oasis Agriculture, Wuwei 733009, China
[c] Center for Agricultural Water Research in China, China Agricultural University, Beijing 100083, China
[d] Department of Crop Production Ecology, Swedish University of Agricultural Sciences, Umeå 90183, Sweden
[e] European Commission Joint Research Center, Food Security Unit – D5, Via Fermi 2749, Ispra I-21027, VA, Italy

ARTICLE INFO

Handling Editor: Dr Z Xiying

Keywords:
Hybrid maize
Irrigation and nitrogen optimization
Optimization framework
Seed vigor
Seed yield

ABSTRACT

Seed yield (SY) of hybrid maize tends to be emphasized over seed quality, which collectively determine maize planting and production. The maize seed production in the Hexi Corridor supports more than half of China's maize cultivation, but the shortage of water resources and inefficient agricultural resource use limit high-yield, high-quality, and high-efficient production of hybrid maize. In this study, the Jensen- and Rao-based models were developed for SY and seed vigor (SV) of hybrid maize based on data collected from multi-year field experiments, and found that the heading and filling stages were sensitive to water and nitrogen (N) for SY, and jointing and filling for SV. Building on these insights, a framework was developed to optimize irrigation and N fertilization management under different hydrological years, considering interactive sensitivity coefficients of water and N at different growth stages, precipitation, and initial soil available water and N content. Results showed that the optimized irrigation (22.6–37.8%) and N fertilization inputs (34.1–53.2%) and N-surplus (35.3–60.6%) were significantly decreased and irrigation water productivity (WP_I) and partial factor productivity from applied N fertilization (PFP_N) were significantly increased compared with the current scenario, regardless of whether SV maximization is set in the optimization framework. The optimized scenario that maximizes both SY and SV objectives requires 0.6–8.8% more water and N inputs than the scenario considering only the maximized SY objective in wet, normal, and dry years. The best optimization scenario evaluated by using the osculating value method considering SY and SV, WP_I, PFP_N, and N-surplus varied between different hydrological years. Our optimization framework and findings would guide high-yield, high-quality and high-resource use efficient production of hybrid maize, with low risk of agricultural N pollution in the Hexi Corridor, and has the potential for further use for optimizing irrigation and fertilization management of other crops.

1. Introduction

Maize products are important as human food, animal feed, and industrial feedstock, and their production largely depends on the seed industry of hybrid maize (Jiang et al., 2020). With growing maize demand and cultivation expansion, the seed production of hybrid maize has also greatly increased (Arisnabarreta and Solari, 2017). The cultivation and production of hybrid maize seeds require not only a suitable environment, but also appropriate management and guidance (Bedő and Barnabás, 2013). Hence, many studies have focused on the optimization of management strategies to achieve high yields and water use efficiency (WUE) (Shi et al., 2022; Wang et al., 2020; Wang et al., 2021). Seed vigor (SV) is an important quality indicator for seed production, determining the potential activity and performance of the seed during germination and establishment, which ultimately affect grain yield (Dalil et al., 2010). Production of hybrid maize with high yield, quality, and resource use efficiency is essential for food security and sustainable agricultural development.

China contributes 23% of global maize seed production (Arisnabarreta and Solari, 2017), of which more than 50% of which is produced in the Hexi Corridor of Northwestern China (Chen et al., 2023). Sufficient sunlight and heat resources are suitable for the growth of hybrid

* Corresponding author at: State Key Laboratory of Efficient Utilization of Agricultural Water Resources, Beijing 100083, China.
E-mail address: dutaisheng@cau.edu.cn (T. Du).

https://doi.org/10.1016/j.agwat.2023.108577
Received 30 August 2023; Received in revised form 13 October 2023; Accepted 30 October 2023
Available online 1 November 2023

maize in the Hexi Corridor, but water is a constraint due to strong evaporation and low precipitation (Chen et al., 2021b; Li et al., 2015). Ensuring the seed production of hybrid maize in this region matters for national food security and regional resource utilization. Typically, excess water and nitrogen (N) fertilizer are applied to achieve high seed production, which reduces WUE and N use efficiency (NUE) and increases the risk of N-related pollution (Sapkota et al., 2022; Chen et al., 2020b). High yield and high WUE can be achieved by prioritizing water supply during water-sensitive stages (heading and filling stages) and reducing water supply during non-sensitive stages (seedling and maturity stages) (Chen et al., 2020a). In contrast, seed vigor requires prioritizing water supply during the jointing and filling stages (Guo et al., 2018; Shi et al., 2020). Therefore, the contrasting water-sensitive stages of seed yield (SY) and SV pose a challenge for optimizing irrigation management.

Effects of water and N inputs on SY and SV have been reported in field experiments (Zhou et al., 2016; Wang et al., 2021). Based on this, models have been developed to characterize the effects at different growth stages (Ran et al., 2017; Chen et al., 2023). Shi et al. (2020) and Wang et al. (2020) developed seed vigor production functions to optimize irrigation scheduling without considering N fertilization and water-N interactions. Consequently, how to optimize the N fertilization to improve seed vigor remains largely unclear. Moreover, accurately quantifying the effects of irrigation and N fertilization inputs on SY and SV is crucial for achieving high-yield and high-quality production of hybrid maize seed.

In this study, we developed and evaluated three production function models for SY and SV simulations of hybrid maize, and then selected the model with best performance as the core to establish an optimization framework. The optimization framework considers the effects of initial soil available water and N and can quantitatively describe the effects of sensitivity to water and N interaction in different stages on SY and SV. Irrigation and N fertilization management were simultaneously optimized for SY, SV, WUE, NUE, and N-surplus. Optimization scenarios were evaluated for different regions and hydrological years by using the osculating value method.

2. Materials and methods

2.1. Description of experimental site

The Hexi Corridor (37°17′–42°48′N, 92°12′–104°20′E) is in the arid inland region of Northwestern China. Zhangye city, located in the Heihe River Basin, and Wuwei city, located in the Shiyang River Basin (Fig. 1), are the important hybrid maize planting areas in the Hexi Corridor (Chen et al., 2023). For Wuwei and Zhangye respectively, the climatic data are as follows: annual average temperature 8.8 ℃, 6.6 ℃; accumulated temperature (>0 ℃) 3550 ℃, 3380 ℃; sunshine duration 3000 h, 2975 h; precipitation 164 mm, 197 mm; and pan evaporation 2000 mm, 2002 mm (Chen et al., 2021a; Li et al., 2019).

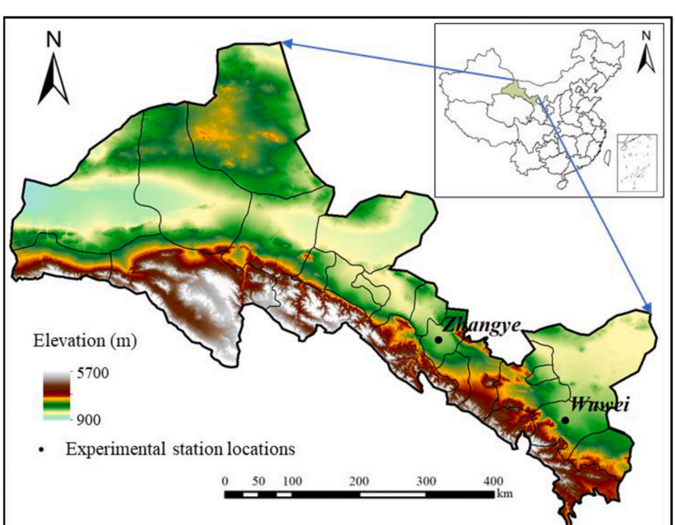

Fig. 1. Digital elevation model (DEM) of the Hexi Corridor and the locations of Zhangye and Wuwei.

2.2. Data collection

In order to establish a water-nitrogen production function of SY and SV, experimental data on water consumption, N uptake, SY, and SV of hybrid maize are necessary. SV indicators can be assessed by a combination of variables, for example germination percentage (GP), germination index (GI), kernel numbers (KN), kernel weight (KW), and pollen viability (PV). We focused on experimental data containing at least 2 variables that can be used for SV evaluation. Based on these criteria, data were obtained from field experiments in Zhangye and Wuwei from 2013 to 2019, and detailed information on the location and period of experiments is shown in Table 1.

Since the number of variables included in the collected measured data that could be assessed for SV may be different, principal component analysis (PCA) was used to re-calculate the SV (Shi et al., 2020; Jiang et al., 2019) based on the collected data rather than using the collected SV data. The eigenvectors and eigenvalues of the covariance matrix of the collected experimental data were calculated. This process constructed a new feature space, projecting the original data onto the eigenvectors to obtain the maximum (d_i^+) and minimum (d_i^-) principal components for each treatment in the collected data. The relative seed vigor (RSV) values corresponding to each treatment were calculated by:

$$RSV_m = \frac{d_m^-}{d_m^+ + d_m^-} \tag{1}$$

where m represents treatment in the collected data.

2.3. Water-nitrogen production functions of seed yield and vigor for hybrid maize

Water production functions describe the relationship between crop yield and water consumption at different growth stages (Chen et al., 2020a; Kipkorir et al., 2002). Fertilization-related factors have been added to establish the relationship between crop yield and crop water and N consumption (Chen et al., 2023; Wang et al., 2021). In this study, we added crop N uptake using the Jensen (Jensen, 1968), Rao (Rao et al., 1988), and Minhas (Minhas et al., 1974) models and selected the model with the best performing simulations. The water-nitrogen production functions of SY and SV for hybrid maize were as follows:

$$\text{Jensenmodel}: RSYorRSV = \prod_{i=1}^{n}\left(\frac{ET_{ai}}{ET_{ci}} \cdot \frac{NU_{ai}}{NU_{mi}}\right)^{\lambda_i} \tag{2}$$

Table 1
Data collected from peer-reviewed published papers on the field experiments of seed maize conducted in Zhangye and Wuwei.

References	Experimental period	Location	Indicators
Shi et al. (2020)	2018–2019	Wuwei	GP, GI, KN, KW
Wang et al. (2019)	2014–2015	Wuwei	KN, KW, PV
Bai (2017)	2016	Wuwei	GP, KN, KW
Lian and Ma (2022)	2016–2017	Zhangye	GP, GI, KW
Zhao et al. (2016)	2013–2014	Wuwei & Zhangye	GP, KW

Note: GP, germination percentage; GI, germination index; KN, kernel numbers; KW, kernel weight; PV, pollen viability.

$$\text{Raomodel}: RSYorRSV = \prod_{i=1}^{n}\left(1-\nu_i\left(1-\frac{ET_{ai}}{ET_{ci}}\cdot\frac{NU_{ai}}{NU_{mi}}\right)\right) \tag{3}$$

$$\text{Minhasmodel}: RSYorRSV = \prod_{i=1}^{n}\left(1-\left(1-\frac{ET_{ai}}{ET_{ci}}\cdot\frac{NU_{ai}}{NU_{mi}}\right)^2\right)^{o_i} \tag{4}$$

where RSY and RSV are relative seed yield and relative seed vigor for hybrid maize, respectively, which are calculated using the actual value (SY_a and SV_a) divided by the maximum value (SY_m and SV_m); 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 in stage *i*, kgN/ha; λ_i, ν_i, and o_i are the interactive sensitivity coefficient of water and N in stage *i* for Jensen, Rao, and Minhas models, respectively. The growth stages are divided into seedling, jointing, heading, filling, and maturity for hybrid maize.

The relationship between SY and SV for hybrid maize and irrigation and N fertilization inputs is established in a nexus of crop consumption of water and N, which requires the characterization of crop consumption of water and N as functions of irrigation, N fertilization, precipitation, and initial available soil available water and N. Based on the results of Chen et al. (2023), the functions of actual crop water consumption (ET_a) and N uptake (NU_a) can be expressed as:

$$ET_{ai} = \begin{cases} I_i + P_i + TAW_{ini} & i = 1 \\ I_i + P_i & i = 2,3,4,5 \end{cases} \qquad NU_{ai} = \mu N_{feri} + \varphi(1-\varphi)^{i-1}N_0 \tag{5}$$

where I_i and P_i are the irrigation and precipitation in stage *i*, respectively, expressed in mm; N_{feri} is N fertilization in stage *i*, expressed in kgN/ha; TAW_{ini} (mm) and N_0 (kgN/ha) are the initial available soil water and N in the 30-cm depth soil layer; μ is the utilization rate of N_{feri} and φ is the utilization rate of N_0, which are set as 0.75 and 0.20 (Mihalache et al., 2019). Based on the observation of TAW_{ini} in Zhangye (Li et al., 2019) and Wuwei (Chen et al., 2020b), 18 mm and 20 mm were set for the optimization of irrigation and N fertilization management for the two regions. The N_0 of Zhangye and Wuwei were set to 105 kgN/ha and 70 kgN/ha, as collected from the Harmonized World Soil Database (HWSD) (Fischer et al., 2008) used in the optimization framework.

The least squares method and sequential quadratic programming were used for calculating the λ_i, ν_i, and o_i for Jensen, Rao, and Minhas models in SPSS (version 20, IBM Corp, Armonk, NY) based on the collected experimental data (shown in Table 1). The collected experimental datasets were divided 1:1 for model calibration and validation. The R^2 and normalized root mean square error (nRMSE) were used to evaluate the performance of the models during calibration and validation. The calibration and validation of the models were performed with the ggplot2 package in R v.4.2.2 (R Core Team, Vienna, Austria).

2.4. Optimization framework of irrigation and N-fertilization management

Genetic algorithm, a powerful and robust global optimization algorithm inspired by natural selection and evolution to find optimal solutions to complex problems (Reca and Martínez, 2006), was used in this study to solve the optimal irrigation and N application schedules. The best performing water and N production functions for the RSY and RSV simulations, irrigation water productivity (WP_I), and partial factor productivity from applied N fertilization (PFP_N) as a group formed the objective functions set:

$$\begin{cases} \max RSY = f_1(I_i, P_i, N_{feri}) \\ \max RSV = f_2(I_i, P_i, N_{feri}) \\ \max WP_I = (RSY\cdot SY_m)\Big/\left(\sum_{i=1}^{n} I_i \times 10\right) \\ \max PFP_N = (RSY\cdot SY_m)\Big/\sum_{i=1}^{n} N_{feri} \end{cases} \tag{6}$$

where I_i, P_i and N_{feri} are the irrigation, precipitation, and N fertilization in stage *i*, respectively; the units of WP_I and PFP_N are kg/m^3 and kg/kgN, respectively. WP_I and PFP_N were used to evaluate the WUE and NUE, respectively.

The constraints of the optimization framework include the irrigation and N fertilization inputs and solubility of the fertilizer in the irrigation water:

$$\begin{cases} I_{\min} \le I_i \le I_{\max} \\ \sum I_{\min} \le \sum I_i \le \sum I_{\max} \\ N_{feri\ \min} \le N_{feri} \le N_{feri\ \max} \\ \sum N_{feri\ \min} \le \sum N_{feri} \le \sum N_{feri\ \max} \\ (N_{feri}/0.46)/I_i \times 10^{-2} \le S \end{cases} \tag{7}$$

where I_{imax} and I_{imin} are maximum and minimum irrigation amount in stage *i*, respectively, mm; $N_{ferimax}$ and $N_{ferimin}$ are maximum and minimum N fertilizer in stage *i*, respectively, kgN/ha; S is the urea solubility and set to 1.05 g/ml (Peng et al., 2016); 0.46 is the N content in urea, and 10^{-2} is the conversion coefficient. In the optimization framework, urea is considered as the source of applied N and is completely dissolved in water when applied to the field. The I_{imax}, I_{imin}, $N_{ferimax}$, $N_{ferimin}$, $\sum I_{imax}$, $\sum I_{imin}$, $\sum N_{ferimax}$, and $\sum N_{ferimin}$ were set to 200 mm, 0 mm, 100 kgN/ha, 0 kgN/ha, 460 mm, 0 mm, 320 kgN/ha, and 0 kgN/ha, respectively, based on data from the Gansu Development Yearbook (https://data.cnki.net/Yearbook/Single/N2022010251) summarized by Chen et al. (2023). Detailed information of the optimization framework is shown in Fig. 2.

Obtaining adequate seed yields was fundamental in practical hybrid maize farming, while seeking better seed vigor on that basis would be a higher production requirement. Therefore, we set one current scenario as a baseline and two optimization scenarios depending on whether SV was used as one of the objective functions: (a) the optimization scenario of achieving synergistic improvement in SY, WP_I and PFP_N as MaxY scenario and (b) the optimization scenario of achieving synergistic improvement in SY, SV, WP_I and PFP_N as MaxYV scenario. Converting multi-objective optimization solutions to a single-objective can prevent conflicts between objectives and save computational costs (Watanabe and Sakakibara, 2005), which we accomplished with the analytic hierarchy process (AHP) method (Zhang et al., 2019) in this study:

$$\begin{aligned} ForMaxY: F &= \omega_1 \times \frac{SY_a}{SY_{max}} + \omega_2 \times \frac{WP_I}{WP_{Imax}} + \omega_3 \times \frac{PFP_N}{PFP_{Nmax}} \\ ForMaxYV: F &= \omega_1 \times \frac{SY_a}{SY_{max}} + \omega_2 \times \frac{SV_a}{SV_{max}} + \omega_3 \times \frac{WP_I}{WP_{Imax}} + \omega_4 \times \frac{PFP_N}{PFP_{Nmax}} \end{aligned} \tag{8}$$

where ω_1, ω_2, ω_3, and ω_4 are the weights of objectives, and the results of judgment matrix and weights are shown in Table 2. Irrigation and N fertilization inputs, SY, and SV in the current scenario are averages of sufficient irrigation and N fertilization treatments (no stress or local practices) from the obtained field experiment data during 2013–2019 (Table 1) as a comparison of the two optimization scenarios. The optimization framework was implemented with the scikit-opt package in Python version 3.7.3.

After optimization, we calculated the N-surplus to evaluate the N budget:

$$N_{sur} = N_{fer} + N_{man} + N_{miner} + N_{dep} - N_Y \tag{9}$$

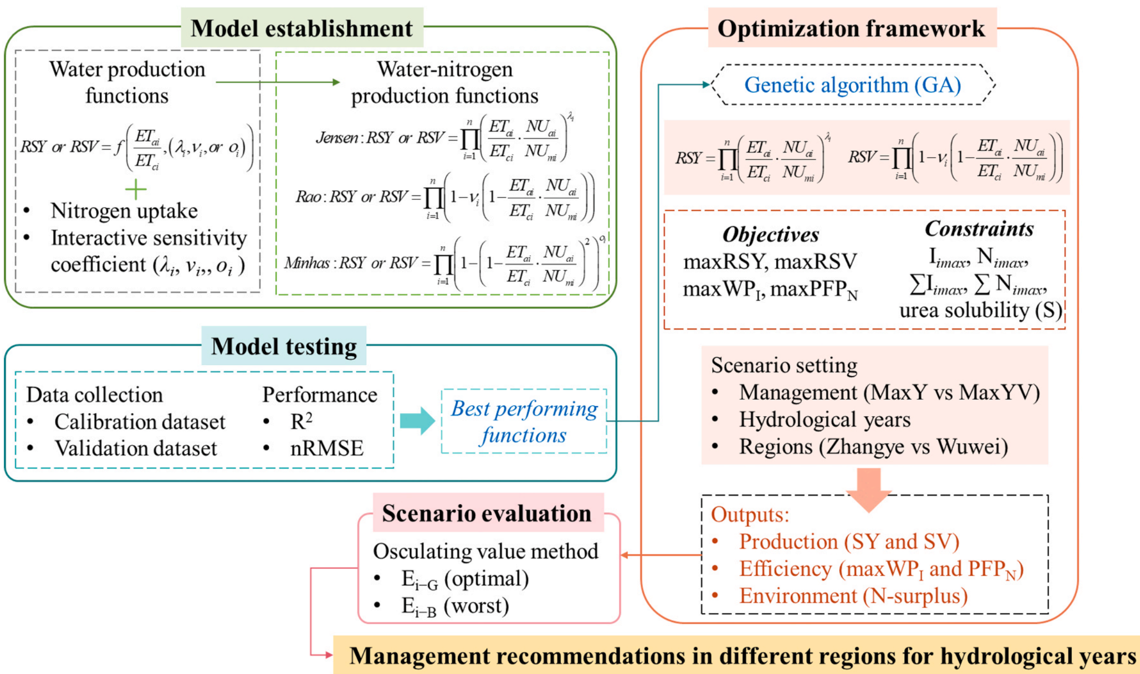

Fig. 2. Optimization framework for seed yield and vigor of hybrid maize in this study.

Table 2
Judgment matrix and weights calculation results under MaxY and MaxYV optimization scenarios by using the analytic hierarchy process (AHP).

MaxY	SY	WP_I	PFP_N	Weights	
SY	1.00	2.00	2.00	0.50	
WP_I	0.50	1.00	1.00	0.25	
PFP_N	0.50	1.00	1.00	0.25	
MaxYV	SY	SV	WP_I	PFP_N	Weights
SY	1.00	1.00	2.00	2.00	0.35
SV	1.00	1.00	1.00	1.00	0.25
WP_I	0.50	1.00	1.00	1.00	0.20
PFP_N	0.50	1.00	1.00	1.00	0.20

Note: SY, seed yield; SV, seed vigor; WP_I, irrigation water productivity; PFP_N, partial factor productivity from applied N fertilization. The MaxY optimization scenario seeks synergistic improvement in SY, WP_I, and PFP_N, whereas the MaxYV scenario also includes SV as an objective.

where N_{fer}, N_{man}, N_{miner}, N_{dep}, and N_Y are N from fertilizer application, manure application, mineralization in the soil, atmospheric deposition, and any part of the crop yield to be removed from the field. In this study, N_{man} was obtained from a 5-arcmin gridded global manure N application dataset (Zhang et al., 2017), N_{dep} was simulated by NCAR Chemistry-Climate Model Initiative (0.5° × 0.5°) obtained from the Inter-Sectoral Impact Model Inter-comparison Project (ISMIP3a) (Tian et al., 2018), and N_{miner} was estimated by dividing the soil organic carbon stock change by the C/N ratio of soil organic carbon (Sanderman et al., 2017). N_Y was calculated by multiplying crop aboveground biomass by crop N concentration, where aboveground biomass was obtained by dividing the simulated crop yields by the harvest index. Harvest index was obtained from Ran et al. (2017) and crop N concentration data was obtained from Chen et al. (2022).

2.5. Hydrological years

The Pearson III probability distribution is a statistical distribution commonly used to model and analyze precipitation data, describing the probability of different precipitation intensities occurring in a given period (Amin et al., 2016). In this study it was used to determine different hydrological years based on 40 years of annual precipitation data from the China Meteorological Administration (1979–2018, https://data.cma.cn). In this study, three hydrological years (precipitation frequency) were determined for Zhangye and Wuwei, based on commonly used classification standards for wet and dry conditions, including wet, normal, and dry years, corresponding to precipitation frequencies of 25%, 50% and 75%, respectively. The precipitation and mean temperature during the hybrid maize growth period were then calculated (Table 3). Growing season and growth stages of hybrid maize were determined using the critical values of 5-day moving average temperature and accumulated growing degree days (Chen et al., 2023).

2.6. Osculating value method

The osculating value method approximates the derivative of a function at a point by fitting a polynomial curve to neighboring data points, and has been confirmed to be useful in assessing the effects of agricultural practices on crop yields (Lou, 2002). The accuracy of the osculating value method depends on the smoothness of the function and the distance of the data points, performing well with close data points but poorly with far ones. Therefore, the optimal (E_{i-G}) and the worst (E_{i-B}) osculating values of a solution (or an indicator) were determined using calculations detailed in Sun et al. (2013). The solution with the lowest E_{i-G} and the highest E_{i-B} was selected as the best solution (Lou, 2002). In this study, we used the osculating value method to evaluate

Table 3
Total precipitation and mean temperature during the growth period of seed maize in different hydrological years in Zhangye and Wuwei.

Station	Variable	Wet year	Normal year	Dry year
Wuwei	Year	1983	2003	1984
	Precipitation (mm)	115	109	85
	Temperature (℃)	19.5	19.2	18.7
Zhangye	Year	1998	2003	1989
	Precipitation (mm)	96	81	63
	Temperature (℃)	17.7	18.8	18.7

Note: Hydrological years included wet, normal, and dry years, which were determined based on precipitation frequency of 25%, 50% and 75% using a Pearson III probability distribution.

optimized irrigation and N fertilization management considering hydrological years, stations, optimized and current scenarios, and the assessment indices included SY, SV, WP_I, PFP_N, and N-surplus. N-surplus was used to evaluate the risk of agri-environmental pollution, WP_I and PFP_N were used to evaluate the agricultural resource use efficiency, and combined with SY and SV (corresponding to yield and quality of hybrid maize) for evaluating co-benefits.

3. Results

3.1. Varied interactive sensitivity coefficients of water and N among growth stages

The interactive sensitivity coefficient of water and N for RSY and RSV differed between growth stages (Table 4). For RSY, high values generally occurred at the heading and filling stages (0.52–0.71), and the low values occurred at the seedling and maturity stages (0.06–0.10) for all models. Thus, RSY of hybrid maize is most sensitive to water and N stress at the heading and filling stages, followed by the jointing stage, and the seedling and maturity stages are the least sensitive. For RSV, high values generally occurred at the jointing and filling stages (0.76–1.01), and the low values occurred at the seedling and maturity stages (0.01–0.07). Thus, RSV is most sensitive to water and N stress at the jointing and filling stages, followed by the heading stage, and seedling and maturity stages.

3.2. Performance of different seed yield and vigor models

Based on the calculated λ_i, ν_i, and o_i for Jensen-, Minhas-, and Rao-based RSY and RSV models, performances of different models were evaluated under different irrigation and N fertilization inputs treatments (Table 5). The performances of the RSY and RSV models differed: for RSY model calibration, the performance of the Jensen model was the best ($R^2 = 0.83$, nRMSE = 21.8%), followed by the Minhas ($R^2 = 0.58$, nRMSE = 23.3%) and Rao ($R^2 = 0.52$, nRMSE = 26.4%) models. For RSV model calibration, the performance of the Rao model was the best ($R^2 = 0.67$, nRMSE = 18.9%), followed by the Minhas ($R^2 = 0.52$, nRMSE = 22.2%) and Jensen ($R^2 = 0.50$, nRMSE = 22.4%) models (Fig. 3). The ranking of model performances was comparatively similar for validation, i.e., the best performances for RSY and RSV simulations were Jensen- and Rao-based models, respectively, while the Minhas-based model had the worst performance for RSY and RSV validation under different irrigation and N fertilization inputs treatments (Fig. 4). Based on the SY and SV performance under different irrigation and N fertilization inputs, we found that the data points with the highest SY or SV (position) did not correspond to the highest irrigation (largest size) and N fertilization inputs (darkest color) (Figs. 3 and 4).

Table 4
Calculation of the interactive sensitivity coefficient of water and N for relative seed yield (RSY) and relative seed vigor (RSV) in different growth stages for Jensen- (λ_i), Minhas- (ν_i), and Rao-based (o_i) models.

Simulated variable	Model	Interactive sensitivity coefficient of water and N				
		S1	S2	S3	S4	S5
RSY	Jensen	0.09	0.67	0.70	0.71	0.08
	Minhas	0.06	0.50	0.52	0.52	0.06
	Rao	0.10	0.63	0.69	0.70	0.07
RSV	Jensen	0.01	0.76	0.59	0.87	0.06
	Minhas	0.01	0.76	0.60	0.92	0.07
	Rao	0.01	0.81	0.61	1.01	0.06

Note: RSY, relative seed yield; RSV, relative seed vigor. S1 to S5 represent seedling, jointing, heading, filling, and maturity stages, respectively.

3.3. Optimization of irrigation and N fertilization in different hydrological years

The optimized level of irrigation and N fertilization inputs for the RSY improvement scenario (MaxY) was lower than for the synergetic RSY and RSV improvement scenario (MaxYV) (0.6–3.2% for irrigation and 1.3–8.8% for N fertilization) in different hydrological years in Zhangye and Wuwei (Fig. 5). The proportion of irrigation in the MaxYV optimization scenario was usually higher than that of the MaxY at the jointing and filling stages, except for the wet year in Zhangye and the normal year in Wuwei. This pattern was not obvious for the optimized N fertilization at all stages between MaxY and MaxYV scenarios. For the MaxY optimization scenario, the proportion of irrigation at the heading stage (33.5–37.6%) and the proportion of N fertilization at the filling stage were the largest (33.2–36.7%) among growth stages. However, for the MaxYV optimization scenario, the highest proportion of irrigation (30.5–41.3%) and N fertilization (28.9–39.1%) occurred at either the jointing or the filling stage, varying with different hydrological years. The proportion of irrigation at the jointing stage exceeded that at the filling stage in the wet year in Zhangye, while in normal and dry years it was lower than that at the filling stage in both Zhangye and Wuwei (also in the wet year in Wuwei).

The optimized irrigation and N fertilization inputs varied in different hydrological years. Generally, the lowest requirements occurred in wet years (298–315 mm and 159–188 kgN/ha for irrigation and N fertilization, respectively) and the highest in dry years (343–364 mm and 181–196 kgN/ha, respectively) (Table 5). Compared with the current scenario, irrigation and N fertilization inputs could be reduced by 22.6–37.8% and 34.1–53.2% under the two optimization scenarios (MaxY and MaxYV). Under the same hydrological year, 0.6–3.2% more irrigation water and 1.3–8.8% more N fertilization were applied for the MaxYV scenario than the MaxY scenario. SY, WP_I, and PFP_N were 1.2–3.6%, 2.0–5.0%, and 3.8–10% lower for the MaxYV scenario than for the MaxY scenario, respectively, while the SV and N-surplus were 7.7–14.5% and 7.1–14.2% higher, respectively. The osculating value method considered SY, SV, WP_I, PFP_N, and N-surplus, with $E_{i\text{-}G}$ and $E_{i\text{-}B}$ representing the optimal and worst osculating values for evaluating the co-benefits of production, resource use efficiency, and environment from different scenarios, respectively (Table 5). Results showed that MaxYV in wet years and MaxY in dry years were better scenarios in both Zhangye and Wuwei regions (Table 5). However, in normal years, MaxY in Zhangye and MaxYV in Wuwei were better scenarios.

4. Discussion

4.1. Key measures to improve seed yield and vigor in hybrid maize production

Previous studies have reported that water and N supply at the heading and filling stages are essential to ensure SY (Chen et al., 2023; Wu et al., 2022), and water status at the jointing and filling stages have a strong influence on SV of hybrid maize (Shi et al., 2020), which is consistent with our findings. We further clarify that the order of influence of different stages on SY of hybrid maize is filling, heading, and jointing stage; whereas for SV it is at the filling, jointing, and heading stage, considering the response of each growth stage to water and N interactions. Mechanistically, sufficient water and N contribute to the development of a strong root system and canopy (during the vegetative growth stage, especially the jointing stage), which enables the plant to obtain the water and nutrients needed for growth and maintain good photosynthesis in subsequent growth stages (Su et al., 2020; Li et al., 2018). Water and N supplies during the heading stage are critical for pollen vigor and pollination, which consequently affect cob size and seed grain establishment (Cheng et al., 2021; Liu et al., 2023). During the filling stage, water or N stress can limit the flow of nutrients from source (leaves and stems) to sink (grains) and the accumulation of

Table 5
Seed yield (SY), seed vigor (SV), irrigation water productivity (WP_I), partial factor productivity from applied N fertilization (PFP_N), and variables from osculating value method under different scenarios for hydrological years in Zhangye and Wuwei.

Stations	Hydrological years	Optimization scenarios	SY (kg/ha)	SV	WP_I (kg/m^3)	PFP_N (kg/kgN)	N-surplus (kgN/ha)	$E_{i\text{-}G}$	$E_{i\text{-}B}$
Zhangye	Wet year	MaxY	7523	0.91	2.42	47.3	107.5	0.03	0.59
		MaxYV	7251	0.98	2.30	45.0	120.6	0.02	0.60
	Normal year	MaxY	7141	0.89	1.97	39.5	145.1	0.14	0.47
		MaxYV	7027	0.97	1.93	37.6	155.7	0.15	0.46
	Dry year	MaxY	7050	0.85	1.94	39.0	148.8	0.16	0.46
		MaxYV	6922	0.96	1.86	35.1	170.0	0.19	0.42
	—	Current	7900	0.70	1.58	23.2	273.1	0.60	0.03
Wuwei	Wet year	MaxY	7683	0.92	2.58	41.8	126.0	0.03	0.39
		MaxYV	7561	1.00	2.51	40.2	135.0	0.02	0.40
	Normal year	MaxY	7664	0.86	2.23	40.6	131.8	0.09	0.35
		MaxYV	7571	0.98	2.17	38.6	142.6	0.08	0.36
	Dry year	MaxY	7413	0.83	2.15	37.8	149.0	0.12	0.31
		MaxYV	7290	0.95	2.05	34.5	169.0	0.15	0.27
	—	Current	7700	0.70	1.67	24.1	261.3	0.41	0.02

Note: $E_{i\text{-}G}$, the optimal osculating value; $E_{i\text{-}B}$, the worst osculating value. Irrigation and N fertilization under MaxY, MaxYV, and current scenarios are shown in Fig. 5.

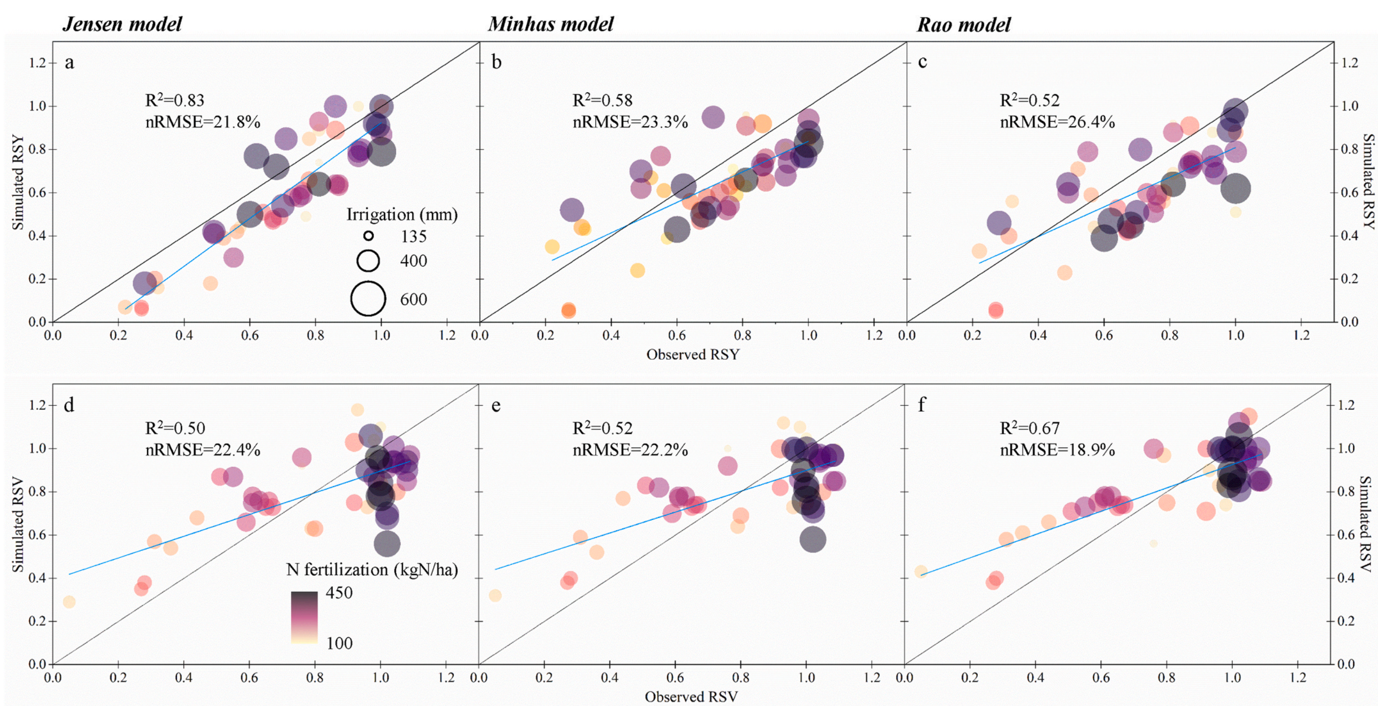

Fig. 3. Calibration of Jensen-, Minhas-, and Rao-based models to estimate relative seed yield (RSY) (top) and relative seed vigor (RSV) (bottom) of hybrid maize under different irrigation and N fertilization inputs. The size of the circle indicates the amount of irrigation corresponding to RSY or RSV, and the color indicates the amount of N fertilization. The solid blue line is a linear regression and the solid black line is a 1:1 line.

nutrients (e.g., starch and protein) in the grains, leading to a reduction in grain yield and quality (Butts-Wilmsmeyer et al., 2019; Su et al., 2020). Practically, excessive N fertilization at the initial stage leads to N losses, whereas applying optimal N at mid- and late-growth stages can significantly improve yield, nutrient accumulation, and NUE in maize (Dathe et al., 2016; Hou et al., 2022). Effects of irrigation on maize yield begin at the jointing stage and water deficit during the filling stage leads to 10–20% yield reduction (Li et al., 2018), while water stress at the vegetative or the maturation stage can increase WUE with minimum yield reductions (Ha, 2017). Moderate deficit irrigation favors higher nutrient yields by increasing nutrient concentrations even with the small risk of yield reduction (Hussain et al., 2020; Kresović et al., 2018). Similar trade-offs exist for SY and SV of hybrid maize (Wang et al., 2020; Guo et al., 2018). Therefore, synergistic improvement of SY and SV with high water and N use efficiency requires balancing water and N supplies at different growth stages.

Compared to the current scenario, the proportion of optimized irrigation and N fertilization inputs at the filling stage to the total inputs in the growing season increased in Zhangye and Wuwei, and a similar situation was observed for optimized irrigation at the heading stage and optimized N fertilization at the jointing stage. However, the optimized proportion of N fertilization at the heading stage was lower than the current scenario (Fig. 5), indicating that N fertilization reductions during this stage had a less pronounced effect on yield and quality, similar to the results of the field experiments reported by Hammad et al. (2011) and Scharf et al. (2002). Sufficient supply and adjustment of irrigation and N fertilization during the critical growth stages of hybrid maize could achieve the improvement of yield, quality, and agricultural resource use efficiency (Table 5), rather than the one-sided pursuit of a single goal of high-yield, high-quality, or high-resource use efficiency.

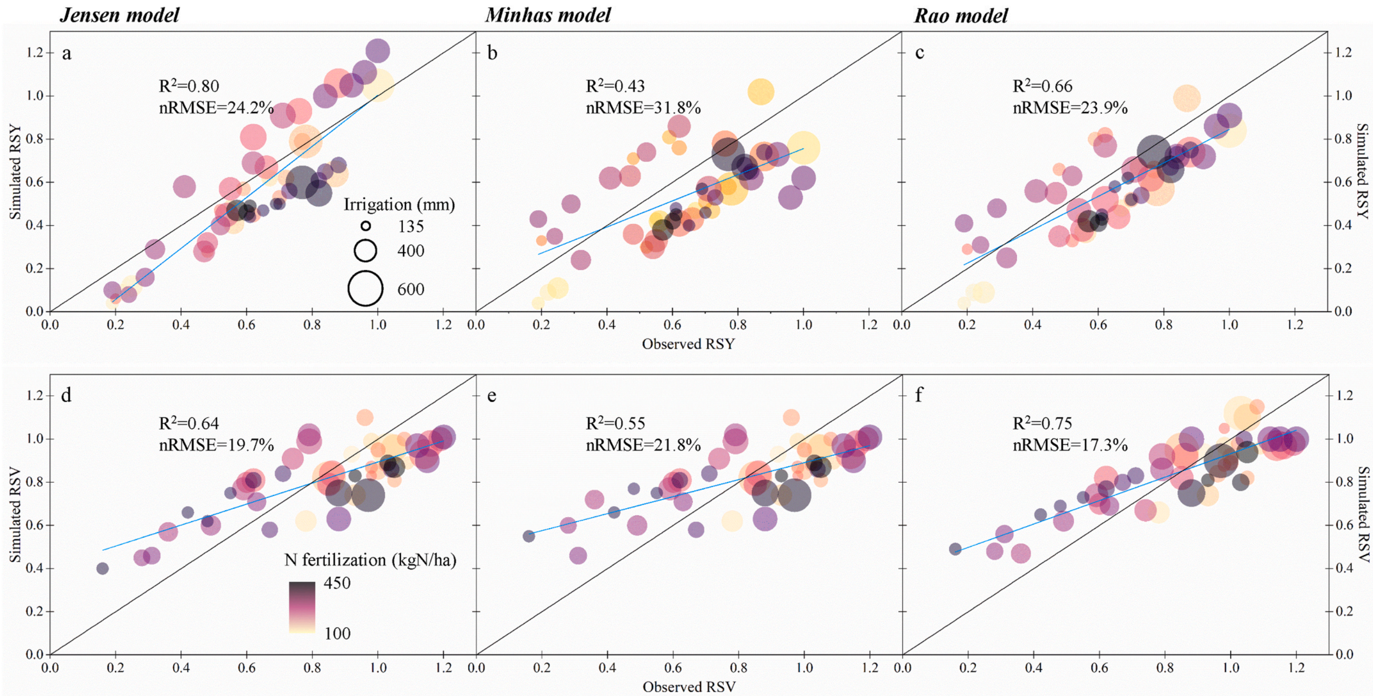

Fig. 4. Validation of Jensen-, Minhas-, and Rao-based models to estimate relative seed yield (RSY) (top) and relative seed vigor (RSV) (bottom) of hybrid maize under different irrigation and N fertilization inputs. The size of the circle indicates the amount of irrigation corresponding to RSY or RSV, and the color indicates the amount of N fertilization. The solid blue line is a linear regression and the solid black line is a 1:1 line.

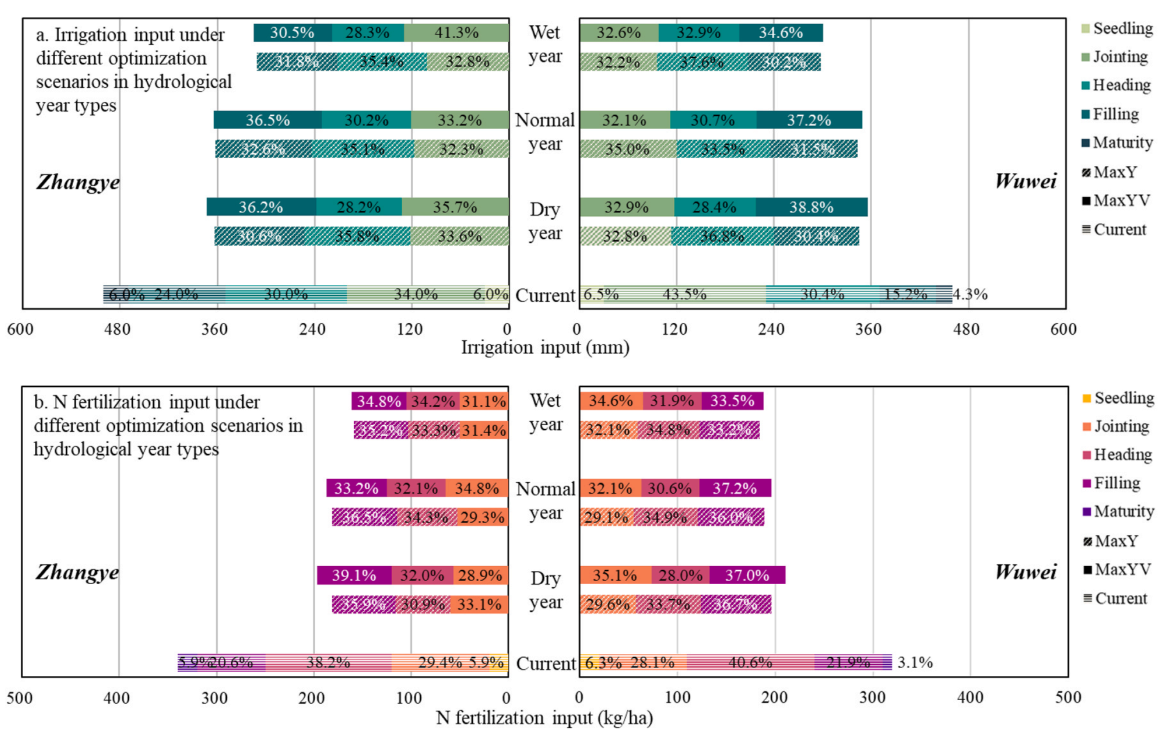

Fig. 5. Optimization of irrigation (top) and N fertilization (bottom) of hybrid maize in different hydrological years (wet, normal, and dry years), compared with the current status (horizontal fill). MaxY (diagonal fill) represents the optimization scenario of achieving synergistic improvement in seed yield (SY), irrigation water productivity (WP_I) and partial factor productivity from applied N fertilization (PFP_N), while MaxYV (solid fill) represents the optimization scenario of achieving synergistic improvement in SY, seed vigor (SV), WP_I and PFP_N. Values (%) indicate the irrigation or N fertilization inputs at stage *i* as a proportion of the total growth period. Different colors in the two ribbons represent growth stages.

4.2. Strategies for synergistically improving seed yield and vigor of hybrid maize

Previous field experiments and regional simulations on hybrid maize have focused on the optimization of high-yield and high-efficient management (Chen et al., 2020a; Guo et al., 2018; Hong et al., 2019), and a few studies have observed and simulated SV under different irrigation and N fertilization management (Shi et al., 2020; Wang et al., 2020; Lian and Ma, 2022). However, studies involving integrated effects of water and N on SV or aiming to achieve synergistic improvement of SY, SV, and agricultural resource use efficiency for hybrid maize have rarely been reported. The optimized irrigation and N fertilization strategies and the corresponding SY and SV in this study varied among hydrological years (Fig. 5 and Table 5), which were related to temperature and precipitation. Temperature and precipitation were taken into account in the optimization framework (Section 2.3), in which the length and process of crop growth was directly affected by temperature (Chen et al., 2023; Zabel et al., 2021), resulting in differences in irrigation and N fertilization optimization results in wet, normal, and dry years. The optimized irrigation and N fertilization inputs are usually highest in dry years and lowest in wet years, but are independent of the variation of the proportion of inputs in different stages over the hydrological years (Table 5 and Fig. 5).

The MaxYV and MaxY optimization scenarios had lower irrigation and N fertilization inputs than the current scenario (Fig. 5 and Table 5), while MaxYV used slightly more irrigation and N fertilization than MaxY. Shi et al. (2022) optimized the irrigation schedule with the objectives of maximizing SY and minimizing irrigation inputs and showed that the optimal proportion of irrigation at the jointing, heading, and filling stages were 19.8%, 35.0%, and 45.2%, respectively, when the SV was greater than 0.8. However, the MaxYV optimization scenario in this study suggested a higher proportion of irrigation at the jointing stage and a lower proportion at the heading and filling stages, which was related to the calculated interactive sensitivity coefficient of water and N (Table 4) and the maximum SV as one of the objective functions with high weight (0.25).

More water and N inputs are required to improve SV and ensure SY, which is consistent with field measurements (Lian and Ma, 2022; Zhao et al., 2016). Excessive fertilization can cause serious environment problems by leading to water, soil and air pollution (Ghaly and Ramakrishnan, 2015). Precision fertilization (Rogovska et al., 2019) and new fertilizer development (Zulfiqar et al., 2019) can improve the co-benefits of yield production, resource use efficiency, and environment. Both MaxY and MaxYV in this study were in the category of precision fertilization, which controlled the fertilization application at both temporal (growth stages) and spatial (region) scales. The N surpluses under MaxYV (120.6–170.0 kgN/ha), although higher than MaxY (107.5–149.0 kgN/ha), are significantly lower than the current scenario for Northwestern China (around 200 kgN/ha, Sapkota et al., 2022), reducing the risk of environmental pollution.

4.3. Importance of including seed vigor for optimization

Attention should be paid to crop quality, and should not be restricted to yield improvement (Liu et al., 2021; Zhou et al., 2020). SV is an important quality characteristic for hybrid maize and affects the growth and yield of the crop (Dalil et al., 2010; Shi et al., 2020). In this study, although the SY in Zhangye and Wuwei under the MaxYV scenario decreased by 171 and 113 kg/ha (−2.3% and −1.5%), respectively, over the MaxY scenario, SV increased by 0.09 and 0.11 (+9.9% and 12.4%), respectively (Table 5), which could improve growth and high-quality yields of the subsequent crop. SYs in the current scenario in Zhangye and Wuwei that were slightly higher (average 458 kg/ha) than the two optimization scenarios came from excessive water and N inputs, which reduced water and N use efficiency (expressed by WP_I and PFP_N in this study) and did not result in good vigor. SV should be improved while maintaining SY and reducing waste of agricultural resources and risk of agro-environmental pollution. Therefore, focusing on maximizing both SV and SY, can be beneficial in the long term, with regard to the co-benefits of productivity and environmental impacts.

4.4. Limitations and outlooks

The production function model developed in this study was static (Chen et al., 2020a). Dynamic models for describing physiological processes and mechanisms associated with SV should be further explored. This would require more field experiments and laboratory testing of SV of hybrid maize. Climatic characteristics of historical hydrological years cannot cover the uncertainty of future climate change, which has unknown potential impacts on SY and SV. The economic benefits and breeding of new cultivars should be considered in the future optimization framework to practically guide development of the seed industry.

5. Conclusion

The developed Jensen- and Rao-based models were the best performing models for simulating SY and SV of hybrid maize, respectively. We found that SY was strongly influenced by water and N status at the heading and filling stages, and SV was strongly influenced by water and N status at jointing and filling stages. Optimization under the MaxYV scenario required 3.1% more water and N input than the MaxY scenario to ensure high-level SV. The proportions of irrigation and N fertilization inputs in different stages varied between the two optimization scenarios, which were associated with inconsistent water and N sensitive stages of SY and SV. Optimized management scenarios were evaluated using the osculating value method, which indicated that MaxYV should be implemented in wet years and MaxY should be implemented in dry years. Optimized management options in normal years varied by region. The best optimized scenario consistently outperformed the current scenario in terms of SV, WP_I, PFP_N, and N-surplus, but with a slight SY reduction. Results from this study can provide guidance for the management of high yield quality for irrigated hybrid maize production in the Hexi Corridor and globally in climatically similar regions, and the optimization framework proposed can be further applied to the synergistic improvement of yield and quality for other crops.

CRediT authorship contribution statement

Shichao Chen: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft. **Wenfeng Liu**: Conceptualization, Methodology, Writing – review & editing. **Julien Morel**: Visualization, Writing – review & editing. **David Parsons**: Methodology, Writing – review & editing. **Taisheng Du**: Conceptualization, Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Acknowledgments

This work was partially supported by National Natural Science Foundation of China (52209072, 52239002, 52109071), the International Postdoctoral Exchange Fellowship Program (No. PC2022063), and the National Key R&D Program of China (No. 2022YFD1900503).

References

Amin, M.T., Rizwan, M., Alazba, A.A., 2016. A best-fit probability distribution for the estimation of rainfall in northern regions of Pakistan. Open Life Sci. 1, 432–440.

Arisnabarreta, S., Solari, F., 2017. Hybrid maize seed production yield associations with inbred line performance in multienvironment trials. Crop Sci. 6, 3203–3216.

Bai, X., 2017. Effects of Density and Water Deficit on the Growth and Yield of Seed Maize in an Arid Region of Northwest China. China Agricultural University, China Dissertation for Master degree, (in Chinese with English abstract).

Bedő, Z., Barnabás, B., 2013. 60 Years of Hungarian Hybrid Maize 1953–2013, Pannonian Plant Biotechnology Association, Martonvásár, Hungary.

Butts-Wilmsmeyer, C.J., Seebauer, J.R., Singleton, L., Below, F.E., 2019. Weather during key growth stages explains grain quality and yield of maize. Agronomy 1, 16.

Chen, S., Parsons, D., Du, T., Kumar, U., Wang, S., 2021b. Simulation of yield and water balance using WHCNS and APSIM combined with geostatistics across a heterogeneous field. Agric. Water Manag., 107174

Chen, S., Liu, W., Yan, Z., Morel, J., Parsons, D., Du, T., 2023. Adaptation strategy can ensure seed and food production with improving water and nitrogen use efficiency under climate change. Earth'S. Future 2, 1–16.

Chen, S., Wang, S., Shukla, M.K., Wu, D., Guo, X., Li, D., Du, T., 2020a. Delineation of management zones and optimization of irrigation scheduling to improve irrigation water productivity and revenue in a farmland of Northwest China. Precis. Agric. 3, 655–677.

Chen, S., Du, T., Wang, S., Parsons, D., Wu, D., Guo, X., Li, D., 2020b. Evaluation and simulation of spatial variability of soil property effects on deep percolation and nitrate leaching within a large-scale field in arid Northwest China. Sci. Total Environ., 139324

Chen, S., Du, T., Wang, S., Parsons, D., Wu, D., Guo, X., Li, D., 2021a. Quantifying the effects of spatial-temporal variability of soil properties on crop growth in management zones within an irrigated maize field in Northwest China. Agric. Water Manag., 106535

Cheng, M., Wang, H., Fan, J., Zhang, F., Wang, X., 2021. Effects of soil water deficit at different growth stages on maize growth, yield, and water use efficiency under alternate partial root-zone irrigation. Water 2, 148.

Dalil, B., Ghassemi-Golezani, K., Moghaddam, M., Raey, Y., 2010. Effects of seed viability and water supply on leaf chlorophyll content and grain yield of maize *(Zea mays)*. J. Food Agric. Environ. 3&4, 399–402.

Dathe, A., Postma, J.A., Postma-Blaauw, M.B., Lynch, J.P., 2016. Impact of axial root growth angles on nitrogen acquisition in maize depends on environmental conditions. Ann. Bot. 401–414.

Fischer, G., Shah, M., van Velthuizen, H., Nachtergaele, F., 2008. Global Agro-ecological Zones Assessment for Agriculture (GAEZ 2008). FAO, Rome, Italy.

Ghaly, A.E., Ramakrishnan, V.V., 2015. Nitrogen sources and cycling in the ecosystem and its role in air, water and soil pollution: A critical review. J. Pollut. Eff. Control 3 (2), 1–26.

Guo, S., Wang, J., Zhang, F., Wang, Y., Guo, P., 2018. An integrated water-saving and quality-guarantee uncertain programming approach for the optimal irrigation scheduling of seed maize in arid regions. Water 7, 908.

Ha, B.M., 2017. A review of growth stage deficit irrigation effecting sticky maize production. Geosci. Eng. 2, 13–18.

Hammad, H.M., Ahmad, A., Wajid, A., Akhter, J.A.V.A., 2011. Maize response to time and rate of nitrogen application. Pak. J. Bot. 4, 1935–1942.

Hong, Y., Berentsen, P., Heerink, N., Shi, M., van der Werf, W., 2019. The future of intercropping under growing resource scarcity and declining grain prices - A model analysis based on a case study in Northwest China. Agric. Syst., 102661

Hou, Y., Xu, X., Kong, L., Zhang, L., Zhang, Y., Liu, Z., 2022. Improving nitrogen contribution in maize post-tasseling using optimum management under mulch drip irrigation in the semiarid region of Northeast China. Front. Plant Sci.

Hussain, S., Maqsood, M., Ijaz, M., Ul-Allah, S., Sattar, A., Sher, A., Nawaz, A., 2020. Combined application of potassium and zinc improves water relations, stay green, irrigation water use efficiency, and grain quality of maize under drought stress. J. Plant Nutr. 14, 2214–2225.

Jensen, M.E., 1968. Water Consumption by Agricultural Plants. Academic Press, New York, USA.

Jiang, X., Zhao, Y., Tong, L., Wang, R., Zhao, S., 2019. Quantitative analysis of tomato yield and comprehensive fruit quality in response to deficit irrigation at different growth stages. HortScience 8, 1409–1417.

Jiang, Z., Liu, C., Ganapathysubramanian, B., Hayes, D.J., Sarkar, S., 2020. Predicting county-scale maize yields with publicly available data. Sci. Rep. 1.

Kipkorir, E.C., Raes, D., Massawe, B., 2002. Seasonal water production functions and yield response factors for maize and onion in Perkerra, Kenya. Agric. Water Manag. 3, 229–240.

Kresović, B., Gajić, B., Tapanarova, A., Dugalić, G., 2018. How irrigation water affects the yieldand nutritional quality of maize (Zea mays L.) in a temperate climate. Pol. J. Environ. Stud. 3, 1123–1131.

Li, D., Du, T., Cao, Y., Kumar Shukla, M., Wu, D., Guo, X., Chen, S., 2019. Quantitative analysis of irrigation water productivity in the middle reaches of Heihe River Basin, Northwest China. Int. J. Agric. Biol. Eng. 5, 119–125.

Li, S., Kang, S., Zhang, L., Du, T., Tong, L., Ding, R., Guo, W., Zhao, P., Chen, X., Xiao, H., 2015. Ecosystem water use efficiency for a sparse vineyard in arid northwest China. Agric. Water Manag. 148, 24–33.

Li, Y., Tao, H., Zhang, B., Huang, S., Wang, P., 2018. Timing of Water Deficit Limits Maize Kernel Setting in Association With Changes in the Source-Flow-Sink Relationship. Front. Plant Sci.

Lian, C., Ma, Z., 2022. Effects of Coupling of Irrigation and Nitrogen Application as Well as Planting Density on Yield and Seed Vigor of Seed Maize Under Ridge Mulching-furrow Irrigation Pattern. Water Sav. Irrig. 1, 31–35.

Liu, L., Sadras, V.O., Xu, J., Hu, C., Yang, X., Zhang, S., 2021. Genetic improvement of crop yield, grain protein and nitrogen use efficiency of wheat, rice and maize in China. Adv. Agron. 203–252.

Liu, P., Yin, B., Gu, L., Zhang, S., Ren, J., Wang, Y., Duan, W., Zhen, W., 2023. Heat stress affects tassel development and reduces the kernel number of summer maize. Front. Plant Sci.

Lou, W., 2002. Comprehensive assessment of agricultural economic projects using osculating method. Syst. Sci. Compr. Stud. Agric. 2, 92–95.

Mihalache, D., Vrînceanu, N., Teodorescu, R.I., Mihalache, M., Bacau, C., 2019. Evaluation of the effect of 15N-labeled fertilizers on maize plant. Rom. Biotechnol. Lett. 1, 193–199.

Minhas, B.S., Parikh, K.S., Srinivasan, T.N., 1974. Toward the structure of a production function for wheat yields with dated inputs of irrigation water. Water Resour. Res. 3, 383–393.

Peng, Q., Wang, P., Ye, S., Tao, J., Luo, X., 2016. Research on metastable zone width of urea crystallization. Chem. Equipment Technol. 37 (6), 18–21.

Ran, H., Kang, S., Li, F., Du, T., Ding, R., Li, S., Tong, L., 2017. Responses of water productivity to irrigation and N supply for hybrid maize seed production in an arid region of Northwest China. J. Arid Land 4, 504–514.

Rao, N.H., Sarma, P.B.S., Chander, S., 1988. A simple dated water-production function for use in irrigated agriculture. Agric. Water Manag. 1, 25–32.

Reca, J., Martínez, J., 2006. Genetic algorithms for the design of looped irrigation water distribution networks. Water Resour. Res. 5.

Rogovska, N., Laird, D.A., Chiou, C.P., Bond, L.J., 2019. Development of field mobile soil nitrate sensor technology to facilitate precision fertilizer management. Precis. Agric. 20, 40–55.

Sapkota, T.B., Singh, B., Takele, R., 2022. Improving nitrogen use efficiency and reducing nitrogen surplus through best fertilizer nitrogen management in cereal production: The case of India and China. Adv. Agron. https://doi.org/10.1016/bs.agron.2022.11.006.

Scharf, P.C., Wiebold, W.J., Journal, J.A.L., 2002. Corn yield response to nitrogen fertilizer timing and deficiency level. Agron. J. 3, 435–441.

Shi, R., Tong, L., Du, T., Shukla, M.K., 2020. Response and modeling of hybrid maize seed vigor to water deficit at different growth stages. Water 11, 3289.

Shi, R., Wang, J., Tong, L., Du, T., Shukla, M.K., Jiang, X., Li, D., Qin, Y., He, L., Bai, X., Guo, X., 2022. Optimizing planting density and irrigation depth of hybrid maize seed production under limited water availability. Agric. Water Manag., 107759

Su, W., Ahmad, S., Ahmad, I., Han, Q., 2020. Nitrogen fertilization affects maize grain yield through regulating nitrogen uptake, radiation and water use efficiency, photosynthesis and root distribution. PeerJ, e10291.

Sun, Y., Hu, K., Fan, Z., Wei, Y., Lin, S., Wang, J., 2013. Simulating the fate of nitrogen and optimizing water and nitrogen management of greenhouse tomato in North China using the EU-Rotate_N model. Agric. Water Manag. 72–84.

Tian, H., Yang, J., Lu, C., Xu, R., Canadell, J.G., Jackson, R.B., Arneth, A., Chang, J., Chen, G., Ciais, P., Gerber, S., Ito, A., Huang, Y., Joos, F., Lienert, S., Messina, P., Olin, S., Pan, S., Peng, C., Saikawa, E., Thompson, R.L., Vuichard, N., Winiwarter, W., Zaehle, S., Zhang, B., Zhang, K., Zhu, Q., 2018. The global N2O model intercomparison project. Bull Am Meteorol Soc. 99 (6), 1231–1252.

Wang, J., Guo, S., Kang, S., Wang, Y., Du, T., Tong, L., 2020. Joint optimization of irrigation and planting pattern to guarantee seed quality, maximize yield, and save water in hybrid maize seed production. Eur. J. Agron., 125970

Wang, Y., Kang, S., Li, F., Zhang, X., 2021. Modified water-nitrogen productivity function based on response of water sensitive index to nitrogen for hybrid maize under drip fertigation. Agric. Water Manag., 106566

Watanabe, S., Sakakibara, K., 2005. Multi-objective approaches in a single-objective optimization environment. 2005 IEEE Congr. Evolut. Comput. 2, 1714–1721.

Wu, H., Yue, Q., Guo, P., Xu, X., Huang, X., 2022. Improving the AquaCrop model to achieve direct simulation of evapotranspiration under nitrogen stress and joint simulation-optimization of irrigation and fertilizer schedules. Agric. Water Manag., 107599

Zabel, F., Müller, C., Elliott, J., Minoli, S., Jägermeyr, J., Schneider, J.M., Franke, J.A., Moyer, E., Dury, M., Francois, L., Folberth, C., Liu, W., Pugh, T.A.M., Olin, S., Rabin, S.S., Mauser, W., Hank, T., Ruane, A.C., Asseng, S., 2021. Large potential for crop production adaptation depends on available future varieties. Glob. Change Biol. 16, 3870–3882.

Zhang, F., Guo, P., Engel, B.A., Guo, S., Zhang, C., Tang, Y., 2019. Planning seasonal irrigation water allocation based on an interval multiobjective multi-stage stochastic programming approach. Agric. Water Manag., 105692

Zhao, J., Fan, T., Wang, S., Wang, J., Sun, J., Li, W.Q., Wang, H., 2016. Effect of nitrogen and irrigation on yield, water and nitrogen use efficiency of corn seed production in Hexi Area in China. J. Nucl. Agric. Sci. 30, 997–1004.

Zhou, H., Chen, J., Wang, F., Li, X., Génard, M., Kang, S., 2020. An integrated irrigation strategy for water-saving and quality-improving of cash crops: theory and practice in China. Agric. Water Manag., 106331

Zhou, Q., Wang, F.X., Zhao, Y., Yang, K., Zhang, Y., 2016. Influence of water and nitrogen management and planting density on seed maize growth under drip irrigation with mulch in arid region of Northwest China. Chin. Agric. Sci. Bull. 21, 166–173.

Zulfiqar, F., Navarro, M., Ashraf, M., Akram, N.A., Munné-Bosch, S., 2019. Nanofertilizer use for sustainable agriculture: advantages and limitations. Plant Sci. 289, 110270.