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ORIGINAL ARTICLE

Modeling crop yield and nitrogen use efficiency in wheat and maize production systems under future climate change

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Abstract In the face of global climate change, changes in nitrogen use efficiency (NUE) have not been widely considered to affect agricultural productivity. A modeling study was conducted to assess the impacts of future climates on crop yields and NUE in two wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) rotation systems and one continuous maize system in northern China. Specifically, the process-based SPACSYS model was used to predict crop yields and NUE by 2100, under four climate scenarios (Baseline, RCP2.6, RCP4.5 and RCP8.5). The model was validated using data from three long-term experiments, each of which included four fertilization practices typical of the regions: non-fertilizer, combined mineral N, phosphorus (P) and potassium (K) (NPK), NPK plus manure and NPK plus straw. Validation showed SPACSYS well-simulated crop yields and N uptake (R^2: 0.41–0.96; RMSE: 6–18%; and EF: 0.41–0.93). Under future climate change, the model predicted changes in maize yield by − 30.69% and 5.98% in northwestern and northeastern China, respectively, and wheat yield by − 16.37% in northwestern China. Future climates would cause greater NUE reductions in the northwest (wheat: 42.79%; maize: 33.73%) than in the northeast (maize: 3.97%) with smaller decreases in crop N uptake and N loss. Furthermore, manure application had higher crop NUEs (wheat: 6.66–31.27%; maize: 23.82–68.19%) and N uptakes than other treatments under future climate change. The results demonstrated the risks of future climate changes on crop yield and NUE in the study regions and can also help target fertilization practices for effectively mitigating climate change.

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Introduction

Today, annual nitrogen (N) fertilizer consumption has reached 100 million tons worldwide, which is almost tenfold more than the consumption in 1960s (Anbessa and Juskiw 2012). In both developed and developing countries, excessive N application is a common practice by farmers to "insure" high crop yields. In these countries, N fertilizer rates have increased by 166–2274% in past five decades (Raza et al. 2018). However, N fertilizers cannot continue increasing crop yields significantly in today's agricultural production. In fact, they even decrease crop yields in poorly managed production systems (Raza et al. 2018). Commonly, less than half of the applied N is recovered by crop, which has led to a low N use efficiency (NUE). In China, the NUE of main grain crops is about 30–35%, which is similar to many other developing countries, such as about 38% in Thailand and about 30% in India (Zhang et al. 2015). Although NUE in some developed countries reached up to 55–65% (like French and US) (Zhang et al. 2015), a considerable NUE decrease has been found recently as compared with that in 1990s (Swaney et al. 2018). As a result of excessive N applications and low NUE, a large amount of N surplus would be lost to the environment through leaching, surface runoff, erosion, volatilization (NH_3) and greenhouse gas (N_2O, NO or NO_2) emissions. Thus, N fertilizer management is an important issue for both crop production and the environment.

Climate change, which is very relevant to agriculture, may threaten crop production and NUE in the future. Future climate trends to be warmer with the temperature projected to increase 1.0–5.0 °C and CO_2 concentration doubled, and the precipitation would increase by almost 10% for the whole world (Ju et al. 2013; Meehl et al. 2007). This has especial implication for China with a vast territory, various climate regions and a large demand of food to feed the population. Northeastern and northwestern China are two typical agricultural production regions, where crop production is greatly influenced by climate characteristics. While the northwestern China has become warmer and wetter, with an increase in air temperature by 1.9 °C in the past 50 years, the northeast China has simultaneously become warmer but drier with increased temperature of 3.6 °C (Qian et al. 2011; Zhou 2012). In the future, different trends of climate are expected for the two regions (Liu et al. 2010a; Gao et al. 2012). In northeastern China, the temperature would increase by 1.97 °C and 2.96 °C from 2005 to 2099 under the RCP 4.5 and RCP 8.5 predictions, and the precipitation would increase by about 3% and 2%, respectively (Zheng et al. 2017). As predicted by Zhang et al. (2010), air temperature in northwestern China would increase by 0.80 to 2.77 °C by 2050, but precipitation would change by − 4.34 to 19.1%. These trends of climate change could have profound impacts on crop yield and NUE in the regions, through influencing N uptake and N losses from the plant–soil system (Fujimura et al. 2012; Ma et al. 2010; Zhou et al. 2012; Wang et al. 2017). Moreover, the two regions have been reported to have different soil N surplus status, i.e., 20–44 kg N ha^{-1} in northeastern China and 51–84 kg N ha^{-1} in northwestern China (He et al. 2018). This may further complicate the impacts of climate on N turnover. Thus, it is highly needed to clarify the effects of climate change on crop yields and NUE in the two typical crop production regions. The results obtained here may also have implications for other regions with similar climate scenarios and agricultural practices.

In addition to climate, N fertilizer management strategies can also greatly affect crop yield, NUE and environmental N loss. Efficient fertilizer management practices have been widely reported to be able to maintain or increase NUE and maintain high grain yields (Anbessa and Juskiw 2012; Duan et al. 2011). In northwestern China, Wang et al. (2014) reported that optimized fertilizer management with 37% lower N application rate increased maize yield by 27% and NUE by 200% compared to farmer's practices with unbalanced and over use of N fertilizer. Combined applications of organic fertilizers (e.g., crop straw and animal manure) and chemical fertilizers were reported to significantly promote crop yields and NUE (Jørgene et al. 2009; Duan et al. 2011). In southern Alberta, Canada, Miller et al. (2009) found that 9 years of combined manure and chemical fertilizer applications substantially improved dry matter yield and N uptake of barley. Moreover, results of eight wheat and maize rotations over 15 years in northern China showed that the treatment with manure plus mineral fertilizers increased wheat and maize yields by an average of 0.55 t ha^{-1} and 0.59 t ha^{-1}, respectively, and significantly reduced environmental N losses, as compared with the treatment where the same total rate of N was applied in the form of chemical fertilizers only (Zhao et al. 2010).

Process-based models have been widely used to assess climate change impacts in agricultural settings to explore relationships between crop yield and phenological or environmental variables (Wang et al. 2011). Recently, an increasing number of studies have been conducted with respect to crop production using model-based decision support tools especially in the context of changing climatic issues (Aslam et al. 2017). The SPACSYS model is a weather-driven, process-based field scale model that has been increasingly used to simulate and predict the effects of climate change on grain yields of wheat and maize, greenhouse gaseous emissions, water balance and movement and the stocks of soil C and N with different fertilizations, and the model has been validated to well simulate crop growth and N cycling in various climatic regions (Wu et al. 2007; Zhang et al. 2016a, b, c). In addition, a review of 30 widespread models (e.g., APSIM, CENTRY, SOILN etc.) with regard to comparing spatial and temporal scales, performance of simulating agricultural biophysical processes and their ability to introduce farmer adaptation and practices under climate change indicated that SPACSYS was one of the three models fitting most features (Shepherd et al. 2011). This further supports that SPACSYS has the capacity to accurately simulate biophysical processes among crop, soil and atmosphere under climate change. Therefore, SPACSYS is selected in this study to evaluate the responses of crop yield and NUE to future climate change under different N fertilizer management practices.

This study aims to: (1) assess the performance of the SPACSYS model to simulate crop yield and NUE in northeastern and northwestern China, using the historical wheat and maize yields and N uptake data obtained from three long-term fertilization trials (23–34 years); (2) quantitatively predict and compare the effect of future climate change on crop yields and NUE in the two typical climatic and crop production regions under different N management practices by 2100.

Materials and methods

Study sites and experimental design

This modeling study was based on data collected from three long-term experiments (experimental durations: 23–34 years) conducted by the Chinese Academy of Agricultural Sciences. The experimental fields were located in Zhangye (ZY, 100°18′00″E, 38°36′00″N), Pingliang (PL, 107°30′00″E, 35°16′00″N) and Gongzhuling (GZL, 124°51′23″E, 43°32′18″N), representing typical climate characteristics and soil types in northwest and northeast of China. The cropping systems, field management practices and soil physical–chemical properties of the three experimental sites are given in Table 1. Soil properties were determined at the start of each experiment, while weather and crop data were monitored throughout the experimental durations. The ZY site is located in an arid climatic region, with an average annual precipitation of 127 mm and annual evaporation of 2345 mm. The PL site is located in a semiarid climatic region, the annual precipitation is 540 mm, and annual evaporation is 1384 mm. The site GZL, one of the main maize planting areas of northeastern China, is located in a semi-humid climatic region with a lower annual temperature of 4.5 °C than the other two sites (7.5 °C and 8 °C, respectively). It is noteworthy that the black soil in the GZL site is a special soil type in China with very high fertility. To replenish the water loss by evaporation, the ZY site was irrigated with an average of 330 mm water for wheat and 485 mm for maize throughout the experiment. In contrast, the crops at PL and GZL were rainfed. The PL and ZY sites consisted of three replicated plots for each fertilizer treatment (described below), and the GZL site had no replicates. Pesticide and herbicide were used at ZY once every 2 or 3 years, and pesticide was used at GZL and PL annually (except 1999 and 2000).

Four fertilizer treatments common for all sites were used for model calibration, validation and projection in this study. They are, specifically, (1) no fertilizer (CK), (2) inorganic fertilizers, i.e., combinations of inorganic N and phosphorus (P) with or without potassium (K) fertilizers (NP or NPK), (3) inorganic fertilizers combined with manure (NPM or NPKM) and (4) inorganic fertilizer combined with crop straw (NPS or NPKS). Details of the experimental design and fertilizer management have been described

Table 1 Background information of the experimental sites

Site	Zhangye	Pingliang	Gongzhuling
Starting year	1982	1979	1990
Location	100°18′00″E	107°30′00″E	124°51′23″E
	38°36′00″N	35°16′00″N	43°32′18″N
Climate type	Mild temperate	Mild temperate	Mild temperate
	Arid	Semiarid	Semi-humid
Annual temperature (°C)	7.5	8.0	4.5
Annual precipitation (mm)	127	540	525
Annual evaporation (mm)	2345	1384	1400
Irrigation (mm)	330 (wheat)	0	0
	485 (maize)		
Sowing date	3/18–3/24 (wheat)	9/10–9/18 (wheat)	4/21–4/29 (maize)
	4/12–4/15 (maize)	4/5–4/20 (maize)	
Harvest date	7/13–7/21 (wheat)	6/25–7/5 (wheat)	9/25–9/28 (maize)
	10/9–10/12(maize)	9/15–10/2 (maize)	
Aridity index	0.19	0.64	0.79
Cropping	Wheat–maize	Wheat–maize	Maize
Plot size (m^2)	33	220	400
Plot replicates	3	3	1
Soil type	Anthrosol	CalcicKastanozem	Luvic Phaeozems
Initial SOC (g kg^{-1})	20.8	6.09	13.23
Total N (g kg^{-1})	0.76	0.95	1.40
Available N (mg kg^{-1})	28.1	55.5	114
Total P (g kg^{-1})	0.82	0.58	1.39
Olsen P (mg kg^{-1})	21.7	7.0	27.0
Total K (g kg^{-1})	N/A	20.5	22.1
Available K (mg kg^{-1})	99.10	164.7	190
pH	8.5	8.2	7.6
Bulk density (g cm^{-3})	1.20	1.30	1.19
Clay (%)	16	34	32

SOC soil organic carbon, *N* nitrogen, *P* phosphorus, *K* potassium

elsewhere (Jiang et al. 2014; Zhao et al. 2010). The treatments of CK, NPK, NPKM and NPKS were used for ZY and GZL, and CK, NP, NPM and NPS were used for PL; no K was applied at PL due to its high soil K content. The treatments allowed a comprehensive evaluation on the impacts of N applications on crop yields and NUE at different sites. Nitrogen input rates and types for all treatments and experimental sites are listed in Table 2. The total amount of N application (mineral and organic) was equal among the three fertilized treatments at GZL. At PL and ZY, N rates were higher in the treatments amended with manure or straw than in the chemical fertilizer treatments, because the organic amendments were used as additional nutrient sources. In the NPKS treatment, the wheat or maize straw (including roots and stubble) was returned to soil shortly after harvest at PL, while the straw was returned before planting at ZY and GZL. The inorganic N, P and K fertilizers were supplied in the form of urea, calcium superphosphate and potassium chloride, respectively. The types of manure applied varied with the experimental sites, depending on the local availability (Table 2), and they were applied on the soil surface before planting at all sites. Consistent treatments were used in all plots throughout the experiments, and the field management practices were used for the model predictions.

Table 2 Nitrogen, phosphorus and potassium application rates in different fertilizer treatments at three experimental sites

Treatment	Zhangye		Pingliang	Gongzhuling
	Wheat	Maize	Wheat/maize	Maize
Nitrogen (kg N ha^{-1})				
NPK (NP)	150	360	90	165
NPKM (NPM)	150 + 77[a]	360 + 96.2[a]	90 + 40[a]	50 + 115[a]
NPKS (NPS)	–	–	90 + 40[a]	112 + 53[a]
Phosphorus (kg P ha^{-1})				
NPK (NP)	26.4[b]	52.8[b]	33	36
	33[c]	68[c]		
NPKM (NPM)	26.4 + 114[a,b]	52.8 + 114[a,b]	33 + 200[a]	36 + 39[a]
	33 + 143[a,c]	68 + 143[a,c]		
NPKS (NPS)	–	–	33 + 22[a]	36 + 6[a]
Potassium (kg K ha^{-1})				
NPK (NP)	49.8[b]	99.6[b]	–	68
	62.25[c]	124.5[c]		
NPKM (NPM)	49.8 + 143[a,b]	99.6 + 143[a,b]	–	68 + 77[a]
	62.25 + 178[a,c]	124.5 + 178[a,c]		
NPKS (NPS)	–	–	–	68 + 58[a]
Type of manure and straw				
Manure	Cow and pig		Cow and pig	Cow and pig
Straw	–		Wheat	Maize

[a] The number after "+" indicates the N, P and K amount from manure or straw

[b] Phosphorus or potassium fertilizer application rate during 1982–1990 at Zhangye site

[c] Phosphorus or potassium fertilizer application rate after 1990 at Zhangye site

Model description

Driven by weather data, the soil, plant and atmosphere continuum system (SPACSYS) model can simulate plant growth, nutrient cycling between plants, soil and microbes, water redistribution and heat transformation at the field scale with a daily time-step. The main advantages of SPACSYS are the comprehensive and detailed simulation of plant growth and development and root systems, and the representation of the processes associated with soil C and N cycling. The impacts of atmospheric CO_2 concentration on plant photosynthesis and stomata conductance were estimated with the equations Thornley (Eq. 3.2s and 3.2u 1998) proposed. The SPACSYS model has 24 organic matter pools, three inorganic N pools and four water pools. The model has been described in detail previously (Bingham and Wu 2011; Wu et al. 2007, 2011). Thus, only a brief summary of processes closely related to this study is presented here. In the SPACSYS model, the main processes on plant growth are plant development, assimilation, respiration, photosynthate and N uptake, plus N fixation by legumes. The soil organic C and N pools are divided into four sub-pools, i.e., fresh organic matter, humus, dissolved organic matter and microbial biomass. The main processes and transformations influencing soluble N pools are mineralization, nitrification, denitrification and plant-N uptake.

NUE calculation

The NUE is calculated as the percentage of N uptake by crop to the fertilizer application rate (Duan et al. 2011; Liu et al. 2003):

$$\mathrm{NUE} = \frac{U_{\mathrm{N}} - U_0}{A_{\mathrm{N}}} \times 100\% \qquad (1)$$

where U_{N} is the total N uptake (g N m^{-2}) by wheat or maize (grain and stover) in a fertilizer treatment, U_0 is the N uptake (g N m^{-2}) by the crop (grain and stover) in the CK treatment, and A_{N} is the total amount of N added (i.e., both inorganic and organic) in the fertilizer treatment (g N m^{-2}).

Model input

The model input data included: (1) daily meteorological data (max temperature, min temperature, annual precipitation, humidity, solar radiation, wind speed); (2) initial soil properties (initial SOC, total N, Olsen P, total K, available K, bulk density, soil moisture, clay content, pH); (3) crop management (crop growth and development period, harvest date, crop varieties, crop nutrient contents); (4) field management (cultivation practices, cultivation depths); (5) fertilization (fertilizer practices, depth of fertilizer application, form and amount of chemical and organic fertilizer, nutrient type and amount in fertilizer); (6) irrigation events (irrigation date, amount and times); (7) seeding (seeding date, amount and times); and (8) drainage (drainage strategies, distance between drainage pipes, depth of the drainage pipe, diameter of pipe). Soil properties, crop and field management practices and soil initial state variables were collected based on the field survey and farm records. The main information is listed in Table 1.

Model calibration, validation and prediction

Grain yields and N contents in grain and stover (N uptake) obtained at harvest of wheat and maize from the NPK (or NP) treatment were used to calibrate the SPACSYS model for each experimental site. The results from the CK, NPKM (or NPM) and NPKS (or NPS) treatments were used for model validation. When there were plot replicates, an average of replicates was used to represent a given variable. Sampling numbers of crop yields, grain N and stover N contents for calibration and validation are shown in Fig. 1. The MOSCEM-UA algorithm (Vrugt et al. 2003) was applied for optimization. For model calibration and validation, the historical weather data for the three experimental sites were collected from the National Meteoritical Information Center (http://data.cma.cn/). For predication of crop yield and NUE from 2015 to 2100, four climate scenarios including baseline, representative concentration pathway (RCP) 2.6, RCP4.5 and RCP8.5 (Riahi et al. 2011; Thomson et al. 2011; van Vuuren et al. 2011) were used for the study regions in northern China. The baseline climate scenario for each site was a repetition of historic data during the experimental periods with a constant CO_2 concentration of 350 ppm. The data of RCP scenario were extracted from the HadGEM2-ES model with a spatial resolution of 0.5° × 0.5° (Collins et al. 2011; Jones et al. 2011). The annual temperatures and precipitation under RCP climate scenarios at three sites are given in Table S1.

Statistical analysis

The statistical indexes (Smith et al. 1997) commonly used to evaluate model performance include the coefficient of determination (R^2), the root-mean-square error (RMSE) and modeling efficiency (EF). In statistics, the performance of model simulation is good when the R^2 and EF are close to 1. For RMSE, the model performs better when the values are closer to 0.

Tests of one-way analysis of variance (ANOVA) and the least significant difference (LSD) methods ($P < 0.05$) were used to test the difference between simulated and observed NUEs under different fertilizer treatments in northeastern and northwestern China during the experimental period, and the tests also be used to compare the difference of annual precipitation among RCP climate scenarios in each experimental site. Tests of two-way ANOVA and LSD ($P < 0.05$) were used to compare the effects of fertilizer treatments and climate scenarios on crop yields, N contents in grain and stover of wheat and maize, and annual crop NUE of each site between 2015 and 2100. The statistical analyses were performed with SPSS 20.0 (SPSS, Inc., 2011, Chicago, USA).

Results

Model calibration and validation

For both calibration and validation, the simulated results of crop yields and N contents in grain and stover fitted well with the observed values (Fig. 1). The statistical analyses of the fitness over the data from all treatments indicated that the SPACSYS model was capable of simulating crop yields and crop N contents for all maize and wheat production regions evaluated here (Table 3). Specifically, the R^2 values ranged from 0.41 to 0.96 with RMSE from 6 to 18% and EF from 0.41 to 0.93. Similarly, the SPACSYS model was also able to satisfactorily simulate crop NUE in northeast and northwest of China. There was

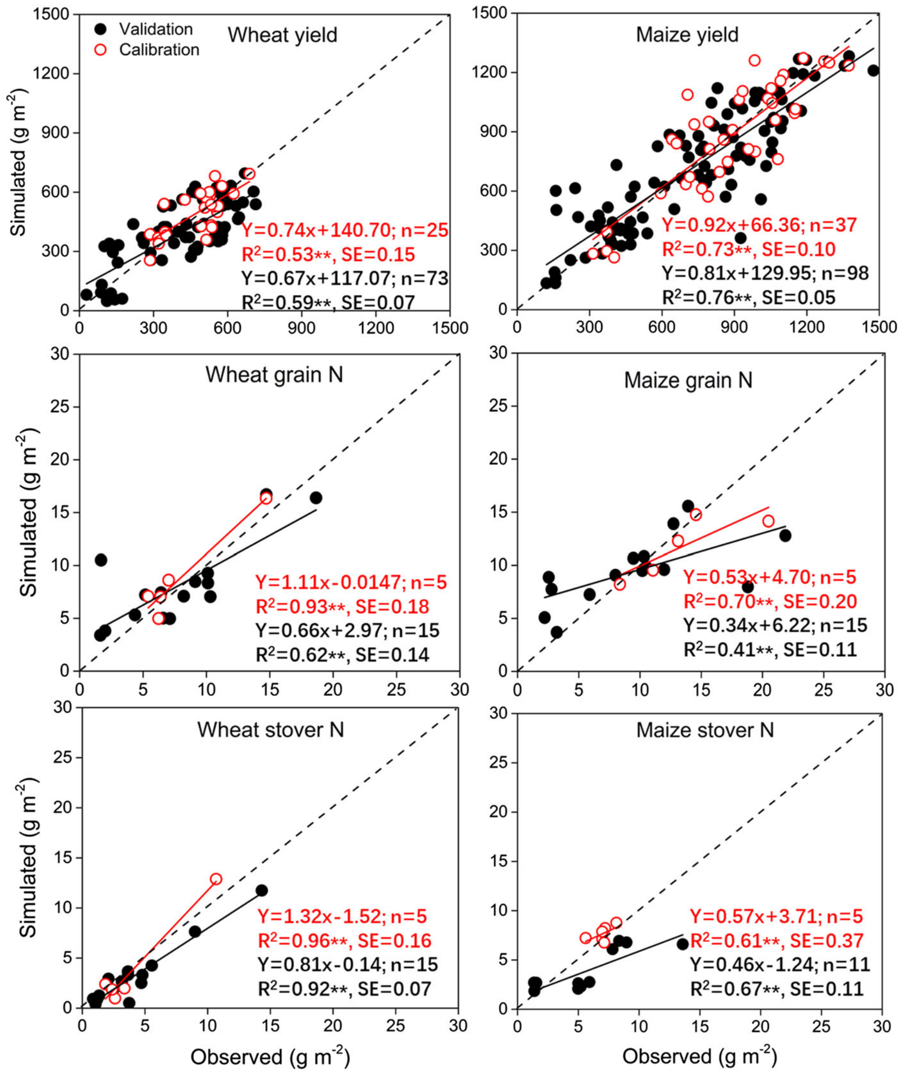

Fig. 1 Relationship between simulated and observed crop yields, grain N and stover N contents based on data from all sites combined (**$P < 0.01$). The straight line is the fitting line of observed and simulated values; the dashed line is 1:1 relationship; R^2 coefficient of determination; *n* number of samples; *SE* standard error on the coefficient

no significant difference between the simulated and the observed NUEs except NPKS (Fig. 2).

Climate change and fertilization impacts on crop yield

The wheat and maize yields under all climate scenarios with different fertilization treatments are presented in Figs. 3 and 4. For all climate scenarios, there was no significant difference ($P < 0.05$) among the N fertilizer treatments with respect to both wheat and maize yield in northwestern and northeastern China. Relative changes of wheat and maize yields in different fertilization treatments under the RCP climate change scenarios are shown in Table 4. As compared to baseline, wheat yield was predicted to decrease by an average of 16.37% under the RCP scenarios in northwest of China. The average relative changes of wheat yield at ZY ranged from − 47.52 to − 13.69% under RCP2.6 and RCP4.5 for all treatments from 2015 to 2100, while it increased by 8.71–28.15% under RCP8.5 from 2041 to 2100 compared with baseline (Table 4). In addition, the wheat yield at ZY had no significant difference among RCP2.6 and RCP4.5 during 2015–2040, but it ranked as RCP2.6 < RCP4.5 < RCP8.5 ($P < 0.05$) during 2041–2100 (Fig. 3). For PL, wheat yield almost decreased in all treatments under RCP2.6 (except CK in 2071-2100) and RCP8.5 with change of − 51.40% to 0.44% from 2015 to 2100, but there was a slight, non-significant

Table 3 Statistical analysis of model performance on crop yields, grain N and stover N contents for data from all sites combined

Statistical indexes	Yield				Grain N				Stover N			
	Wheat		Maize		Wheat		Maize		Wheat		Maize	
	C[a]	V[b]	C[a]	V[b]	C[a]	V[b]	C[a]	V[b]	C[a]	V[b]	C[a]	V[b]
R^2	0.53	0.59	0.73	0.76	0.93	0.62	0.70	0.41	0.96	0.92	0.61	0.67
RMSE (%)	17	13	17	17	18	12	6	13	12	11	9	18
EF	0.41	0.58	0.72	0.84	0.88	0.80	0.79	0.84	0.93	0.84	0.57	0.70

[a]Calibration

[b]Validation

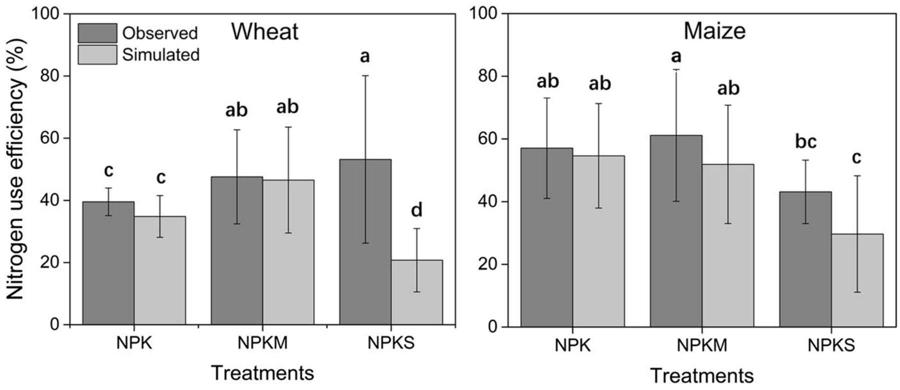

Fig. 2 Comparison of simulated and observed annual crop nitrogen use efficiencies based on data from all sites combined. Different letters indicate significant difference at 0.05 level for different treatments

increase of 5.72–14.53% under RCP4.5 for NPK, NPKM and NPKS (Table 4). Over all treatments, the wheat yield at PL ranked as RCP2.6 ≤ RCP8.5 < RCP4.5 during 2015–2100 (Fig. 3).

The maize yield decreased by an average of 30.69% for all treatments under the RCP scenarios in northeastern China. The relative changes of maize yield ranged from − 79.87 to 5.85% at ZY and from − 33.99 to − 1.26% at PL for all treatments from 2015 to 2100 compared with baseline (Table 4). The maize yield at ZY ranked as RCP2.6 < RCP4.5 < RCP8.5 ($P < 0.05$) for NPK and NPKM during 2071–2100 (Fig. 4). The maize yield at PL is ranked as RCP2.6 < RCP4.5 = RCP8.5 during 2015–2040. In addition, the maize yield significantly decreased over time under RCP8.5 at PL, with a rank of RCP2.6 = RCP4.5 > RCP8.5 from 2071 to 2100 for all treatments (Fig. 4). On the contrary, the maize yield at GZL increased by an average of 5.98% for all treatments under the RCP scenarios. The maize yield at GZL increased with a relative change of 6.30–37.10% during 2015–2070 under RCP4.5 and RCP8.5 for all treatments (Table 4; Fig. 4), but it decreased by 0.79–14.66% during 2071–2100 under most RCP scenarios (except CK under RCP4.5). The maize yield at GZL ranked as RCP2.6 < RCP4.5 < RCP8.5 ($P < 0.05$) during 2015–2040. In addition, the maize yield decreased over time under RCP4.5 and RCP8.5 for all treatments, and the maize yield under RCP8.5 during 2071–2100 was significantly lower than that under other RCP scenarios for all treatments.

Climate change and fertilization impacts crop N removal

The annual N contents of crop grain and stover decreased under most RCP scenarios compared with baseline for each fertilization treatment in both northeastern and northwestern China (Table S2 and

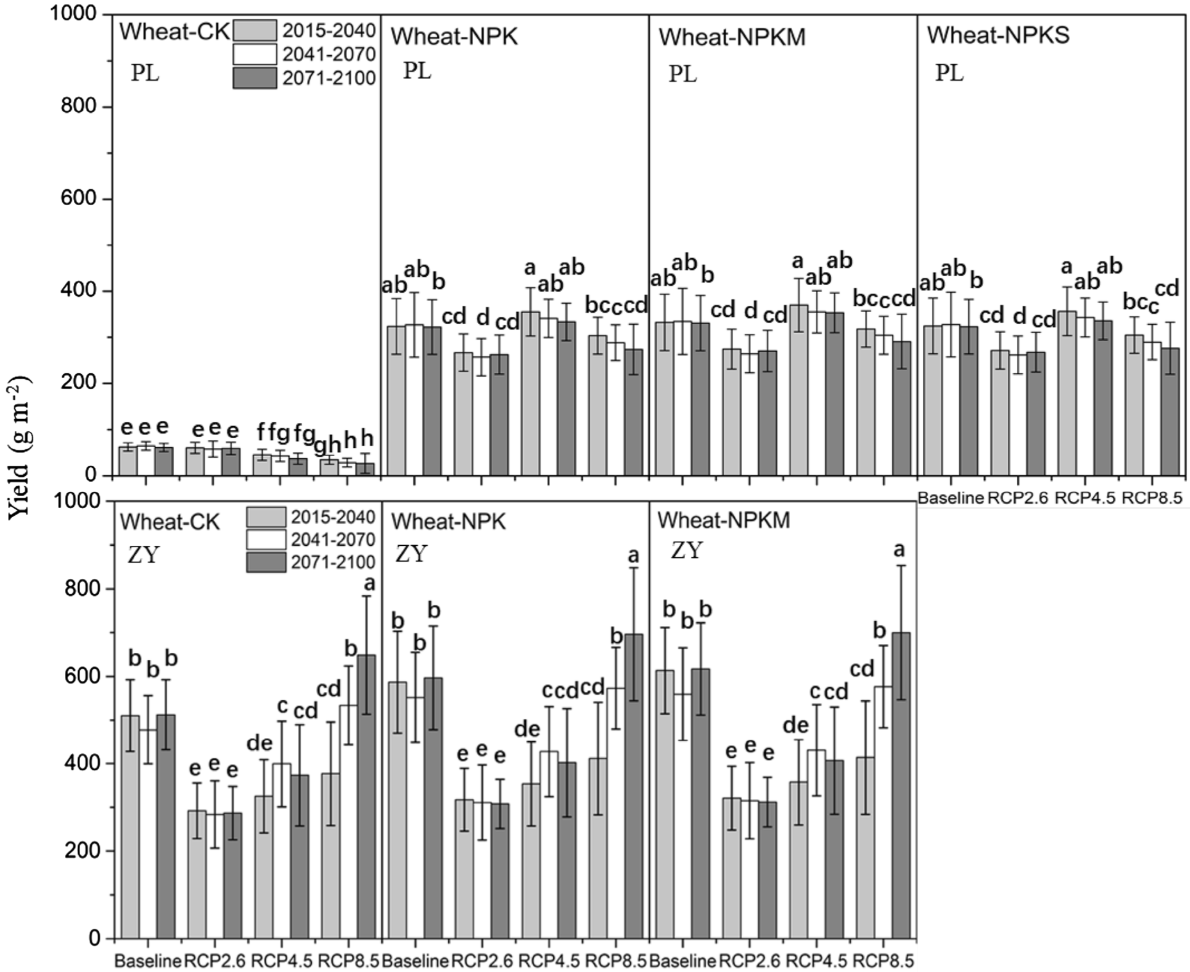

Fig. 3 Annual wheat yield (g m^{-2}) during different periods under future climate scenarios in northwestern China. Different letters indicate significant difference among different periods, climate scenarios and treatments ($P < 0.05$)

Figure S1 to S4). In all climate scenarios, manure amendment resulted in higher wheat grain (4.32–11.97 g m^{-2}) and stover N (1.39–2.88 g m^{-2}) and maize grain (4.26–32.52 g m^{-2}) and stover N (1.34–9.13 g m^{-2}) than other treatments (1.80–10.68 g m^{-2} and 1.70–30.50 g m^{-2} for wheat and maize grain N content, respectively; 0.26–2.42 g m^{-2} and 0.40–9.31 g m^{-2} for wheat and maize stover, respectively) (Figure S1–S4). The wheat grain and stover N contents almost decreased for all treatments at PL with change of − 58.61% to 9.45% and − 51.83% to 9.48%, and the maize grain and stover N contents decreased with change of − 50.00% to − 14.95% and − 44.05% to 9.21%, respectively. For an individual fertilization treatment (except CK), the average N content in wheat grain and stover ranked as RCP8.5 ≤ RCP2.6 < RCP4.5 among the RCP scenarios at PL. Maize grain and stover N contents under RCP4.5 at PL were slightly higher than other climate scenarios but with no significant difference for most time periods (Figures S2 and S4). At ZY, the highest N contents in crop grain and stover were found under RCP8.5 with the lowest reduction in wheat grain N (6.72–28.27%), maize grain N (28.34–85.76%) and stover N (23.63–77.07%) and the highest increasing (57.20–176.73%) in wheat stover N. The maize grain N content at GZL decreased during 2041–2100 with change of − 19.43% to − 0.38% for all treatments across the RCP scenarios (Table S2), and there was no significant difference in maize grain N among the three RCP scenarios from 2015 to 2070. During 2071–2100, in contrast, the

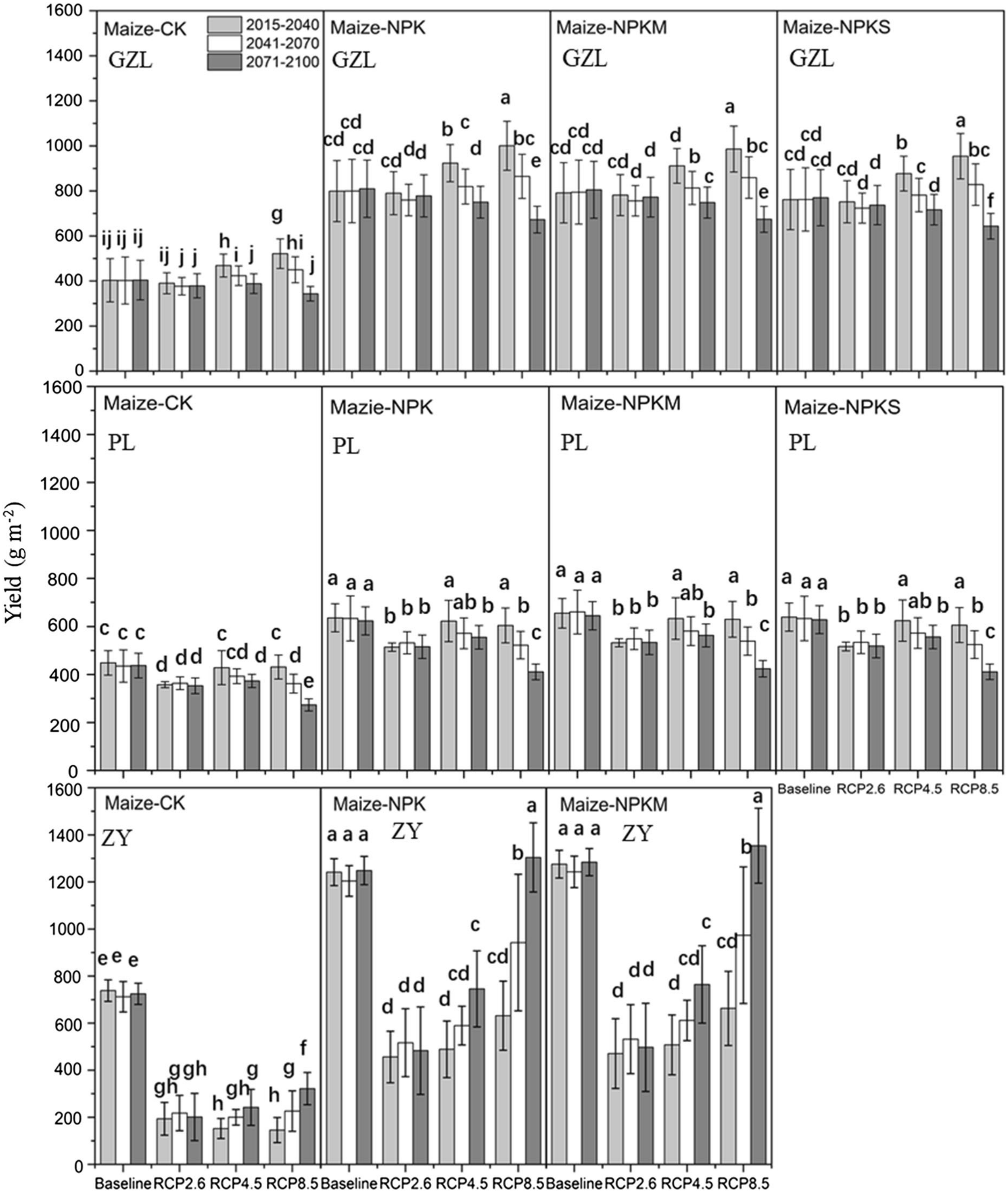

Fig. 4 Annual maize yield (g m^{-2}) during different periods under future climate scenarios in northwestern and northeastern China. Different letters indicate significant difference among different periods, climate scenarios and treatments ($P < 0.05$)

Table 4 Relative changes of wheat and maize yields and nitrogen use efficiencies under RCP scenarios compared with baseline (%)

Treatment	Periods	Zhangye					
		Wheat			Maize		
		RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Yield							
CK	2015–2040	− 42.31*	− 34.78*	− 24.16*	− 73.57*	− 79.20*	− 79.87*
	2041–2070	− 39.41*	− 13.69*	15.94	− 68.93*	− 71.91*	− 67.94*
	2071–2100	− 42.72*	− 24.22*	28.15*	− 72.09*	− 66.54*	− 55.03*
NPK	2015–2040	− 44.76*	− 37.31*	− 26.77*	− 63.21*	− 60.45*	− 48.59*
	2041–2070	− 41.64*	− 19.02*	9.38	− 56.17*	− 49.86*	− 21.17*
	2071–2100	− 45.90*	− 29.75*	21.05*	− 61.06*	− 40.13*	4.89
NPKM	2015–2040	− 47.48*	− 40.16*	− 30.39*	− 63.05*	− 59.99*	− 47.56*
	2041–2070	− 41.61*	− 19.46*	8.71	− 56.87*	− 50.65*	− 21.46*
	2071–2100	− 47.52*	− 31.68*	16.10*	− 61.09*	− 40.35*	5.85
NPKS	2015–2040	–	–	–	–	–	–
	2041–2070	–	–	–	–	–	–
	2071–2100	–	–	–		–	–
Nitrogen use efficiency							
NPK	2015–2040	− 71.02*	− 67.10*	− 40.17*	− 55.23*	− 58.43*	− 49.42*
	2041–2070	− 66.10*	− 72.86*	− 51.38*	− 50.88*	− 51.36*	− 32.38*
	2071–2100	− 70.99*	− 77.62*	− 70.99*	− 55.28*	− 48.25*	− 16.67*
NPKM	2015–2040	− 64.32*	− 55.31*	− 43.89*	− 47.81*	− 51.07*	− 42.35*
	2041–2070	− 59.67*	− 64.94*	− 55.14*	− 43.05*	− 43.00*	− 22.40*
	2071–2100	− 63.79*	− 73.34*	− 64.81*	− 48.97*	− 41.21*	− 8.39
NPKS	2015–2040	–	–	–	–	–	–
	2041–2070	–	–	–	–	–	–
	2071–2100	–	–	–	–	–	–

Treatment	Periods	Pingliang						Gongzhuling		
		Wheat			Maize			Maize		
		RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Yield										
CK	2015–2040	− 4.77	− 26.60*	− 43.56*	− 19.33*	− 3.66	− 2.88	2.92	22.91*	37.10*
	2041–2070	− 10.41	− 30.73*	− 53.67*	− 15.01*	− 7.64	− 15.26*	1.13	14.48	19.42
	2071–2100	0.44	− 38.38*	− 51.40*	− 18.37*	− 13.44	− 36.76*	− 0.79	1.12	− 9.94
NPK	2015–2040	− 15.20*	12.66	− 3.77	− 18.45*	− 1.26	− 4.33	1.78	18.51*	28.88*
	2041–2070	− 18.15*	8.04	− 8.62	− 14.60*	− 7.92	− 16.19*	− 1.74	6.37	11.38
	2071–2100	− 16.40*	5.72	− 13.03*	− 16.65*	− 10.09*	− 33.50*	− 1.30	− 5.14	− 14.66*
NPKM	2015–2040	− 14.95*	14.53	− 1.88	− 17.99*	− 2.56	− 2.91	1.72	18.11	28.15*
	2041–2070	− 17.68*	10.11	− 5.63	− 15.62*	− 10.50	− 17.09*	− 1.49	6.30	11.40
	2071–2100	− 16.26*	9.10	− 9.89*	− 16.58*	− 11.83*	− 33.68*	− 1.42	− 4.82	− 13.97*
NPKS	2015–2040	− 13.93*	12.74	− 3.61	− 18.44*	− 1.49	− 4.60	− 6.11	18.38*	29.16*
	2041–2070	− 16.80*	8.42	− 8.34*	− 14.25*	− 7.78	− 15.76*	− 1.47	6.83	12.23
	2071–2100	− 15.09*	6.19	− 12.43*	− 16.84	− 10.62*	− 33.99*	− 1.47	− 4.54	− 13.99*

Table 4 continued

Treatment	Periods	Pingliang						Gongzhuling		
		Wheat			Maize			Maize		
		RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Nitrogen use efficiency										
NPK	2015–2040	− 51.14*	− 33.74*	− 14.62*	− 47.42*	− 29.32*	− 35.09*	− 2.57	1.86	4.69
	2041–2070	− 56.19*	− 22.05*	− 20.25*	− 30.89*	− 23.24*	− 27.13*	− 5.65*	− 2.27	− 4.24*
	2071–2100	− 58.61*	− 28.32*	− 33.47*	− 31.00*	− 26.33*	− 36.05*	− 7.26*	− 6.50*	− 13.25*
NPKM	2015–2040	− 39.42*	− 8.32*	− 29.77*	− 11.46	− 24.22	− 15.18	− 1.31	1.39	1.43
	2041–2070	− 51.33*	− 2.38	− 23.74*	− 22.21*	− 26.38*	− 33.69*	− 3.40*	− 1.57	− 4.18*
	2071–2100	− 48.44*	3.02	− 42.21*	− 6.57	− 10.77	− 20.64*	− 6.59*	− 4.33*	− 7.77*
NPKS	2015–2040	− 45.37*	− 18.75*	− 7.17	− 40.87*	− 25.97*	− 34.60*	− 3.59	1.75	4.71
	2041–2070	− 56.27*	− 2.37	− 10.03*	− 30.76	− 24.94	− 34.12*	− 6.60*	− 4.01	− 5.43*
	2071–2100	− 60.14*	− 8.25	− 26.92*	− 21.98	− 34.85*	− 45.81*	− 7.27*	− 9.33*	− 15.85*

*The crop yield or nitrogen use efficiency under the RCP climate scenario changed significantly compared with baseline ($P < 0.05$)

maize grain N content decreased significantly under RCP8.5 for all treatments (Figure S2), along with its declining trend over time (Figure S2). Maize stover N at GZL decreased under all RCP scenarios with change of − 31.46% to − 0.16% in NPK, NPKM and NPKS (Table S2).

Climate change and fertilization impacts on annual NUE

In general, the RCP climate scenarios had negative effects on NUE for all sites in northwestern and northeastern of China compared with baseline, with an average reduction of 62.87% (40.17–77.62%) for wheat and 42.56% (8.39–58.43%) for maize at ZY, 29.49% (− 3.02% to 60.14%) for wheat and 27.83% (6.57–47.42%) for maize at PL, and 3.97% (− 4.71% to 15.83%) for maize at GZL, respectively. The wheat NUE under RCP2.6 at PL was significantly lower than that under RCP4.5 and RCP8.5 ($P < 0.05$) during 2015–2100 for all treatments (Fig. 5). The maize NUE at ZY ranked as RCP2.6 = RCP4.5 < RCP8.5 ($P < 0.05$) during 2041–2100 for all treatments, and it increased significantly over time under RCP8.5 for NPK and NPKM. In northeastern China (GZL), there was no significant difference in maize NUE among the RCP scenarios from 2015 to 2070, but the maize NUE decreased significantly under RCP8.5 during 2071–2100 in NPK and NPKS compared with that under other RCP scenarios (Fig. 6). In addition, different fertilizer management strategies influenced wheat and maize NUE significantly. For a given climate scenario, the crop NUE under NPK (7.19–39.26% for wheat; 22.12–73.61% for maize) was greater than that of NPKM (6.66–31.27% for wheat; 23.82–68.19% for maize) and NPKS (9.24–23.72% for wheat; 27.56–54.57% for maize) (Figs. 5, 6). Furthermore, maize had greater NUE than wheat between 2015 and 2100 under both the baseline and the RCP climate scenarios for all fertilizer treatments (Figs. 5, 6).

Discussion

Model performance

Overall, SPACSYS performed well to simulate wheat and maize yields, N contents of crop grain and straw with the R^2 ranging from 0.41 to 0.96, RMSE from 6 to 18% and EF from 0.41 to 0.93 for both calibration and validation (Figs. 1, 2; Table 3). Previously, Zhang et al. (2016c) applied SPACSYS in North China plain, and their results indicated that the model could well simulate crop yield in fields amended with inorganic fertilizers and manures (straw). Our results here have confirmed the findings of Zhang et al. (2016c) and further found that SPACSYS could well simulate N uptake by maize and wheat. Even so, it should be noted that the model still has some inevitable errors with the

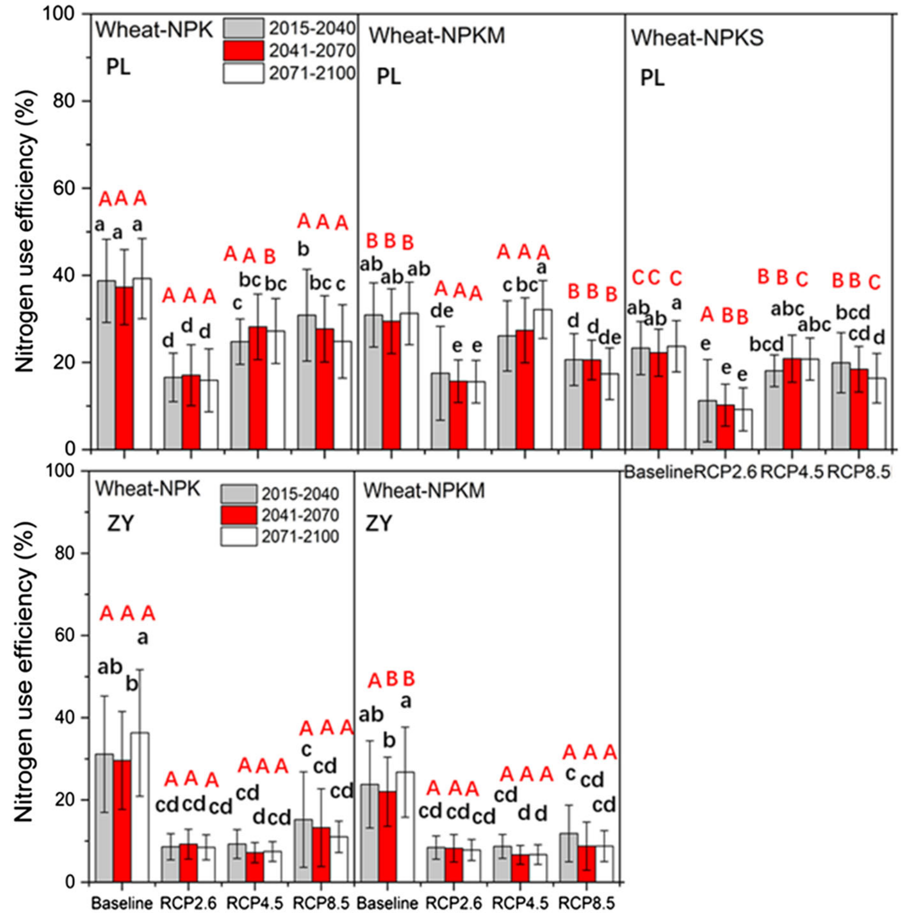

Fig. 5 Annual NUE (%) of wheat during different periods under future climate scenarios in northwestern China. Numbers with different lowercase letters indicate significant difference between different periods and different climate scenarios in an individual fertilization treatment ($P < 0.05$). Numbers with different capital letters indicate significant difference in different treatments under an individual climate scenario in an individual period ($P < 0.05$)

respect that the model considerably underestimated wheat NUE in NPKS. The discrepancy between the simulated and observed results may be due to the following reasons. (1) The model failed to simulate the changes of soil microbial environment resulting from applications of pesticides and herbicides; (2) the simulations represent averaged conditions of an experimental plot, but observations are usually obtained from a particular part of the plot; and (3) in Zhangye, the field plots were changed to wheat and maize stripping after 2006, which was not reflected in model simulations. This may have contributed to the difference between observed and simulated results in this site.

The model also underestimated maize grain N content by 50% for validation with the low R^2 of 0.41. This may be due to an erroneous measurement for NPKS at GZL in 1998 ($R^2 = 0.62$, without this value). In 1998, the simulated value (7.97 g m^{-2}) was incredibly lower than the observed (18.81 g m^{-2}). Also, the measured value of 18.81 g m^{-2} in 1998 is significantly higher than the values measured in other years for the same treatment. For the other years (2005–2007), the simulated results are well related to the observations (e.g., observation vs. simulation: 10.53 g m^{-2} vs. 9.81 g m^{-2}; 9.46 g m^{-2} vs. 10.65 g m^{-2}; 10.33 g m^{-2} vs. 10.81 g m^{-2}). Thus, it is likely that the observed value in 1998 for NPKS is erroneous.

Climate change impacts on crop yield

For northwestern China, yields of wheat and maize were predicted to decrease by an average of 16.37% and 30.69% under the RCP scenarios by the end of twenty-first century compared with baseline (Table 4). The predicted trend was supported by previous findings (Xiong et al. 2008; Xuan et al.

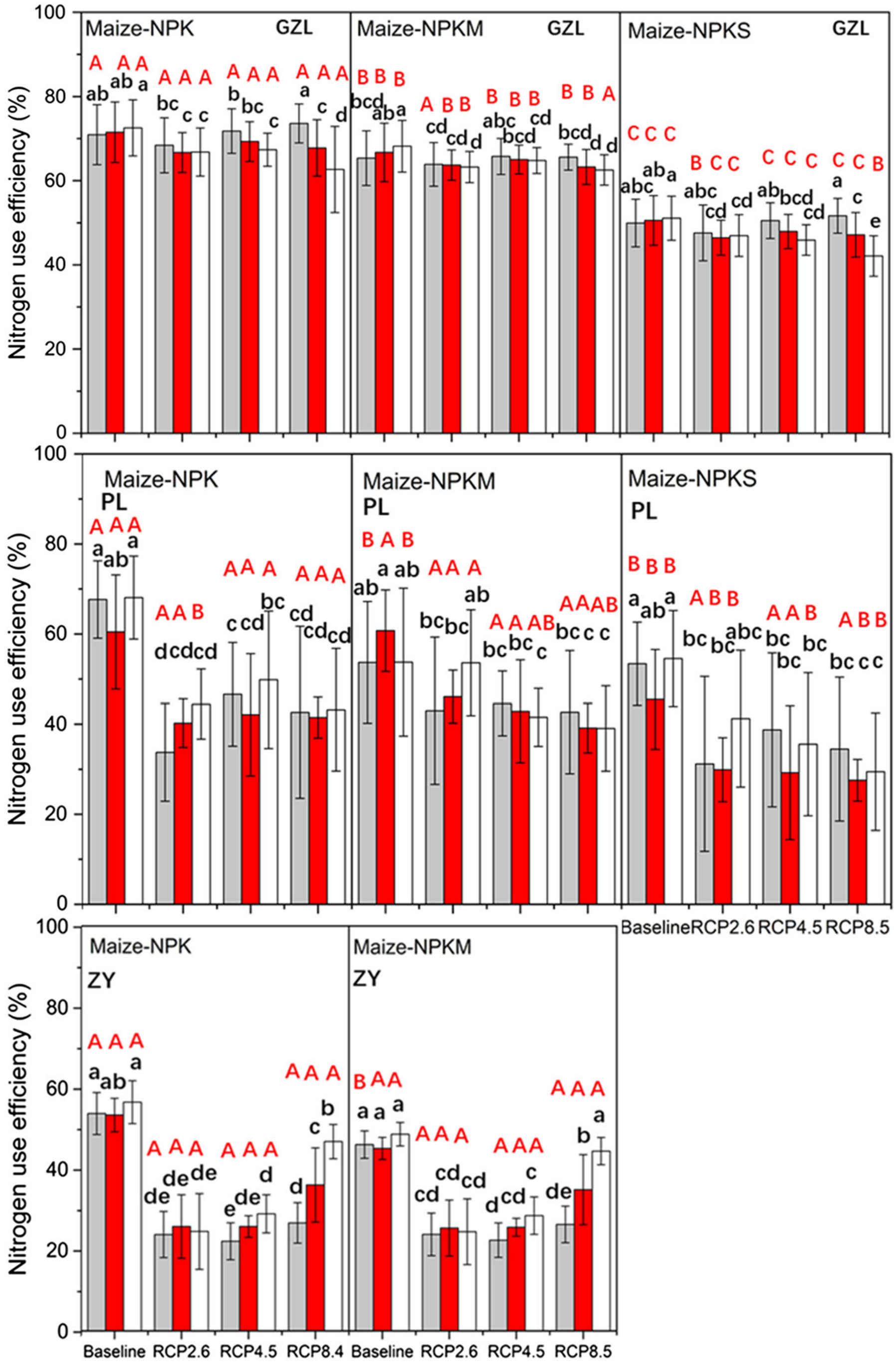

Fig. 6 Annual NUE (%) of maize during different periods under future climate scenarios in northwestern and northeastern China. Numbers with different lowercase letters indicate significant difference between different periods and different climate scenarios in an individual fertilization treatment ($P < 0.05$). Numbers with different capital letters indicate significant difference in different treatments under an individual climate scenario in an individual period ($P < 0.05$)

2014), and the trend was likely associated with the elevated temperature and the increasing frequency and amount of precipitation. The elevated temperature and more frequent rainfall events can lead to a lower crop yield with less N uptake, because they can reduce the amount of N in the vegetative organs during the functional period, which may further make changes to a series of plant physiological functions and result in the decrease in N transfer rate and N content in crop grains (Asseng et al. 2004). In addition, the RCP scenarios had different effects on crop yields, depending on the different magnitude of changes in RCP climate factors. In our study, there was an increasing trend in crop yield at ZY among the three RCP scenarios: RCP8.5 > RCP4.5 > RCP2.6 for all treatments during 2041–2100. The trend may be because the decrease in crop yield was offset partly by the enhanced CO_2 concentration, i.e., the so-called CO_2-fertilizer effect (Amthor 2001; Lin et al. 2005; Lobell and Field 2008). The crop yield under RCP8.5 showed a significant increase over time, in which the yield was even higher than that in baseline during 2071–2100. This further verifies that the 'CO_2-fertilizer effect' can offset the negative effects of climate change on crop production. However, the crop yield at PL showed a different trend compared with ZY, with respect that the crop yield under RCP8.5 was lower than RCP4.5 and in an order of RCP2.6 < RCP8.5 < RCP4.5 for all treatments in most simulated periods (Fig. 3; Table 4). It has been reported that the most relevant meteorological factor limiting crop yield on this semiarid region (Loess Plateau) in China is precipitation during the growing season, and that rainfall is the predominant factor determining yield in the unirrigated agricultural area (Qiu et al. 2015; Rockström et al. 2010). A field experiment in a rainfed spring wheat region of northeastern China concluded that supplemental irrigation (from 30 to 90 mm) could play a crucial role in maintaining crop yield in the context of global climate change (Xiao et al. 2005). Specifically, the authors claimed that a supplemental irrigation of 90 mm would increase crop yield by 6.3% as compared to an irrigation of 60 mm, under increasing CO_2 concentration and temperature (Xiao et al. 2005). Thus, some agricultural practices, like irrigation, can be applied in regions with similar climates as PL to adapt agricultural production to climate change in the future.

In northeastern China, future climate change was predicted to have a significantly positive impact on maize yield during 2015–2070 (6.30–37.10%) under RCP 4.5 and RCP8.5 for all treatments (Table 4), but the maize yield decreased during 2071–2100 (from − 14.66 to − 0.79%) under all RCP scenarios (Fig. 4; Table 4). Some studies suggested that the maize yield of northeastern China would decrease under increasing precipitation and temperature, even when CO_2 fertilization was taken into account (Lin et al. 2017; Wang et al. 2011). However, some studies supported our results and indicated that maize production in the rainfed region of northeastern China, where GZL site is located, would increase with increasing CO_2 concentrations (Xiong et al. 2007; Jia and Guo 2010; Zhao et al. 2014). Xiong et al. (2007) indicated that the CO_2 fertilization effect is more beneficial to rainfed maize than to irrigated maize, and a very limited photosynthesis increase in maize under irrigation caused by elevated CO_2 might not offset the adverse impacts in crop production caused by warming temperature. In addition, the maize yield under RCP4.5 and RCP8.5 decreased significantly over time for all treatments, and the crop yield during 2071–2100 was lower than that in baseline (Fig. 4; Table 4). This indicated that the positive effect of climate change on maize yield in northeastern China could not sustain for a long term. Measures to alleviate the long-term effects of climate change on crop yields should be further assessed in this region.

Climate change impact on annual crop NUE

In the present study, future climate change was predicted to decrease crop NUE in both northwestern (42.79% for wheat and 33.73% for maize) and northeastern China (3.97%) under the RCP scenarios for all treatments. The decrease in NUE may partly be due to the reduction in N removal by crops (Table S2) form the soil–crop system. The highest crop NUE values were found under RCP4.5 at PL and RCP8.5 at ZY, where the greatest N removal for either wheat or maize was also predicted (Figure S1–4), and there was no significant difference at GZL for maize NUE and N removal under the RCP scenarios in most periods from 2015 to 2100. The finding is supported by Challinor et al. (2014) who found that total N uptake was affected greatly by plant biomass and that the effect of treatments on N uptake was similar to their effect on grain yield. In addition, decreased crop NUE might have also resulted from the increase in N loss through leaching, surface runoff and denitrification under the RCP scenarios (Table 5). The concentrated and large rainfall could promote N loss in the form of NO_3^- through leaching and surface runoff in China (Zhou et al. 2012), which would reduce crop NUE.

Although the crop NUE all decreased in northwestern and northeastern China, the magnitude of reduction in northwestern China (2.37–77.62%) was greater than the reduction in the northeast (1.31–15.85%) with smaller decreases in crop N uptake (Table S2) and N loss (Table 5) under future climate changes. The contrasting results may be related to the overall levels of the NUE in the two regions. The crop NUE in the northeast (42.11–73.61% for maize) was generally greater than in the northwest (6.66–49.75% for wheat and 22.12–68.10% for maize), which indicated more efficient nutrient management in the northeast to maintain crop NUE than in the northwest. The patterns of NUE changes in the two regions may also be related to their different climatic characteristics. Association of NUE with regional climates has been reported elsewhere, too. In a study with synchronized experiments, Ying et al. (1998) pointed out that due to the influence of climate, NUE of rice in the Yunnan Province of China (subtropics) was much greater than that in the Philippines (tropics). In the USA, Swaney et al. (2018) found that over the past 30 years the wheat NUE decreased by almost 13% in temperate continental climate zone but by only 3% in temperate meadow climate zone. Furthermore, maize had greater NUE than wheat in both northeastern and northwestern China (Figs. 5, 6) between 2015 and 2100 under baseline and RCP climate scenarios, and the decrease in maize NUE (1.31–58.43%) was lower than wheat (0.35–77.62%) under most RCP scenarios for all treatments (Table 4). Those patterns may be because that the optimum temperature of C3 plant for gross photosynthesis was lower than that of C4 plants (Graß et al. 2015). C4 plants had a high CO_2 fixing efficiency that led to a high crop yield per unit of plant-N accumulation, and a higher utilization rate of N inside plants (even C3 plants) had a higher absorption rate and accumulation in the same soil N level (Rowan and Robert 1987).

Fertilization impact on annual NUE

Crop yields increased with both chemical and organic amendments under all future climate scenarios, and there was no significant difference between NPK, NPKM and NPKS for wheat or maize yield (Figs. 3, 4). This indicated that the total N applied had likely met the requirement of wheat and maize in the study regions.

The response of crop NUE varied with fertilizer treatments, though future climate decreased crop NUE under most RCP scenarios. For an individual climate scenario, wheat and maize NUEs from NPK and NPKM treatments were significantly greater than NPKS in both northwestern and northeastern China (Figs. 5, 6). In addition, the grain and stover N contents of wheat and maize in NPKM were higher than other treatments (Figure S1–4). Thus, the NPKM treatment appeared to be the most sustainable fertilizer strategy under future climate change. The combination of inorganic fertilizers and manure could effectively increase soil total N and available N contents, which had likely contributed to the greater NUE of NPKM than NPKS (Sommerfeldt et al. 1988). After 17 years of fertilization, the total N and available N contents in the 0–20 cm soil layer at GZL were 1.88 g kg^{-1} and 184.94 mg kg^{-1} for NPKM, respectively, which were higher than the respective 1.53 g kg^{-1} and 131.21 mg kg^{-1} in NPKS (Zhang et al. 2012). In addition, manure can improve soil microbial environment and promote nutrient absorption by crops, leading to a greater N uptake (Zhong et al. 2010). As shown in a 30-year fertilizer experiment at PL, furthermore, manure amendment resulted in higher soil enzymatic activities of urease with 9.42 mg NH_3 kg^{-1} h^{-1} than NPS with 7.93 mg NH_3 kg^{-1} h^{-1} (Liu et al. 2010b), which may have also contributed to the promoted NUE in the manure treatment combined with chemical fertilizers. In addition, considering the fact that crop NUE can change with the proportion of inorganic N in total N applied (Swaney et al. 2018), further study should focus on identifying appropriate N proportions of manure and chemical fertilizer to achieve balance between crop production and environmental sustainability.

Table 5 Annual leached N loss, runoff N loss and denitrification N loss of Zhangye, Pingliang and Gongzhuling under all climate scenarios between 2015 and 2100 (kg N ha^{-1})

Treatment	Climate scenarios	Zhangye			Pingliang			Gongzhuling		
		Leached loss	Runoff loss	Denitrification loss	Leached loss	Runoff loss	Denitrification loss	Leached loss	Runoff loss	Denitrification loss
CK	Baseline	61.69	1.19	11.62	61.46	7.33	22.69	43.71	2.42	22.28
	RCP2.6	79.35	2.52	12.41	65.83	7.34	22.80	49.30	3.92	25.82
	RCP4.5	73.10	2.73	13.18	60.51	6.86	24.65	46.97	3.33	25.98
	RCP8.5	63.16	2.92	14.81	60.12	8.24	27.55	46.56	5.20	30.09
NPK	Baseline	253.94	1.27	10.96	90.99	7.79	17.05	87.96	0.98	13.18
	RCP2.6	277.85	2.82	11.19	99.21	8.44	17.20	102.22	1.78	18.08
	RCP4.5	276.94	3.05	12.02	97.92	7.42	18.36	95.76	1.69	19.35
	RCP8.5	256.54	3.18	13.28	99.95	9.19	20.88	98.72	3.03	24.90
NPKM	Baseline	322.55	1.17	10.66	139.24	7.75	17.06	73.52	0.88	13.05
	RCP2.6	349.48	2.82	11.25	137.02	8.40	17.40	85.15	1.74	17.89
	RCP4.5	349.38	3.01	11.98	134.02	3.91	17.14	79.54	1.71	19.26
	RCP8.5	333.27	3.13	13.22	116.83	5.11	18.95	82.67	3.02	24.69
NPKS	Baseline	–	–	–	104.91	5.48	18.85	72.33	1.03	13.64
	RCP2.6	–	–	–	130.71	4.47	16.09	83.67	1.91	18.44
	RCP4.5	–	–	–	118.51	3.92	16.97	78.34	1.81	19.69
	RCP8.5	–	–	–	104.65	5.12	18.89	79.85	3.16	25.09

Conclusions

This study demonstrated the successful validation of the SPACSYS model for simulating crop yields and N uptake in wheat–maize rotation in arid and semiarid regions and in maize monoculture system in semi-humid region of China. The study supports to expanding the application scope of SPACSYS to simulate N cycling, and results provide strong evidence on the response of crop yield and NUE to future climate changes and different fertilizer treatments in northern China. As predicted by SPACSYS, future climate change would reduce wheat and maize yields in northwestern China, increase maize yield in north-eastern China and decrease NUE in both regions during 2015–2100. Compared with chemical fertilizer and straw amendment, combined applications of manure and chemical fertilizers had the greatest potential to mitigate the negative impacts of climate change on crop N uptake and NUE. The findings of this study can help to develop nutrient management strategies for improving crop yield and N use efficiencies while reducing environmental N losses. In the future, more research is needed to optimize the combination of manure N and chemical N to address risks associated with climate change.

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