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Modeling nitrogen leaching in a spring maize system under changing climate and genotype scenarios in arid Inner Mongolia, China

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ABSTRACT

Although the impacts of climate change on crop yield and production in China have been studied, the potential impacts on nitrate leaching are less well-known. In this study, we considered how climate change and crop genotypes with different N uptake capacities could affect soil water drainage, nitrate leaching, and grain yield under currently optimized irrigation and fertilization practices in the spring maize system of northwest China. After testing the performance of the WHCNS (soil Water Heat Carbon Nitrogen Simulator) model, a total number of 420 simulations spanning representative climate projections (2036–2065), genotypes, and time spans led to three key findings. First, the projected climate changes had no significant effects on soil water drainage and thus no impact on nitrate leaching, because the latter was primarily influenced by drainage. Second, the effects of genotype changes on reducing nitrate leaching via increasing N uptake were marginal over the whole growth period, again because these had no significant effect on soil water drainage. Finally, the projected yield reduction (around 6.5%) occurred only in the hottest climate scenario (RCP8.5), in which transpiration was probably a more significant parameter leading to yield differences between climates. We conclude that, to offset the projected yield reduction due to temperature increases, improved agricultural technologies and practices will be needed to cope with decreased crop transpiration. In addition, reducing nitrate leaching through genetic improvement of N uptake should not be considered a research priority for mitigating the effects of current and projected climate scenarios.

1. Introduction

Nitrogen (N) is an essential nutrient for most crops that can be provided directly by fertilization or indirectly through atmospheric deposition, irrigation water, or fixation, all of which can then be converted to nitrate through mineralization and nitrification (Randall and Mulla, 2001). Incomplete N utilization by crops produces residual soil nitrate, which is water soluble and susceptible to leaching into groundwater, particularly in regions dominated by light-textured sandy soils with low water-holding capacity. This process can reduce nitrogen use efficiency and result in negative environmental consequences such as eutrophication and other water quality issues (Daniel et al., 1998; De Jong et al., 2008).

Nitrate leaching in agricultural field conditions is complex and site-specific. Numerous studies have conducted in-situ experiments in agricultural ecosystems in order to better understand the potential impacts of environment and field management (e.g., irrigation and fertilization) on nitrate leaching (Dirnbock et al., 2016; Kurunc et al., 2011; Poch-Massegú et al., 2014; Tarkalson et al., 2006; Wiesler and Horst, 1993; Woli and Hoogenboom, 2018). However, the direct determination of nitrate leaching based on field experiments is time-consuming and costly with regard to the complicated interactions of crops with environment and management, which can be characterized as "Genotype × Environment × Management". Therefore, process-based crop models have become a common and useful method for effectively and inexpensively evaluating nitrate leaching under varying conditions including different cropping systems and environmental settings.

Although extensive research exists with regard to best management practices for the reduction of nitrate leaching under different soil and climate conditions (Doltra and Muñoz, 2010; Kurunc et al., 2011; Li et al., 2007; Woli et al., 2016), the effects of climate change are less

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Abbreviations: E_a, Evaporation; T_a, Transpiration; ET_a, Evapotranspiration; WHCNS, soil Water Heat Carbon Nitrogen Simulator

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understood (Dirnbock et al., 2016). Whilst it is clear that alterations in temperature and precipitation patterns will have a significant impact on crop yields, it is less certain whether the implementation of current field management practices will be sufficient to maintain nitrate N leaching levels in the context of climate change.

Crop N uptake is another factor with the potential to influence nitrate leaching. Although modern crop science has increased the grain yield per unit of applied N, research has yet to fully consider how crop varieties with different N uptake capacity could reduce nitrate leaching in addition to optimizing their use of N fertilizers. Our most recent study considered the impacts of climate change on crop yield and how to develop varieties to cope with these changes (Qin et al., 2018), while a field lysimeter study conducted by Carey et al. (2017) used two crops with different N uptake capacities to test their effect on nitrate leaching. Their results showed that crop type could significantly influence nitrate leaching, leading us to consider whether genotypes with varying N uptake capacity could affect nitrate N leaching.

We focused on spring maize because this is a widely planted and well-adapted crop type in Alxa Left Banner, Inner Mongolia, northwest China, that is quite important to local farmers. Our previous research in this area has focused on the optimization of irrigation and fertilization application to reduce nitrate leaching, but in this study we focused on nitrate leaching loss in regard to genotype with the goal of maintaining crop yields while protecting the future environment under climate change scenarios.

We used a common process-based agricultural crop model to project the impacts of climate and genotype change on soil water drainage, nitrate leaching, crop N uptake, and yield of spring maize in a light-textured soil under currently optimized irrigation and fertilization practices. Thereby, our study intends to identify future management strategies for maintaining spring maize yields while safeguarding the environment in Inner Mongolia, China.

2. Material and methods

2.1. Study site

The study site was located within Alxa Left Banner in Inner Mongolia, northwestern China (37°24´–41°52´ N and 103°21´–106°51´ E). The soils here are alluvial mixed with gray desert soils (further details given in Table 1). The average annual precipitation in the area is 116 mm, 70%–80% of which occurs in the growing season (April to October); the total potential evaporation (E_a) reaches 3005 mm/year. The single-crop oasis-based cropping system is dominated by spring maize (60%–70% of the farmland). Irrigation is mostly drawn from groundwater at a depth of about 40–70 m (Hu et al., 2008). The groundwater nitrate concentration is around 20.0 mg N L^{-1}, compared to 25.7 mg N L^{-1} for precipitation (Liang et al., 2016b).

Soil samples from depths ranges of 0–20, 20–40, 40–60, 60–80, 80–100, 100–120, 120–140, 140–160, and 160–180 cm were collected during the following seven key crop development stages: sowing, emergence, elongation, tasseling, flowering, booting, and ripening. Each fresh soil sample was extracted with 2 mol L^{-1} KCl to determine the concentrations of NO_3-N using a continuous flow analyzer (TRAACS 2000, Bran and Luebbe, Norderstedt, Germany) (Liang et al., 2016b).

2.2. Model choice

We used the WHCNS process-based agricultural crop model (soil Water Heat Carbon Nitrogen Simulator), which integrates biological, physical, and chemical processes to simulate soil water movement, soil heat and N transport, and crop growth. This model has been used extensively by many studies on the effect of different agricultural management practices on crop yield and N use efficiency (Li et al., 2015; Liang et al., 2018, 2016b). As nitrate leaching is affected by both water flow and N transformation, the WHCNS model is suitable for characterizing the response of nitrate leaching to climate and genotype change under the study area's agricultural cropping system. A particularly strong point of the model is its detailed description of soil E_a, crop transpiration (T_a), soil water movement, soil temperature, soil inorganic N immobilization in biomass, nitrification, and crop growth (Liang et al., 2016a). This allows the WHCNS model to analyze the effects of various agricultural management practices (such as sowing date, crop rotation, irrigation, and fertilizer application) on water and N dynamics along with crop growth. As previous studies have described the model's main framework and presented its parameters along with a sensitivity analysis (Liang et al., 2016a), we do not provide further detail here.

2.3. Model calibration, evaluation, and statistical analyses

The WHCNS model was calibrated and evaluated using a two-year (2008–2009) field experiment with different irrigation and fertilizer treatments presented in our previous study (Liang et al., 2016b). The basic crop parameters for modeling, listed in Table 2, were adopted from (Hu et al., 2008). Three statistical indices were used to evaluate model performance. First, the root mean square error (RMSE) was used to summarize the total differences between observed and simulated values. Second, the index of agreement ($0 < d < 1$) was used as a descriptive measure as it is both a relative and bounded measure (Willmott, 1982): the closer the value of d is to 1, the better the model performance. Third, a paired-t test conducted by SAS PROC TTEST software (SAS, 2009) was used to test the differences between observed and simulated values. The effects of climate scenarios, genotypes, and their interactions on WHCNS-simulated outputs were analyzed by using SAS PROC GLM software (SAS, 2009).

2.4. Model development

Historical daily weather measurements from 1981 to 2010 were

Table 1
Physical and hydraulic properties of a soil profile at the study site in Alxa Left Banner, Inner Mongolia, China (Hu et al., 2008).

Soil Layer (cm)	BD (g cm^{-3})	Particle fraction (%)			Texture (USDA)	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (cm^{-1})	n	K_{sat} (cm d^{-1})
		Sand	Silt	Clay						
0–25	1.42	31.4	66.5	2.1	Silt loam	0.041	0.33	0.0179	1.77	62.6
25–45	1.45	62.8	36.2	1.0	Sandy loam	0.135	0.36	0.0097	1.62	80.6
45–60	1.44	28.6	69.0	2.4	Silt loam	0.109	0.36	0.0238	1.50	51.4
60–70	1.44	78.8	19.9	1.3	Loamy sand	0.078	0.26	0.0208	1.45	70.6
70–90	1.48	10.1	85.0	4.9	Silt	0.119	0.29	0.0333	1.61	33.1
90–123	1.36	83.4	15.5	1.1	Loamy sand	0.071	0.27	0.0285	1.31	34.6
123–160	1.26	13.0	82.4	4.6	Silt	0.079	0.25	0.0352	1.25	41.5
160–180	1.62	74.3	24.9	0.9	Loamy sand	0.075	0.24	0.0188	1.18	62.6

Note: BD is bulk density; $\boldsymbol{\theta_r}$ is the residual water content; $\boldsymbol{\theta_s}$ is the saturated water content; $\boldsymbol{\alpha}$ is the inverse of the air-entry value; n is a pore size distribution index; $\boldsymbol{K_{sat}}$ is the saturated hydraulic conductivity.

Table 2
Main crop parameters used in the WHCNS model (Hu et al., 2008).

Parameters	Description	Maize
Tbase	Base temperature (ºC)	10
Tsum	Accumulated temperature (ºC)	1700
Ke	Extinction coefficient	0.6
K-ini	Crop coefficient in initial stage	0.6
K-mid	Crop coefficient in middle stage	1.2
K-end	Crop coefficient in end stage	0.7
SLA-max	Maximum specific leaf area ($m^2\,kg^{-1}$)	30
SLA-min	Minimum specific leaf area ($m^2\,kg^{-1}$)	12
AMAX	Maximum assimilation rate ($kg\ ha^{-1}\,h^{-1}$)	50
R-max	Maximum root depth (m)	1.2
N_{min}	Minimum crop N concentrations when N is non-limited ($kg\ N\ m^{-2}$)	1.1

obtained from the China Meteorological Data Service Center point data set (http://data.cma.cn/). We used daily weather variables (precipitation, maximum temperature, minimum temperature, humidity, solar radiation) for the current climate (baseline years 1981–2010) and followed the methods described by Lobell et al. (2015) to develop the future climate. We also used three general circulation models (GCMs) (BCC-CSM1.1 (m), CSIRO-Mk3.6.0, and HadGEM2-AO) that were proven by the fifth coupled model inter-comparison project to be suitable for capturing temperature and precipitation tendency in China (Ying and Chong-Hai, 2012). Two representative concentration pathways, RCP4.5 and RCP8.5, were used with a future climate time horizon of 2050 (2036–2065). Considering the data availability for climate scenarios, we assumed that the weather inputs for modeling were the same as the baseline scenario, except for temperature and precipitation. The CO_2 concentration for the future climate was held at the baseline value (354 ppm). The annual mean temperature and accumulative precipitation for the growing season are shown in Fig. 1 and the main model parameters are shown in (Table 2). For spring maize, we used two levels of N uptake genotypes: the current level ($N_{uptake} = 1.1$) and an increased level ($N_{uptake} = 1.3$).

2.5. Simulation design

After comprehensively considering the impact of climate and genotype in our study area, we defined 4 simulation runs combining varying amounts of climate and genotype change: 3 (GSMs) × 2 (climate scenarios, RCP4.5 and RCP8.5) × 2 (genotypes) × 30 (years) + (one baseline) × 2 (genotypes) × 30 (years) = 420. The relevant field management practices are shown in Table 3. Practices such as irrigation and fertilization are time-dependent and critical for water and nitrogen balance. The scheme for spring maize in our case was adopted from Hu et al. (2008), and takes the timing of seeding, irrigation, and fertilization into consideration in the optimization criteria. The pure nitrogen fertilizer rate is 138 ($N\ kg\ ha^{-1}$), which is within a reasonable range compared to the locally recommended fertilization rate for spring maize (Li et al., 2012). The N that leached out of the root zone (120 cm) could not be easily utilized by crops again. However, it is possible for upward soil water movement to carry nitrogen back to the root zone. Therefore, we set the soil profile as 180 cm for a robust simulation based on the soil profile structure. It was assumed that the nitrogen that moved beyond this depth could not be utilized by the crop. The nitrogen content in the seeds was about 20 ($g\ kg^{-1}$), while the seeding rate in our case was 30 ($kg\ ha^{-1}$). The nitrogen input from seeds is less than 1 ($kg\ ha^{-1}$) and therefore ignored in the nitrogen balance calculations. The initial soil water content and nitrate concentration in the soil profile was fixed for each climate × genotype × year run and the field management was fixed based on optimized recommendations defined by previous research (Liang et al., 2016b). Although in reality such practices could change over time as plant breeding and agronomic research develops, this approach was intended to provide a projected baseline for the future.

3. Results and discussion

3.1. Initial model performance

Fig. 2 shows the measured and simulated soil water content and nitrate concentration with calibrated model parameters using 2008 field data. In general, the simulated values agreed well with the measured values at all depths. The model parameters were further evaluated using three statistical indices and 2009 field data (Table 4). The WHCNS model accurately predicted soil water content and nitrate concentration and produced good results with regard to biomass and grain yield. These results demonstrated that the model is acceptable for simulating soil water, N movement, and crop growth in the study area, so we proceeded to an analysis of the soil water drainage, crop N uptake, nitrate N leaching, and yield with regard to changes in climate and genotype.

3.2. Climate change and genotype effects on water drainage and water balance

Changes in climate (RCP4.5 and RCP8.5) did not affect soil water drainage significantly (ANOVA p value = 0.0813) (Table 5). This result fell within our expectations because individual rainfall events in the region seldom exceed 10 mm under any climate scenario and total growing season precipitation only accounts for around 1/3 of the total water input. Therefore, irrigation is the main driving factor for soil drainage. As mentioned above, our previous research in this area had aimed to minimize soil water drainage due to excessive irrigation while

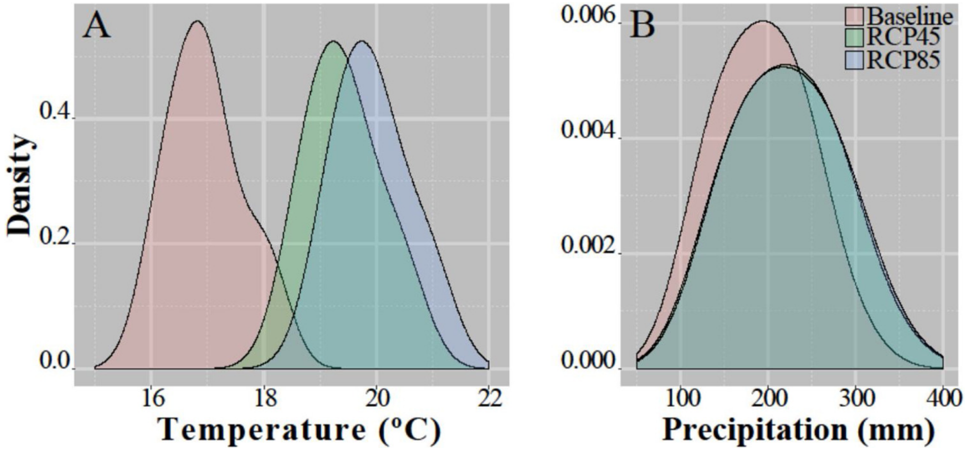

Fig. 1. Frequency distributions of (A) growing season (April to September) mean temperature and (B) average accumulated growing season precipitation for the baseline (1981–2010), RCP4.5, and RCP8.5 climate scenarios. The mean value for the RCP4.5 and RCP8.5 climates was averaged from three general circulation models (BCC-CSM1.1 (m), CSIRO-Mk3.6.0, and HadGEM2-AO).

Table 3
Optimized field management scheme for spring maize in the study area.

Action	Schedule							Seasonal total
		Jun 2	Jun 21	Jul 13	Aug. 3	Aug. 26		
Sowing date	Apr. 12							
Irrigation (mm)		100	100	100	100	90		490
N fertilization (kg N ha^{-1})		138						138
Harvest date							Oct. 18	

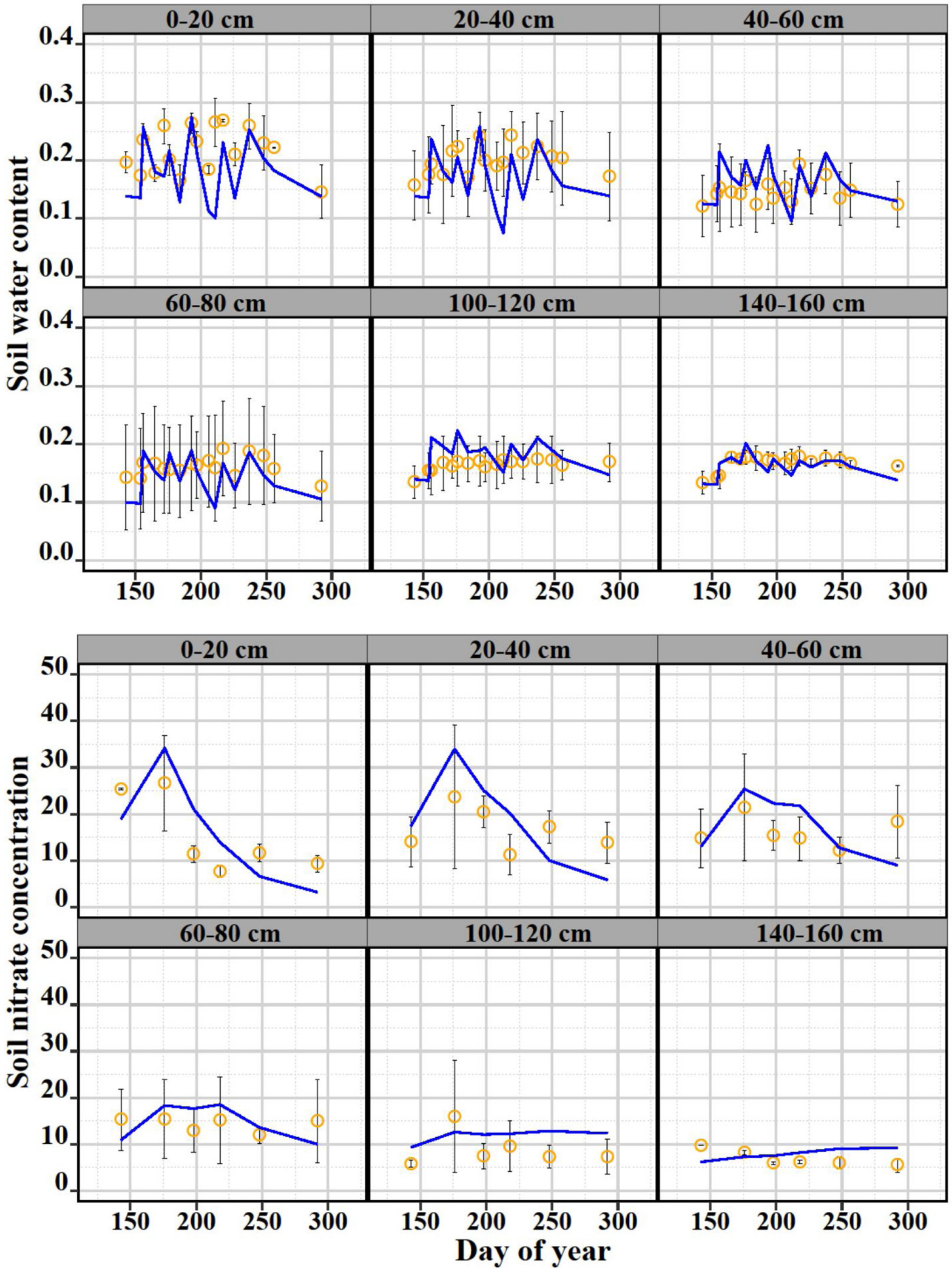

Fig. 2. Comparison of simulated (blue line) and measured (mean ± standard deviation) volumetric water content (cm^3 cm^{-3}) and soil nitrate concentration (mg kg^{-1}) at different depths in a 2008 field test (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 4
Statistical indices of WHCNS model accuracy for soil water content, soil nitrate concentration, biomass, and yield in 2009 (Liang et al., 2016b).

Item	RMSE	d	P
Soil water content ($cm^3\,cm^{-3}$)	0.024	0.816	0.990
Soil nitrate concentration ($mg\,kg^{-1}$)	5.1	0.895	0.892
Biomass ($kg\,ha^{-1}$)	1497	0.990	0.281
Yield ($kg\,ha^{-1}$)	643	0.892	0.285

Note: *P* value from paired t-test.

maintaining high crop yields (Liang et al., 2016b). The minor effect of climate change on soil water drainage indicates that the current water management methods are also appropriate in future climate scenarios in this context.

Table 6 shows the modeling results across the 1.8 m soil profile under the different climate and genotype scenarios. Climate change had a significant effect on the soil water balance. Although there was more water input from increased precipitation and less net water loss from E_a and drainage, the soil water balance decreased with increasing temperature, which we mainly attribute to reduced crop water consumption (T_a). This result agreed with the finding of Hawkins et al. (2013) that the amount of T_a was directly associated with temperature increase. Therefore, in regard to the maximization of water use, it is necessary to further investigate how to cope with decreased T_a due to temperature increase; we did not consider this in the current study.

The changes in genotype had no significant effect on soil water drainage, water balance, and other water-related items. An interactive effect between the genotype and these items was also not apparent (Table 5). The amount of drainage for each climate under the same genotype showed no difference, demonstrating that crop N uptake procedure had a marginal effect on water dynamics (drainage, E_a, and T_a) in our cropping system under current optimized irrigation and fertilizer input levels (Table 6). This can be explained by the fact that these two genotypes are the same in most crop parameters except for in N uptake. Because these two genotypes share the same parameters within the leaf index, their performance in terms of evapotranspiration and drainage are similar, especially when N stress is low. These results matched those of Carey et al. (2017), who reported that crops with different N uptake potential had no significant effect on soil water drainage when N supply was not limited.

3.3. Climate change and genotype effects on N uptake, nitrate leaching, and N balance

The mean crop N uptake was significantly higher in the future genotype ($311.6\,kg\,N\,ha^{-1}$) as compared to the current genotype ($271.3\,kg\,N\,ha^{-1}$) (ANOVA p values < 0.05). This increase was expected because the N_{min} (minimum crop N concentrations when N is non-limited), a sensitive parameter for the process of N remobilization adopted from the Daisy model (Hansen et al., 1991), is critical for determining the final N concentrations at the end of crop growth. This result was also in agreement with the finding of Stockle and Debaeke (1997) that crop N uptake was tightly associated with N_{min} (Stockle and Debaeke, 1997).

The crop N uptake between the baseline and climate scenarios decreased as temperature increased (Table 6). The present crop model regarding N uptake is based on the thermal unit concept, which implies that crop development from emergence to harvest can be described in terms of a temperature sum (Hansen et al., 1991). Temperature increases can aggravate abiotic stress for the process of nitrogen transportation from the soil to the shoot, which could reduce the crop's N concentration (Hansen et al., 1991). This reduction in N uptake occurs in combination with lower above-ground biomass (data not shown) and yield in the future climate scenarios.

The changes in the climate (RCP4.5 and RCP8.5) had no significant effect on nitrate N leaching (Table 6). However, these results did not conform to the findings of several other studies that higher temperature would result in lower nitrate leaching due to an increase in evapotranspiration (ET_a) and soil mineralization rates, thus accelerating the rates of N uptake and crop growth (Schweigert et al., 2004; Wick et al., 2012). Similarly, Jabloun et al. (2015) also suggested that N leaching would increase with an increase in temperature due to an increase in mineralization (Jabloun et al., 2015). The simulated nitrogen leaching

Table 5
Analyses of covariance for WHCNS model output variables' response to climate and genotype change.

Variables	Source	DF	Type III SS	Mean Square	*F*	*P* value
E_a (mm)	Genotype	1	0.0076	0.0076	0.00	0.9970
	Scenario	2	22872	11436	22.12	< .0001
	Genotype × Scenario	2	0.00357	0.00178	0.00	1.000
T_a (mm)	Genotype	1	0.01089	0.01089	0.00	0.9981
	Scenario	2	98227	49114	25.97	< .0001
	Genotype × Scenario	2	0.0227	0.0114	0.00	1.000
ET_a (mm)	Genotype	1	0.003	0.003	0.00	0.9988
	Scenario	2	26351	13175	10.45	< .0001
	Genotype × Scenario	2	0.034	0.017	0.00	1.000
Drainage(mm)	Genotype	1	0.05	0.05	0.00	0.996
	Scenario	2	10289	5144	2.55	0.0813
	Genotype × Scenario	2	0.03	0.02	0.00	1.000
Water balance (mm)	Genotype	1	0.0302	0.0302	0.00	0.9941
	Scenario	2	171190	85595	156.84	< .0001
	Genotype × Scenario	2	0.1036	0.0518	0.00	0.9999
N uptake ($kg\,N\,ha^{-1}$)	Genotype	1	72,955	72,955	108.40	< .0001
	Scenario	2	81492	40,746	60.50	< .0001
	Genotype × Scenario	2	72	36	0.050	0.9478
N leaching ($kg\,N\,ha^{-1}$)	Genotype	1	14	14	0.020	0.8902
	Scenario	2	10	5	0.010	0.9933
	Genotype × Scenario	2	1	0	0.000	0.9997
Nitrogen balance ($kg\,N\,ha^{-1}$)	Genotype	1	70430	70430	87.15	< .0001
	Scenario	2	125939	62970	77.92	< .0001
	Genotype × Scenario	2	87.12	43.56	0.05	0.9475
Yield ($kg\,ha^{-1}$)	genotype	1	235,344	235,344	0.10	0.7541
	Scenario	2	28265080	14,132,540	5.91	0.0033
	Genotype × Scenario	2	176662	88,331	0.04	0.9637

Note: E_a, evaporation (mm); T_a, transpiration (mm); ET_a, evaportranspiration (mm).

Table 6
Water and N balance simulated by the WHCNS model under changing climate and genotype scenarios.

	Item	Genotype$_{current}$			Genotype$_{future}$		
		Baseline	RCP45	RCP85	Baseline	RCP45	RCP85
Water balance (mm)	Irrigation (mm)	490	490	490	490	490	490
	Precipitation (mm)	190	213	215	190	213	215
	E_a (mm)	147	167	174	147	167	174
	T_a (mm)	436	396	381	436	396	381
	ET_a (mm)	584	563	555	584	563	555
	Drainage (mm)	155	141	138	155	141	138
	Balance (mm)	−59.0	−1.3	12.2	−58.9	−1.3	12.2
	Draining ratio %	22.6	19.8	19.3	22.6	19.8	19.3
Nitrogen balance (kg N ha^{-1})	Fertilizer	138.0	138.0	138.0	138.0	138.0	138.0
	Deposition	48.8	54.7	55.2	48.8	54.7	55.2
	Irrigation N	98.0	98.0	98.0	98.0	98.0	98.0
	Net mineralization	83.8	89.6	90.9	83.8	89.6	90.9
	Volatilization	13.0	13.6	13.8	13.0	13.5	13.7
	Crop N uptake	299.9	262.4	251.7	341.8	302.5	290.5
	Denitrification	5.1	6.0	6.3	5.0	6.0	6.3
	Leaching	109.7	110.1	109.5	109.3	109.5	108.9
	Balance	−59.1	−11.8	0.7	−100.5	−51.1	−37.2
	Leaching ratio %	38.3	37.6	37.3	38.2	37.4	37.1
Yield (kg ha^{-1})		11812	11889	11049	11973	11925	11069

Note: E_a, evaporation (mm); T_a, transpiration (mm); ET_a, evaportranspiration (mm).
Water Balance = (Irrigation + Rainfall) – (ET_a + Drainage).
Nitrogen Balance = (Fertilizer + Deposition + Irrigation N + Net mineralization) – (Volatilization + Crop N uptake + Leaching + Denitrification).

was around 110 kg N ha^{-1} (Table 6), which is within a similar range to the results from another field study equipped with a lysimeter for maize (Jia et al., 2014).

Precipitation, field management practices, and genotype theoretically all affect crop growth, water balance, nitrogen balance, and thus nitrate N leaching through the soil.

In our case, neither the climate and genotype nor their interactions had a significant effect on nitrate N leaching (Table 5). The disagreement of our results with those of prior research could be due to the following two reasons. First, climate change did not significantly influence soil water drainage, which has a dominant effect on nitrate leaching. In our case, as growing season precipitation only accounted for 1/3 of the total water input and individual rainfall events in the region seldom exceed 10 mm, irrigation become the main impetus for drainage (unlike studies in other regions). Second, although the increase in growing season precipitation for the climate scenarios was ~13% from the 1981–2010 baseline climate, E_a was projected to increase by ~16%, leading to a relatively small decrease (approximately 10%) in drainage. Similar studies conducted in semi-arid irrigated conditions also found that nitrate leaching through the soil was mainly influenced by irrigation (Chilundo et al., 2018; Tarkalson et al., 2006; Yahdjian and Sala, 2010).

The effects of genotype change on N leaching via increasing N uptake seemed marginal over the whole crop growth period. This differed from our expected hypothesis that increasing N uptake could reduce nitrate leaching. However, as mentioned above, the nitrate leaching is dominated by soil water drainage and so N uptake capacity did not affect the processes of soil water use and drainage. A field study by Wiesler and Horst (1993) observed that maize cultivars showed differences in the utilization of soil nitrate and thus nitrate leaching via different sowing dates. Instead of the genetic improvement of N uptake potential applied in our study, Wiesler and Horst (1993) considered the N uptake behavior of cultivars with regard to the timing of maturity. This mitigation strategy may not be suitable in our study area as the optimal sowing window is very narrow. However, this consideration inspired us to further conduct a detailed genotype × environment × management study that considered changes in heat and precipitation caused by climate change.

Both changes in climate and genotype had a significant effect (ANOVA $p < 0.0001$) on the N balance, which we mainly attribute to their effect on N uptake (Table 5). The N balance was negative under most climate × genotype conditions except for the current genotype under the RCP8.5 climate pathway, illustrating that the current optimized irrigation/fertilizer methods work well for minimizing nitrate leaching and stabilizing the N balance. This also indicates that nitrate leaching has reached an optimized balance where the small amount of leaching seems inevitable based on our current knowledge regarding cropping systems.

3.4. *Climate change and genotype effects on yield*

Among the three climate conditions, only the hottest (RCP8.5) had a significant influence on yield (Table 5). Unlike the dominance of nitrate leaching by drainage, the effect of climate change on crops is complex. A number of recent studies have quantitatively evaluated the direct effects of climate change on maize yield at the field scale using simulation models, showing that a combination of changes in temperature and precipitation can bring either positive or negative effects (Jones and Thornton, 2003; Li et al., 2011; Xiong et al., 2007). Van der Velde et al. (2014) also evaluated the indirect effects of climate change by quantifying the impacts of changing fertilizer use efficiency under future climates, finding that phosphorus applications would have to increase to close yield gaps due to climate change.

Although precipitation in our arid study area is very valuable resource for crop production, its limited availability means that it meets only 15% of crop water demands (Hu et al., 2008; Liang et al., 2016b). Therefore, crops in the RCP8.5 climate could not benefit from the modeled small increase in precipitation. As a combined effect, T_a has been used as an indicator of maize yield, as it is dominated by temperature and available water (irrigation and precipitation) (Fig. 3). Djaman et al. (2013) concluded that T_a had a strong positive relationship with maize yield based on a two year field test. Araya et al. (2017) found that reductions in T_a were mainly caused by a shortening growing period. Similarly, the T_a in our study showed a high correlation coefficient with yield (0.679 and 0.696 for the current and future genotype, respectively) (Fig. 3). Therefore, T_a is probably a major parameter influencing yield differences between the three climate scenarios. In addition, significant yield reductions might occur due to the combined effects of heat stress and a shortening growing period (data not shown). The yield between baseline and mild climate change

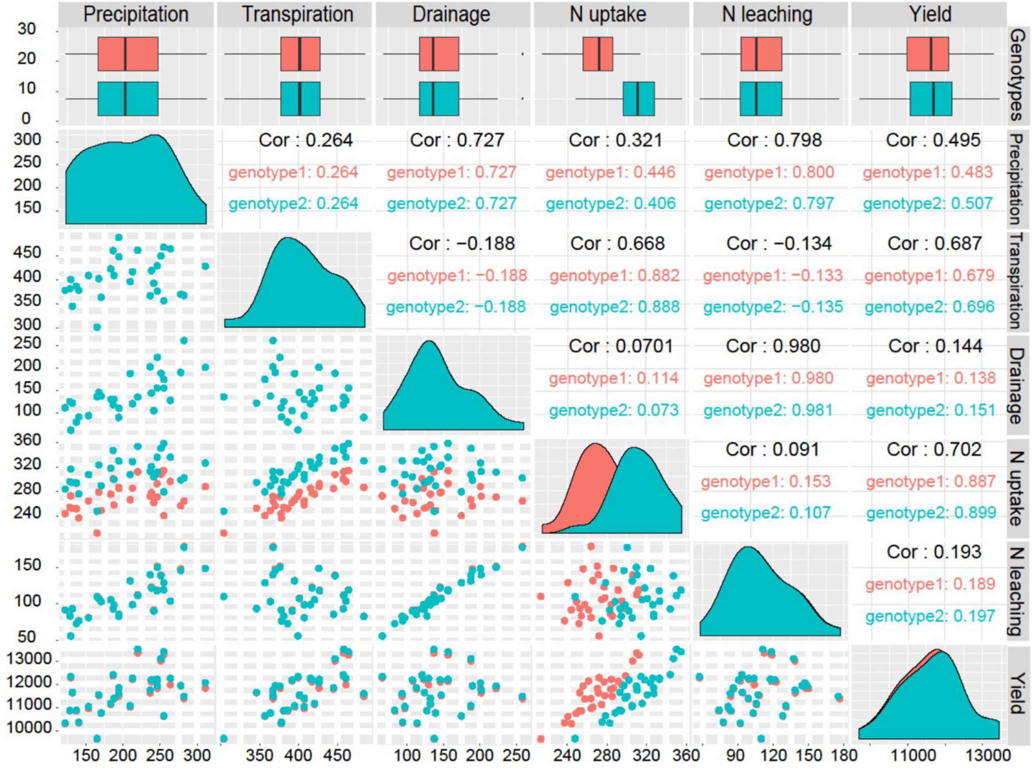

Fig. 3. Correlation matrix for growing season accumulated precipitation, transpiration (T_a), soil water drainage, crop N uptake, soil nitrate leaching, and yield for current genotype (genotype1) and future genotype (genotype2) based on mean of all climate scenarios (baseline, RCP4.5 and RCP8.5).

(RCP4.5) was not significant, indicating that maize yields will be only mildly affected by changes in climate that are less conducive to maize production overall in our growing setting.

Although high N uptake is favorable for crop yields when N supply is limited, the genotype changes in our study did not affect yield significantly under any climate conditions (Table 5), probably due to the maize reaching its actual potential when N is already being managed under an optimized balance. In addition, the yield was a combined function of water, fertilizer, and climate. In our study, fertilizer N and irrigation were used together to maximum maize yield, in which case higher N uptake could not contribute to yield increase when the water supply was otherwise the limiting factor.

The complex Genotype × Environment interaction in our model may not have fully represented the relationship between N uptake and yield since we did not calibrate and evaluate the model with different genotypes. However, we consider the simulated result to be reasonable because 1) the designed future genotype with high N uptake is within a suitable range compared to the previously developed Daisy model (Hansen et al., 1991); 2) a 13% increase in N uptake for a local breeding program is also feasible when compared to the commercially released cultivars in North China (Chen et al., 2013).

The overall integration of climate change impacts on maize yield, as expressed in terms of genotype changes in which local farmers can participate, is clearly extremely complex. However, although this study was not designed to build an ideal type for future climate settings, our results can provide useful guidance for future agronomic breeding research in the study area.

4. Conclusions

Nitrate leaching has long been a focus of agricultural field management research in northwestern China's spring maize cropping system, given the high risk of water pollution in this area. One aspect of this has been the development of crop models with the robust treatment of water, nitrogen dynamics, and crop growth. After establishing the good performance of the WHCNS model for these purposes, we simulated nitrate leaching and other processes in the soil-plant system under baseline and climate change conditions with two genotypes that have different N uptake capacity.

Our results showed that climate changes had no significant effect on soil water drainage in the arid, irrigation-dominated study area. As drainage is the predominant driver of nitrate leaching, the latter was not impacted by climate change. These results indicate that the current optimized irrigation/fertilizer practices work well to minimize nitrate leaching and stabilize the N balance for projected climate changes. They also indicate that nitrate leaching has reach an optimized balance where a small amount of leaching seems inevitable based on current knowledge of the cropping system.

Our study shows that the effect of genotype change on reducing nitrate leaching via increasing N uptake is marginal over the full growth period, which did not match our expectations. However, this result is reasonable as the genotype change did not affect the dominant process of soil water drainage. Therefore, reducing nitrate leaching via genetic improvement of crop N uptake may not be a priority for research on mitigation strategies for climate change. Significant yield reductions were only predicted to occur in the hottest scenario, in which the T_a was probably a major parameter leading to yield difference between the climate scenarios. Therefore, from the point view of maximizing efficient water use, further research should investigate ways to cope with decreased T_a due to temperature increases.

Finally, the WHCNS model may not fully represent the complex Genotype × Environment interactions for the relationship between N uptake and yield since we did not calibrate and evaluate the model with different genotypes even though the simulated N uptake was within a reasonable range. As a final caveat, we note that the WHCNS model does not characterize the crop N distribution within above-ground biomass (e.g., straw and grain N). Further simulations should be conducted to investigate the relationship between N uptake and nitrate leaching in more detail.

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