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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

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; θ_r is the residual water content; θ_s the saturated water content; α is the inverse of the air-entry value; n is a pore size distribution index; K_{sat} is the saturated hydraulic conductivity.