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Response of crop yield and nitrogen use efficiency for wheat-maize cropping system to future climate change in northern China

Shuo Liang[a,b], Yuefen Li[a], Xubo Zhang[b,*], Zhigang Sun[b,c], Nan Sun[d,*], Yinghua Duan[d], Minggang Xu[d], Lianhai Wu[e]

[a] College of Earth Sciences, Jilin University, Changchun 130061, China
[b] Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 100101, China
[c] College of Resources and Environment, University of Chinese Academy of Sciences, Beijing, 100190, China
[d] Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences/National Engineering Laboratory for Improving Quality of Arable Land, Beijing 100081, China
[e] Sustainable Agriculture Systems, Rothamsted Research, North Wyke, Okehampton, Devon EX20 2SB, UK

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ABSTRACT

Climate change and excessive fertilization will threaten the crops yields and nitrogen utilization in coming decades. The aim of this study is to quantify the response of crop yields and nitrogen use efficiency (NUE) to different fertilization strategies and climate change scenarios in the northern China by 2100 using the process-based SPACSYS model. The model was calibrated and validated with the data from four long-term experiments with winter wheat (*Triticum Aestivium* L.) and summer maize (*Zea mays* L.) rotation in the northern China. Five fertilizer treatments based on the long-term experiments were chosen: non-fertilizer (CK), a combination of mineral nitrogen, phosphorus and potassium (NPK), NPK plus manure (NPKM), a high application rate of NPKM (hNPKM) and NPK plus maize straw (NPKS). The model simulations and projections were performed under four different climate change scenarios including baseline, RCP2.6, RCP4.5 and RCP8.5. Validation demonstrated that SPACSYS can adequately simulate crop yields, N uptake and annual NUE for the wheat–maize rotation. Without considering the impact of cultivar change, maize yield would increase by an average of 8.5% and wheat yield would decrease by 3.8%, and the annual NUE would decrease by an average of 15% for all fertilization treatments under RCP climate scenarios compared with the baseline. This might be the interactive effects among elevated CO_2 concentration, more concentrated and intensive rainfall events, and warming temperature. For each climate scenario, manure amendment could alleviate the negative influences of future climate change on crop growth and nitrogen utilization, given that manure applied treatments had higher soil organic matter and persistent supply of nutrients, which resulted in a more stable crop yield and N removal by wheat and maize than other treatments. In addition, the highest and most stable annual NUE (38.70–52.78%), crop yields and N removal were found in hNPKM treatment until 2100. The results could provide a reference for nitrogen fertilization in study regions to improve crop yield and nitrogen use efficiency and minimize environmental risks in the future.

1. Introduction

Nitrogen use efficiency (NUE) is a key indicator to assess the N uptake by crops and can be used to address environmental pollution from mineral N input (Duan et al., 2011; Lassaletta et al., 2014; Raun and Johnson, 1999; Zhang et al., 2015). It has been widely reported that NUE of main crops approximately reach to 30% in China, which is far lower than that in United States (approximately 65%) and other developed countries (Duan et al., 2014; Lassaletta et al., 2014; Liu et al., 2010b). Especially in the north of China, a main cereal production area dominating by a wheat-maize rotation (Li et al., 2015; Xiao and Tao, 2016; Zhao et al., 2009), NUE is only about 16–18% due to excessive use of mineral N from 1987 to 2015 (*ca.* 200% of increment) (Cui et al., 2010; National Bureau of Statistics of China, 2016). Improper utilization of mineral N led a huge N loss to the environment *via* greenhouse gas (GHG) emissions, ammonia volatilization and leaching with the fact

* Corresponding authors.
E-mail addresses: zhangxb@igsnrr.ac.cn (X. Zhang), sunnan@caas.cn (N. Sun).

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Table 1
Information of location, climate type and initial soil properties of four experimental sites.

Items	Changping (CP)	Zhengzhou (ZZ)	Xuzhou (XZ)	Yangling (YL)
Starting year	1990	1990	1981	1990
Location	116°15′22″E 40°13′22″N	113°40′00″E 34°47′00″N	117°17′30″E 34°17′00″N	108°00′48″E 34°17′51″N
Climate type	Semi-humid	Semi-humid	Semi-humid	Semi-arid
Annual temperature, °C	11.0	14.5	14.0	13.0
Annual precipitation, mm	600	632	860	575
Annual evaporation, mm	2310	1450	1870	993
Irrigation[a], mm	300	225	–	270
Irrigation times	2(wheat) 2(maize)	3(wheat) 2(maize)	–	1(wheat) 2-3(maize)
Aridity index	0.65	0.83	1.16	0.84
Plot size, m^2	200	400	33.4	196
Replicates	1	1	4	1
Soil type	Haplic Luvisol	Calcaric Cambisol	Calcaric Cambisol	Cumulic Anthrosol
Initial SOC[b], g kg^{-1}	7.10	6.60	6.26	7.44
Total N[b], g kg^{-1}	0.79	0.65	0.66	0.83
Available N, g kg^{-1}	0.05	0.08	0.07	0.06
Total P[b], g kg^{-1}	0.69	0.65	0.74	0.83
Olsen P, mg kg^{-1}	4.6	6.5	12.0	9.6
Total K[b], mg kg^{-1}	14.6	16.9	22.7	21.6
Available K, mg kg^{-1}	65.4	74.0	62.0	194.0
pH	8.2	8.3	8.2	8.6
Bulk density, g cm^{-3}	1.58	1.55	1.25	1.35
Clay, %	10	13	6	17

[a] Both wheat and maize season had irrigation.
[b] SOC means soil organic carbon; N means nitrogen; P means phosphorus; K means potassium.

that cereal crop yields however did not increase obviously (Driscoll et al., 2003; Zhang et al., 2015; Zhu and Chen, 2002). Thus, maintaining a high productivity level while promoting NUE should be achieved urgently for China's agricultural sustainability.

Future climate has been projected that temperature and precipitation will increase by 1.0–5.0 °C and 9–11%, respectively, and CO_2 concentration will increase to 560 ppm at the end of this century (Ju et al., 2013; Meehl et al., 2007), which further brings more challenges for agricultural production (Challinor et al., 2014; Graß et al., 2015). It has been reported that future climate change would be highly likely to have a negative impact on agricultural productivity in the northern China (Xiao and Tao, 2016). It has been proved that changes in temperature, precipitation, solar radiation and CO_2 concentration would alter NUE of crops through the changes in crop N removal and N losses from a plant-soil system (Dahal et al., 2014; Fujimura et al., 2015; Ma et al., 2010; Meng et al., 2014). Thus, clarifying the effects of climate change on crop yields and NUE is highly needed for maintaining agricultural productivity and reducing N losses for food security and a clean environment in the northern China.

Previous studies indicated that grain yield and NUE for the main crops can be maintained or increased by the appropriate fertilization strategies reasonably (Benbi and Biswas, 1997; Chen et al., 2013). It was reported that NUE of wheat in the treatment with balanced application of N, P and K fertilizers (NPK, with an average of 49.5%) was significantly higher than that in the treatment with N applied alone (with an average of 10.5% and an annual decreasing rate of 1.2%) in four typical soils of China (Yan et al., 2011). In addition, mineral fertilizers combined with animal manure resulted in a higher and stable yield compared with NPK after 15 years fertilization for wheat and maize in China, and the highest mean NUE (49%) was from NPKM treatment (Duan et al., 2014). A long-term experiment in the Northeast of China indicated that 18 years of manure or straw incorporation improved 218% and 192% of maize yield compared with no fertilization, respectively (Zhang et al., 2012). It also indicated that NPK plus manure led to the highest soil fertility, which further promoted the productivity and stability of wheat and maize yields at Xuzhou (Jiang et al., 2006).

Simulation models have been used for quantitatively assessing the effects of future climate change on crop growth and N utilization as field or laboratory experiments could be time consuming and expensive (Dueri et al., 2007; Li et al., 2014, 2017; Zhang et al., 2016c). However, studies on modeling N utilization mainly focused on N transfer progresses in the plant-soil systems, and very rare studies focused on simulation and prediction of NUE in agricultural systems (Gabrielle et al., 2002; Hansen et al., 1991; Kaur et al., 2012; Probert et al., 1998). The SPACSYS model that is process-based and at field scale, provides detailed processes of plant growth and development, carbon (C) and N cycling and water redistribution (Wu et al., 2007, 2015) and has been proved that the model has capable on simulating and predicting the impacts of climate change on the grain yields of wheat and maize, the GHG emissions and the stocks of soil C and N in China (Zhang et al., 2016a,b,c). Although the model has been applied in various environmental conditions and field management practices, it is still needed to validate it with more experimental datasets and test it with broader climatic conditions, especially the projected climates. Thus, it would be helpful to use the model to address how cereal crop growth and N utilization responds to climate change with different fertilization strategies in the north of China.

Our objectives of this study are to calibrate and validate the SPACSYS model in terms of grain yield and N removal based on the datasets from the long-term fertilization trials (more than 20 years) located in the north of China; and to assess the effects of various climate change scenarios with fertilization strategies on the yield, N removal and NUE of wheat and maize by 2100 in this region.

2. Methods and materials

2.1. Study site and experimental design

Long-term field experiments (more than 20 years) with a typical double cropping (wheat-maize rotation) from four sites were used in this study. The sites were located in Changping (CP), Zhengzhou (ZZ), Xuzhou (XZ) and Yangling (YL). The long-term experiment in Zhengzhou where it is also located in the study region of northern China has been used to validate the model (Zhang et al., 2016c). In this study, simulated crop yields of ZZ from the previous study were used directly to calculate the average yield of northern China during the prediction period. However, the ZZ site will be treated the same as the