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Reducing greenhouse gas emissions from a wheat–maize rotation system while still maintaining productivity

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ABSTRACT

High-input agriculture in China has successfully increased crop productivity in the past decades, but at a significant environmental cost. It is essential to improve management strategies to mitigate greenhouse gas (GHG) emissions and other environmental costs, while maintaining grain yields. However, there is a lack of studies to evaluate mitigation strategies under long-term climate variability. This paper combines field experimental data and soil–plant systems modeling to investigate the potential for improving water and nitrogen management of a wheat–maize double cropping system in North China Plain. The APSIM model was calibrated against the data and then applied to simulate crop yield and N_2O emissions from soil in response to irrigation and nitrogen inputs. Our results show that the N fertilizer rate and irrigation amount under the local farmer practice could be reduced by 28% and 14% without sacrificing crop yield. This in turn led to a reduction in GHG emissions by 31%, mainly attributed to the decrease in emissions from the production and transportation of N fertilizer and direct N_2O emissions from soil. Additionally, the results indicate that the direct N_2O emissions from soil was positively correlated with N inputs, implying an increasing emission factor (N_2O produced per unit of N input) with N application rates. It is concluded that potential exists to optimize N fertilizer rate and irrigation amount to reduce GHG emissions while still maintaining crop yield in the agro-ecosystems in North China Plain.

1. Introduction

Increases in agricultural inputs to produce more food and satisfy global demand has caused substantial greenhouse gas (GHG) emissions. It is responsible for 10–12% of total global anthropogenic emissions of GHG, and for approximately 60% of nitrous oxide (N_2O) and 50% of methane (CH_4) emissions (IPCC, 2007, 2014). In China, GHG emissions from agricultural production systems in 2005 account for more than 15% of China's total GHGs, nearly 90% of N_2O and 60% of CH_4 emissions (Wang et al., 2010a). The North China Plain (NCP) is one of the most intensive agricultural regions in China, providing more than 50% and 33% of nation's wheat and maize production (Liang et al., 2011). It contributes a large portion to the national total GHG emissions, especially N_2O. It is important to improve the agricultural management to increase or maintain productivity, while reducing the associated environmental costs.

In the NCP, approximately 70% of the total cultivated land is under a winter wheat–summer maize cropping rotation (Zhang et al., 2006). The total N fertilizer inputs are as high as 600 kg N ha^{-1} yr^{-1} (Zhong et al., 2006) and irrigation water use in some regions can reach 420 mm per year (Liu et al., 2004). The high inputs of synthetic N fertilizer and irrigation water have led to increased N_2O emissions (Zhang et al., 2014), accompanied by the energy costs and CO_2 emissions associated with lifting water from wells for irrigation and the production and transport of N fertilizer (Lal, 2004; Zhang et al., 2013). Additionally, depletion of groundwater resources and pollution of surface and groundwater bodies have caused serious environmental and ecological problems (Liu et al., 2001, 2005). In recent years, China's population growth has slowed (Peng, 2011) and China is becoming increasingly self-sufficient in terms of grain production. There is an urgent need to re-assess the management strategies to improve the eco-efficiency of the cropping systems, that is, to maintain the same productivity with less GHG emissions and other environmental costs.

While a few recent studies have attempted to address these issues, there is still a lack of knowledge to assess management practices under long-term climate variability. Chen et al. (2014) showed that reduction in GHG emissions per unit yield production could be achieved by optimizing N applications based on data from 1 to 4 years experiments, with no detailed information on the impact of long-term climate variability on agricultural inputs and crop productivity. Li et al. (2008) simulated the response of N_2O emissions to N fertilizer application and climatic variability using the WNMM model, while Li et al. (2010) analyzed the potential for reducing GHG emissions based on long-term simulations of

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Table 1
Soil property at Huantai.

Depth (m)	BD (g cm^{-3})	pH	OM (g kg^{-1})	TN (g kg^{-1})	LL (mm mm^{-1})	DUL (mm mm^{-1})	SAT (mm mm^{-1})
0–0.2	1.42	8.29	18.81	1.09	0.100	0.338	0.424
0.2–0.4	1.64	8.83	13.18	0.68	0.110	0.280	0.341
0.4–1.1	1.43	8.67	9.89	0.51	0.110	0.320	0.420
1.1–1.7	1.55	8.61	4.41	0.35	0.120	0.310	0.375
1.7–2.0	1.65	8.66	2.75	0.27	0.140	0.280	0.337

BD — bulky density, OM — organic matter, TN — total nitrogen, LL — lower limit of plant extractable water content, SAT — saturated water content, DUL — water content at drained upper limit.

soil organic carbon (SOC) and N_2O using the DNDC model, but their analysis did not include upstream emissions from agricultural input.

The agricultural production system model (APSIM) simulates the responses of both the productivity and environmental impacts (e.g. soil carbon change and sequestration, GHG emissions, N leaching) of cropping systems in response to environmental changes and management interventions (Holzworth et al., 2014). It also offers flexibility to specify management options and crop rotations. Previously, it has been successfully used in China to evaluate impact of climate and management variations on crop productivity and resource use efficiency (Fang et al., 2010; Guo et al., 2010; Wang et al., 2010b). However, it has not been tested and adopted to evaluate influence of climate variation and management practices on GHG emissions from agro-ecosystems in China.

The objectives of this study are to: (1) further test the APSIM model to simulate crop yield, soil water and N dynamics, including N_2O emission under different N treatments at Huantai site in North China Plain, and (2) use the validated model to explore management strategies that have the potential to reduce application of N fertilizers and irrigation and the subsequent GHG emissions, while still maintaining the grain yields under long-term climatic conditions.

2. Material and methods

2.1. Field site and experimental data

A two-year (2008–2010) field experiment was conducted in Huantai County, Shandong Province (36°58′N and 117°59′E, groundwater table of 8–12 m). The site is about 17 m above sea level, with a typical temperate monsoon climate (annual mean air temperature of 13.9 °C and average annual precipitation of 547 mm for the period 1990–2010) and a wheat–maize cropping rotation system representative of the production in the NCP. The wheat cultivar Jimai-22 and maize cultivar Huanfeng-16 were used in the experiment. Before the experiment started, the site was under a maize–wheat–maize rotation, that is, two seasons of maize and one season of wheat were grown from June 2007 to September 2008. No fertilizers were applied in the pre-experimental period in an effort to equalize soil fertility in space. The soil is classified as a Calcaric Cambisol (WRB, 2006) with a silt loam texture. Other soil properties are given in Table 1.

Four N treatments were applied: no N (CK), farmer conventional N (FC-N), reduced N (RE-N) and reduced N with manure (RE-NM; Table 2). There were three replicates of each treatment applied in a random block design. For wheat and maize, the N fertilizer was applied at sowing (basal N application) to soil depth of 20 and 10 cm, respectively, followed by top-dressing N at the jointing stage (wheat) and the large bell stage (maize) to the soil surface. In all treatments, the basal P and K fertilizers were also applied, which contained 45 kg P ha^{-1} and 50 kg K ha^{-1} for wheat, and 48 kg P ha^{-1} and 91 kg K ha^{-1} for maize. Before sowing wheat, the maize residue was incorporated into the surface 0.2 m layer with a rotary tiller. The wheat residue was left on the soil surface after harvest and the maize was subsequently sown through the wheat residue.

Wheat biomass was sampled at emergence, tillering, jointing, flowering and harvest stages of growth. Maize biomass was sampled at jointing, large bell, silking, milk ripe and harvest. Plant samples were oven-dried and weighed to determine the biomass. The N content in biomass and grain were determined using semimicro-Kjeldahl digestion (Thomas et al., 1967). Soil water content was measured with a time domain reflectometry (Trime-IPH) down to 120 cm depth with 20 cm of interval every 7 days from 14 April 2009 to 10 November 2009.

Soil samples for measuring nitrate (NO_3^-) content (0–10 cm) were taken daily for approximately 10 days following fertilization and biweekly in the remaining period. The three replicated subsamples were taken immediately to the field laboratory and frozen at −18 °C. After thawing at 4 °C for 24 h, 12.0 g of fresh soil was extracted with 50 mL of a KCl-solution (2 M, shaken for 30 min). Extracts were frozen at −18 °C and later analyzed with an automated nitrogen analyzer (San++ Continuous Flow Analyzer, Skalar Analytical B.V., Netherlands). Soil NO_3^- concentration (mg L^{-1}) was converted to kg ha^{-1} using soil bulk density, soil depth, weight of wet soil extracted and water content.

N_2O fluxes were measured with static, opaque chambers, which were mounted onto the permanently installed base frames. The chambers were

Table 2
The experimental design at Huantai.

Treatments				Wheat	Maize
Four N treatments (kg N ha^{-1})	CK	Base N		0	0
		Top-dressing N		0	0
	FC-N	Base N		126(U) + 36(DP)	122(U) + 43(DP)
		Top-dressing N		108(U)	165(U)
	RE-N	Base N		54(U) + 36(DP)	77(U) + 43(DP
		Top-dressing N		90(U)	120(U)
	RE-NM	Base N		54(ON) + 36(DP)	77(U) + 43(DP
		Top-dressing N		90(U)	120(U)
Flood irrigation (mm)		2008–2009	Times	3	1
			Amount	180	60
		2009–2010	Times	4	1
			Amount	280	70
Dry residue amount returned before each season (kg ha^{-1})			2008–2009	4160	4215
			2009–2010	4875	3487

U, DP, and ON denote urea, diammonium phosphate, and composted chicken manure, respectively. Irrigation and residue practices for four N treatments are all identical.