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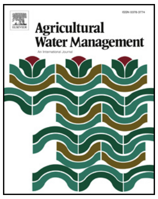

Improving nitrogen and water use efficiency in a wheat-maize rotation system in the North China Plain using optimized farming practices

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ABSTRACT

Excessive nitrogen (N) application and shortage of water are the major obstacles to sustainable agricultural development in the high-yielding regions of the North China Plain. New cropping systems need to be created that use integrated management practices to improve the utilization of nitrogen and water and to reduce the emissions of greenhouse gases. We conducted a 4-year (2011–2015) field experiment in Huantai county using three cropping treatments: local farmers' conventional practices (FP), recommended farming management (REC), and no N fertilization (CK). The study revealed that, the mean annual grain yield of FP and REC was both 16.5 Mg ha^{-1} which was higher than CK (7.9 Mg ha^{-1}). In comparison with FP, the REC treatment showed N fertilizer and groundwater input reduced by 43% and 28% with increasing of 79.3% and 61.7% of N use efficiency (NUE) and irrigation water use efficiency (IWUE), respectively. The REC treatment demonstrated consistently lower N_2O emissions (36% on average) compared with the FP treatment. The annual net global warming potentials of the REC and CK treatments were 37% and 73% lower, respectively, than that of the FP treatment. The water footprint of the REC treatment was 30% (the Water Footprint Assessment method) to 37% (the Life Cycle Assessment method) less than that of the FP treatment. These results indicate that REC is a promising and feasible treatment for ensuring environmentally friendly, and energy-efficient sustainable agriculture in the high-yielding regions of the North China Plain.

1. Introduction

The North China Plain (NCP) is one of the most important grain production regions in China produced 67% of nation's wheat and 28% of nation's maize (NBSC, 2015), and wheat-maize rotation is the main cropping system in the region (Tian et al., 2017; Zhang et al., 2017a). In the conventional cropping systems, excessive irrigation (up to 667 mm yr^{-1}, Shi et al., 2013) and over-fertilization (550 − 600 kg N ha^{-1}, Ju et al., 2009; Tan et al., 2017) have been adopted as the key farming practices since the 1980s to achieve high crop yields. These had resulted in lower efficiency of irrigation water and nutrient use and increasing greenhouse gas (GHG) emissions and non-point source agricultural pollution (Yang et al., 2015a, b; Huang et al., 2017; Tan et al., 2017). To address these challenges, high-output, low-pollution agriculture, with highly efficient use of fertilizer and water, has been suggested and implemented in recent years by the Chinese government and farmers in the country in general and in the NCP in particular (Chen et al., 2014; Li et al., 2015).

Many studies have been conducted in the NCP on how to improve water and nutrient use efficiency and to reduce GHG emissions while maintaining a high crop yield (Hartmann et al., 2015; Yan et al., 2015; Wang et al., 2016a; Meng et al., 2017). Trials have been carried out on optimized fertilization and irrigation (Lin et al., 2015), a combination of mineral and organic fertilizers (Ding et al., 2013; Gao et al., 2015), optimum nitrogen (N) fertilization with straw incorporation (Huang et al., 2013a), and deep tillage (Wang et al., 2016b). These investigations demonstrated promising agronomic and environmental benefits and have been used to make recommendations for better farming practices. However, most of these studies focused on only one or two of the above-mentioned measures. In reality, farmers need to adopt several measures to improve farming practices and production. A key hypothesis is that an integration of the previously mentioned farming practices would allow high productivity, efficient utilization of water and fertilizer resources, and low GHG emissions. The effectiveness of

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these practices depends highly on edaphic and climatic conditions (Cai et al., 2013; Tan et al., 2017), and therefore field studies of only one or two seasons' duration cannot sufficiently address temporal variations across different farming years. Thus, there is an urgent need to study the efficacy and sustainability of integrated farming management practices through long-term field experiments.

Agricultural irrigation is the major source of water consumption in agriculture system. In previous evaluations of water utilization, the amount directly used for irrigation was used as the main indicator of agricultural irrigation use. However, this ignores the indirect water consumption from the production chemical fertilizers and other agricultural materials, water utilization by the soil, and the effect of fertilizer and pesticide pollution on water resources. To address these shortcomings, Hoekstra created the water footprints (WF) concept (Hoekstra and Hung, 2002). The WF is a comprehensive indicator of freshwater use and has three components: blue, green, and grey water. The green, blue, and grey WF components refer to the consumptive use of rainwater, surface and groundwater, and the freshwater required to assimilate the load of pollutants, respectively (Hoekstra et al., 2011). The WF evaluation broadens the connotation of the traditional water resources evaluation system, establishes relationships between physical and virtual water, and accurately reflects the ownership of, and demand for, water resources. The Water Footprints Assessment (WFA) method is used to calculate water resources in agro-ecosystems (Hoekstra et al., 2011). The Life Cycle Assessment (LCA) method is also used in agro-ecosystems (Liang, 2009; Liang et al., 2018). Ridoutt and Pfister (2010) suggested that the WF should be expressed as a single index (H_2O-eq) in the same manner that the carbon footprint is expressed as CO_2-eq. A water stress index has also been introduced to compare the water consumption impacts and water scarcity among different countries and regions (Jeswani and Azapagic, 2011). Both the LCA and WFA methods can be used to compare the water resource utility of different products, services, and systems (Zonderland-Thomassen and Ledgard, 2012; Herath et al., 2013; Lovarelli et al., 2016).

In the present study, to study the environmental problems caused by over application of fertilizer in the NCP region, a four-year (from 2011 to 2015) field experiment was carried out in an intensively farmed wheat-maize production area in the NCP. The aim of the study was to analyse the effects of integrated management practices on crop production, N and water utilization, and GHG emission reduction.

2. Materials and methods

2.1. Experimental site

A long-term field experiment was established in October 2008 at the Agro-ecosystem Experiment Station of the China Agricultural University, Shandong Province (36.57 °N, 117.59 °E). This area has a temperate monsoon climate, with a dry and cold season from October to May, and a wet and hot season from June to September. The soil is classified as an aquic inceptisol (a calcareous, fluvo-aquic clay loam). The soil has bulk density of 1.5 g cm^{-3}, pH of 7.7, soil organic matter (SOM) content of 18.75 g kg^{-1}, and total N (TN) content of 1.1 g kg^{-1}. The initial SOM and TN contents in soil layers was shown in Table S1.The growing year was from October of the current to October of the following year. Daily precipitation and mean air temperature over the experimental period was shown in Fig. 1. In summary, annual precipitation and mean air temperature were 404 mm and 13.1 °C, respectively, in the 1st year; 775 mm and 12.2 °C in the 2nd year; 355 mm and 13.9 °C in the 3rd year; and 466 mm and 13.7 °C in the 4th year.

2.2. Experiment designing and field management

A randomized block design was employed with four replicates for each of the three treatments: (1) local farmers' conventional practices (FP), based on the local average rate of N fertilization and irrigation, maize straw burning (ash was buried into soil), wheat straw incorporation (buried into soil), and rotary tillage (~15 cm) before wheat sown; (2) recommended farming management (REC), with optimized N fertilization (balanced N fertilization and the partial substitution of mineral N with organic manure), water-saving irrigation, wheat and maize straw incorporation (buried into soil), and deep tillage (~25 cm) before wheat sown; and (3) no N fertilization (CK), reduced irrigation, straw incorporation (left on the ground), and no tillage. Each experimental plot had an area of 25 × 18 m^2. Detailed N fertilizer and irrigation over the experimental period were presented in Table 1.

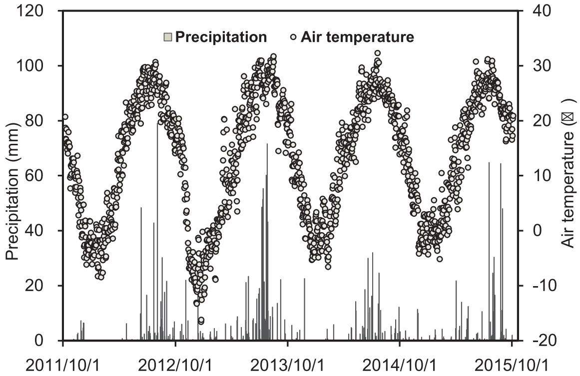

Fig. 1. Daily precipitation and mean air temperature during the 4-year study period.

For FP treatment winter wheat was sown in early October, and maize was interplanted with wheat at the end of May. For REC and CK treatment the cropping system was wheat and maize rotation, winter wheat was sown in early October, summer maize was planted in the middle of June. In the FP treatment, urea was applied at 300 kg N ha^{-1} yr^{-1} for winter wheat and summer maize, respectively. The ratio of N as basal fertilizer to top-dressing (at the shooting stage) fertilizer during the winter wheat and summer maize seasons was 1:1. In the REC treatment, the amount of fertilizer N applied depended on the crop N requirements and the amount of residual soil nitrate-N (0–100 cm) present before sowing (balanced N fertilization) (Cui et al., 2008). In this practice, nitrate-N was measured before fertilization, and the amount of nitrate-N fertilizer was calculated as crop N requirement minus the amount of residual soil nitrate-N. For REC, one third of N was applied from broiler manure as basal fertilizer for winter wheat and

Table 1
Nitrogen (N) input rate and groundwater input during the 4-year study period.

		N input rate (kg ha^{-1})			Groundwater input (mm ha^{-1})		
		FP	REC	CK	FP	REC	CK
Wheat	2011–2012	300	92(31)	0	300	225	225
	2012–2103	300	71(24)	0	200	150	150
	2013–2014	300	218(73)	0	300	225	225
	2014–2015	300	211(70)	0	400	300	300
	Mean	300	148(50)	0	300	225	225
Maize	2011–2012	300	194(65)	0	200	150	150
	2012–2103	300	182(61)	0	300	150	150
	2013–2014	300	210(70)	0	300	225	225
	2014–2015	300	181(60)	0	200	150	150
	Mean	300	192(64)	0	250	169	169
Annual	2011–2012	600	286(96)	0	500	375	375
	2012–2103	600	253(85)	0	500	300	300
	2013–2014	600	428(143)	0	600	450	450
	2014–2015	600	392(130)	0	600	450	450
	Mean	600	340(114)	0	550	394	394

Numbers in brackets are the N input from manure application. Data of grain yield are means ± standard error (n = 4).