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Modelling to increase the eco-efficiency of a wheat–maize double cropping system

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ABSTRACT

The winter wheat- summer maize rotation is the main cropping system in the North China Plain (NCP). While its productivity has been constantly increased, the sustainability of the double cropping system has been increasingly questioned due to the high resource use and negative environmental impact. This paper combined field data with scenario modelling to investigate the productivity, resource (water and nitrogen) use efficiency and environmental impact of the wheat–maize rotation in response to management changes at a representative site Wuqiao in NCP. In addition the potential options to increase the system's eco-efficiency, i.e., producing more with less input and less negative impact on the environment were explored. The results show that 180 kg/ha/year of nitrogen could be considered as the optimal N rate for summer maize. For the wheat–maize double cropping rotation, 225 mm of irrigation water for wheat and 330 kg N/ha (150 for wheat and 180 for maize) are required to maintain the potential grain yield at 18 t/ha and to have minimum impact on environment in terms of N leaching to the groundwater and N loss due to denitrification. These derived rates are 175 mm/year less and 120 kg N/ha less than the highest irrigation and N rates currently practiced. The reduced water and N inputs could reduce the annual totals of drainage, N leaching and denitrification N loss to a minimum of 117 mm, 12 kg N/ha and 28 kg N/ha, respectively. Our simulation results also enabled derivation of yield response curves to water and nitrogen inputs, which can be used to optimise N applications under various levels of irrigation water inputs.

1. Introduction

The winter wheat- summer maize double cropping system in the North China Plain (NCP) has been considered as an example of successful intensification of agricultural systems (Wang et al., 2012). The system produces two crops per year with the growing season of wheat from October to June and of maize from June to early October. The total grain production in NCP accounts for >50% and >33% of the nation's wheat and maize productions (Liang et al., 2011), respectively. While its productivity has been constantly increased in the last four decades, the intensive use of water for irrigation and chemical fertilizers has led to serious negative impacts on the environment (Wang et al., 2008), leading to cessation of surface water flows, depletion of ground water resources, pollution to surface and ground water, and increase of greenhouse gas emissions (Ju et al., 2009). Therefore, the sustainability of the double cropping system has been increasingly questioned.

Considerable experimental work has been conducted to investigate possible ways of increasing grain yield for both winter wheat and summer maize crops in the NCP. In order to maximise grain yield of winter wheat, irrigation needs to be applied and the amount of water needed for irrigation changes with the inter-annual variation of rainfall in the wheat season. One to three times of irrigation (each 75–80 mm) was recommended in the middle to northern part of the NCP (Li et al., 2005; Wang et al., 2000; Wang et al., 2004b; Zhang et al., 2005; Zhang and Yu, 2003). Pre-sowing irrigation of winter wheat is considered to be essential for achieving both high yields and high water use efficiency (WUE) (Lan and Zhou, 1995; Wang et al., 2000; Wang et al., 2004b; Zhang et al., 2006). For the summer maize crop, since its growing period

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coincides with the summer rainy season, irrigation is not necessary in most years. To maintain the maximum yield level of both crops, the recommended nitrogen (N) application rate ranges from 150 to 240 kg N/ha/year for wheat and 90 to 360 kg N/ha/year for maize, respectively (Du et al., 2009; Liang et al., 2011; Lü et al., 2011; Qin, 2012; Wang et al., 2009; Wang, 2004b; Wu, 2005; Zhang, 2009; Zhao et al., 2006). While such recommendations aim to target the maximum crop productivity, high rates of water and N inputs often result in low resource use efficiency. Furthermore, local farmers often apply irrigation and N fertilizers at higher rates than recommended, exacerbating the water and nitrogen problems and the negative impact on the environment.

Further experimental research in recent years has focused on understanding of the processes controlling crop water and nitrogen uses both temporally and spatially. Due to the contrast in climatic conditions and in the length of the growing seasons, along with hereditary characteristics, winter wheat can grow much deeper roots (up to 200 cm) than maize (up to 120 cm) (Wu, 2005; Wu et al., 2009; Zhou et al., 2008). The shallower maize root system together with the concentrated summer rainfall allows water and nitrogen to move below the maize root zone, leading to potentially significant water and nitrogen losses into the groundwater system. However, due to the coincidence of the end of maize growth and the end of the rainy season, the water and nitrogen in those deeper layers do not move further. The deep-rooted winter wheat crop is able to take up a large fraction of the water and nitrogen back before the next rainy season comes (Wu et al., 2009; Zhou et al., 2008). Such differences in use of water and nitrogen by the two crops across time and soil depth create an opportunity for better management of water and nitrogen applications for improved efficiency. However, this result was only based on experimental work in a couple of years, an understanding of the impact of the long-term inter-annual climate variability is still lacking. Such understanding is essential for development of management strategies to improve water and nitrogen use efficiency under the variable climate.

Agricultural systems modelling has been proven to be an effective means to investigate the potential impacts of climate variability and management interventions on crop productivity, resource use efficiencies, and environmental impact of farming systems. In recent years, the farming systems model APSIM (Keating et al., 2003; Wang et al., 2002) has been intensively used as a tool to analyse the yield and resource use efficiency of the wheat-maize system in NCP. Several studies showed that once the model was properly calibrated, it was able to predict the biomass growth, grain yield, crop water and nitrogen uptake in response to water and nitrogen supply (Chen et al., 2010a,b,c), therefore it can be used to explore strategies for increasing water and nitrogen use efficiencies in NCP (Chen et al., 2010a; Fang et al., 2010). One modelling study that focused on possible ways to increase the eco-efficiency of the double cropping system has indicated real potential to increase production while reducing environmental risks (Carberry et al., 2013). The concept of eco-efficiency is to promote eco-friendly production systems, higher eco-efficiency means a system can produce more grains with less input and less impact on the environment. In spite of these previous studies, there is still a lack of systematic investigation on how application of water and nitrogen interacts to determine production and environmental outcomes in the wheat-maize double cropping systems in NCP, which is essential for understanding the impact of declining groundwater resources for irrigation, and its subsequent consequences.

In this study, we combine field measurement data, cropping systems modelling, and scenario analysis to investigate the productivity, resource (water and N) use efficiency and environmental impact of the wheat-maize double cropping systems as they respond to management changes at the representative site of Wuqiao in NCP. Availability of irrigation water is considered as a main driver influencing systems performance, because it is the most limiting factor at the study site. Environmental impact is expressed as water and nitrogen losses that could otherwise contribute to the productive use of resources. The aim is to explore potential options to increase the eco-efficiency of the wheat-maize system in the future, i.e. producing more grain with less water and N inputs and less negative impact on the environment.

2. Materials and methods

2.1. Study site, climate and experimental data

The study was carried out at Wuqiao (WQ) site (37°41′N, 116°37′E, altitude 20 m above sea level, groundwater Table 6–9 m) in the middle of Heilonggang Catchment in Hebei Province, China. The study site was characterised by a summer monsoon climate, with average annual temperature of 12.9 °C and annual rainfall of 550 mm (1961–2010). About 64% of the annual rainfall is received in the summer months from July to September. For the wheat–maize double cropping system, the growing season of wheat is from mid-October to early June, and of maize from mid-June to early October. The soil at the site is classified as a Calcaric Fluvisol (FAO, 1990) with a sandy clay loam texture and a deep soil profile down to at least 200 cm. The topsoil (0–20 cm) had a pH of 7.8 and contained about 11.7 g kg^{-1}organic matter, 0.78 g kg^{-1}total N, 0.02 g kg^{-1}available P, and 0.30 g kg^{-1} available K. Detailed soil profile characterisation can be found in Zhao et al. (2014)

Data used for further model verification (for wheat) was from field experiments (Table 1) conducted at the Wuqiao site in 2009–2010 wheat growing seasons (Exp 1) and 2009–2010 wheat-maize rotation seasons (Exp 2). Exp 1 covered the impact of five N application rates on wheat growth under sufficient water supply, while Exp 2 covered impact of four irrigation levels under enough N supply. All the experiments were conducted with randomized complete block design with irrigation water supply ranging from 75 mm to 375 mm per season and fertilizer-N (urea-N) application rates ranging from 0 to 330 kg N/ha, each with three replicates. In Exp 1, the wheat cultivar 'Shijiazhuang 15′ was sown on 12 October with plant densities 570 plants m^{-2}. In Exp 2, the wheat cultivar 'Shijiazhuang 8′ was sown on 12 October with plant densities 600 plants m^{-2}. Weeds, insect pests and diseases were properly controlled and the crops were not limited by other nutrients. Crop samples were collected 5–7 times from 0.2 m^2 quadrates to measure leaf area index (LAI), above-ground biomass, grain yield and yield components. LAI was measured using LI-COR 3000c. All plant samples were oven dried at 70 °C to constant weight to measure biomass. At maturity stage, plants from 2 m^2 were harvested for the determination of grain yield.

Daily climate data from 1961–2012 including daily maximum and minimum temperature, rainfall, and sunshine hours were obtained from the weather station of Wuqiao County. Daily solar

Table 1
Water and nitrogen treatments in experiments conducted at Wuqiao

Experiment	Irrigation treatments[a]	N application[b] (kg N/ha)	Wheat cultivar
Exp1	W3	0, 123, 192, 261, 330	Shijiazhuang15
Exp2	W1, W2, W3, W5	158	Shijiazhuang8

[a] W1–W3 represents one to three times of irrigation, each of 75 mm applied at sowing, jointing and flowering, respectively. W5–75 mm applied at sowing, upstanding, jointing, booting and mid grain filling.

[b] All the N was applied at sowing if N rate was less than 123 kg N/ha. Otherwise, 123 kg N/ha was applied at sowing, and the rest at jointing.