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Performance of different cropping systems across precipitation gradient in North China Plain

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ABSTRACT

Overuse of groundwater for irrigation under the current high yielding wheat-maize double cropping system has led to quick depletion of groundwater resources in North China Plain (NCP). Experimental work conducted for a relatively short period (several years) to explore water-saving cropping systems at limited sites offers useful, but limited insights regarding future sustainable cropping systems in NCP to balance productivity and groundwater usage. An understanding of the performance of various alternative cropping systems under the long-term inter-annual climate variability across the precipitation gradient in NCP is needed, but yet lacking. Our study provides a systematic assessment on productivity and environmental impact of 5 alternative cropping systems along a precipitation gradient across NCP, through combination of cropping systems modelling and scenario analysis. Our results show that the groundwater neutral cropping systems change from single summer maize, single spring maize, to wheat-maize double rotation from dry to wet areas across the precipitation gradient. Water restriction will inevitably lead to crop yield reduction (by 2–9 t/ha) and water saving depending on the choice of alternative cropping systems and location precipitation. Reduced water availability for irrigation will also reduce the amount of mineral nitrogen required and the associated N loss to the atmosphere and to the ground water. The reduction on N input was estimated to be 20–190 kg N/ha/year and N loss was 5–35 kg N/ha/year for the most productive cropping systems under rainfed conditions. A value for groundwater use is also estimated based on the extra grain yield produced with irrigation. The results provide the scientific basis for the design of future sustainable cropping systems, and future policies for water pricing and agricultural inputs (water and nitrogen).

1. Introduction

North China Plain (NCP), the largest agricultural production area in China, plays a principal role in ensuring China's food security. The emphasis on food security in the past has led to the development of the high input (i.e. intensive use of groundwater for irrigation > 300 mm/year and application of mineral nitrogen fertilizers > 300 kg N/ha/year) and high-yielding (> 15 t/ha/year) wheat-maize double cropping system in NCP. Such development has also led to severe negative impacts on the environment (Wang et al., 2008) such as rapid depletion of ground water resources, pollution of water ways and increased greenhouse gas emissions (Zhao et al., 2015). Groundwater levels in certain areas of the NCP have declined more than 40 m over the last four decades (van Oort et al., 2016). Clearly, the water consumption of the current winter wheat - summer maize double cropping system in this region is not sustainable (Yang et al., 2015). Climate change with predicted temperature rise and precipitation reduction would further aggravate the ground water shortage in the NCP (Xiong et al., 2009). Therefore, in recent years, the overall performance of the double rotation systems has been attracting increasing attentions due to concerns regarding food security under climate change and also been challenged for the environmental impacts of cropping systems especially on available water resources (Zhao et al., 2015). The continuous groundwater depletion must be stopped to conserve the aquifers and to avoid further negative ecological impacts (Wang et al., 2008).

Considerable experimental work has been conducted to investigate possible ways of reducing irrigation input so as to reduce groundwater usage in the NCP. This includes changing to water-saving cropping

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systems and improving water use efficiency (Fang et al., 2010; Zhang et al., 1999; Zhang et al., 2004). Increasing water use efficiency helps ensure sustainable use of the limited groundwater resources at regional and site-specific levels in NCP, but is not a sufficient solution to the problem of declining water resources (Kendy, 2003; Kendy et al., 2004). Liao and Huang (2004) indicated that alternative cropping systems which require less water may be helpful to mitigate the water shortage problem. Winter wheat–summer maize-spring maize rotation (three crops in two years) and monoculture system such as continuous spring maize (one crop a year) had been studied as alternatives to examine the possibility of replacing the conventional system of winter wheat-–summer maize rotation in order to reduce water use but still maintain the productivity at acceptable level (Liu et al., 2008a; Liu et al., 2008b; Zhang et al., 2011). Meng et al. (2012) through a six years field study, found that 35% and 61% of irrigation water could be reduced in winter wheat-summer maize-spring maize rotation and continuous spring maize cropping systems, respectively, compared to conventional winter wheat-summer maize rotation cropping system. And the yield reduction were 16% (4.9 t/ha) and 31% (9.2 t/ha), respectively. However, annual groundwater use was still 190 mm in winter wheat-summer maize-spring maize rotation and 94 mm in continuous spring maize cropping system. Sun et al. (2011), through 2 years field study at two sites in NCP, found that the groundwater consumption in the continuous spring maize cropping system was on average 139 mm per year.

The winter wheat-summer maize rotation practice will have to be replaced in the near future (Wang et al., 2008; van Oort et al., 2016). It is unclear when exactly ground water use will become economically impracticable, but that moment is upcoming. Middle ground options (e.g. with less or more efficient irrigation) have been studied intensively especially in the northern part of NCP (van Oort et al., 2016; Xiao et al., 2017). One possible crop management option would be under zero irrigation with rainfed agriculture. Zero irrigation would increase the ground water recharge: in wet years part of the precipitation will drain below the root zone, replenishing the aquifer, even though the yield penalties of zero irrigation are very large (Wang et al., 2008).

Despite those previous studies, there is no comprehensive research on the effect of different cropping systems on total annual crop production and groundwater recharge across precipitation gradient in NCP. In addition, results from previous studies were mainly based on experimental work in a couple of years with limited types of cropping systems. An understanding of the impact of the long-term inter-annual climate variability and together with various alternative cropping systems (such as continuous winter wheat or summer maize) across precipitation gradient in NCP is still lacking.

The objective of this paper is to investigate the impact of different alternative cropping systems on the total productivity (crop yield), water use (ET), ground water recharge, nitrogen (N) demand by crops and N loss from leaching and denitrification. We also analyse the potential impact on economic return and regional water resource with the possible future scenario in the NCP when irrigation would no longer be possible, and compare these with the current practice. Due to the availability of experimental data to have confidence in simulation of the wheat and maize crops and also considering the importance of wheat and maize crops in the near future of NCP, we focus on wheat- and/or maize-based cropping systems only in this study. At least for the near future, a complete shift from full irrigation to completely rainfed agriculture is unlikely in certain areas of NCP. In that case, we further analysed the value of the groundwater used for irrigation of crops.

2. Method

2.1. Study region and site selection

Six sites (Fig. 1) were selected based on annual precipitation from the observational stations of the National Meteorological Networks of Central China Meteorological Agency (CMA), to represent the north-south precipitation gradient across NCP. The study region was characterised by a summer monsoon climate, with 71% of the annual precipitation concentrated in the summer maize growing season from June to September (Table 1).

Historical climate data from 1961 to 2012 were obtained from CMA, including daily average, maximum and minimum temperature, sunshine hours, and precipitation. Sunshine duration was converted into daily solar radiation using the Angstrom formula (Angstrom, 1924).

2.2. APSIM model and its parameterization

The APSIM model (Holzworth et al., 2014; Keating et al., 2003; Wang et al., 2002) version 7.5 was used to simulate above-ground biomass, grain yield, and water use of wheat and maize crops at the study sites. In APSIM, phenological development of wheat and maize crop from emergence towards maturity is driven by accumulation of thermal time, with the rate of accumulation modified by vernalisation and photoperiod for wheat and photoperiod for maize before floral initiation. Growth of aboveground biomass is simulated using stage-dependent radiation use efficiency (RUE) together with the intercepted radiation. RUE is further modified by suboptimal temperatures and stresses of water and nitrogen if the water and/or nitrogen supply is not sufficient to meet the crop demand. A detailed description of APSIM can be found on http://www.apsim.info.

APSIM has been extensively validated for wheat and maize in NCP. For general performance of APSIM, we rely on the model validation (> 32 sites across NCP) of previous studies (Chen et al., 2010a,b,c; Gaydon et al., 2017; Li et al., 2014; Li et al., 2016; Sun et al., 2015; Sun et al., 2016; van Oort et al., 2016; Wang et al., 2013; Wang et al., 2012; Wang et al., 2014; Xiao et al., 2017; Zhang et al., 2012; Zhao et al., 2015; Zhao et al., 2014a,b) where they showed that the APSIM model was able to predict the crop biomass growth, grain yield, crop water and nitrogen uptake of wheat and maize in response to water and nitrogen supply in NCP.

During the past fifty years, cultivars of both wheat and maize were changed frequently. For the long-term simulations described below, to eliminate the impact of cultivar changes, the modern summer maize cultivar 'ZD958' and spring maize cultivar 'XY335', and the modern wheat cultivars 'JM22' were used with cultivar parameters obtained from Chen et al. (2010a) and Xiao et al. (2017), respectively. Tables 2 and 3 summarise the key cultivar parameters used for wheat and maize crops, respectively. In all simulations, winter wheat and summer maize were sown in October and middle of June based on the typical sowing time in NCP. Spring maize was sown in early April which has been demonstrated to be the best sowing time for high yields (Tao et al., 2013). Table 4 summarises the sowing dates used for different crops and sites.

Typical soil in this study area was a loam like soil with light loam texture in the surface and changing to clay loam in deep soils to a depth of 2 m at least. For simplicity, we used one typical soil to conduct the simulations (Table 5). Maximum root depth of winter wheat and maize were set to 2 m and 1.2 m respectively, according to the finding of Zhou et al. (2008) and Wu et al. (2009). This gives a potential available water capacity (PAWC) of 410 mm for wheat and 245 mm for maize.

2.3. Cropping system types

Five types of cropping system were simulated for the analysis in this study (Table 6). The winter wheat-summer maize (Wt-Mz) double cropping rotation is the current dominant system practiced under irrigated conditions. We used it as the baseline for comparing to the alternative cropping systems in Table 6.