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Impact of different cropping systems and irrigation schedules on evapotranspiration, grain yield and groundwater level in the North China Plain

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ABSTRACT

Water shortage is the most limiting factors for the crop production in the North China Plain (NCP). The alternative cropping systems and the water-saving irrigation schedules are the main measures to reduce the groundwater level decline. In this study, APSIM model was used to simulate the effects of four different cropping systems (winter wheat and summer maize cropping system (WW-SM); winter wheat cropping system (WW); summer maize cropping system (SM); winter wheat –summer maize – spring maize cropping systems (WW-SM-sM)) under four different irrigation schedules (normal irrigation (NI); critical irrigation (CI); minimum irrigation (MI); and rain-fed (RF)) on evapotranspiration (ET), water use efficiency (WUE) groundwater table level and crop water productivities in the NCP. Results showed that the WW-SM cropping system had the higher grain yield and ET under NI, CI, MI, and RF conditions. Grain yield reduction (GYR) was decreased with the irrigation amount decreased for the WW cropping system, SM cropping system, and WW-SM-Sm cropping systems which ranged from 21.59% to 48.11%, from 16.71% to 46.93%, from 15.82% to 43.92%, and from 5.09% to 27.22% under the NI, CI, MI and RF irrigation schedules, respectively. For WUE and the economic water use efficiency (WUEe), WW-SM and WW-SM-sM had the higher value, WW and SM had the lower value. The differences for the different cropping systems were mostly caused by the grain yield and the soil evaporation. Meanwhile, the water-saving irrigation schedules and cropping systems both could reduce the groundwater table decline compared to that under normal irrigation and traditional cropping system. There all had the significant impact on groundwater table changes for both the irrigation schedules and cropping systems. However, water restriction will lead to crop yield reduction and water saving depending on the chosen alternative cropping systems and irrigation schedules. Results strongly suggest that the critical irrigation and WW-SM-sM cropping system could mitigate the groundwater over-exploitation and ensure the food safety in the NCP.

1. Introduction

Water shortage is becoming the most serious threaten to the sustainable development of agriculture in the North China Plain (NCP), where produced more than 5.3% of the national grain yield whereas the water resources are less than 0.6% of the national total (2009–2013) (Fang et al., 2010; Luo et al., 2018). In order to obtain the higher agricultural production, groundwater has been pumped to irrigate in the past 40 yrs which resulted in the groundwater table continuous decline (Sun et al., 2015; van Oort et al., 2016; Kang et al., 2017). The annual groundwater overdraft has averaged approximately 6 billion $m^3 year^{-1}$ over the past ten years in the Hebei province (Announcement of the Hebei provincial government, 2016). Groundwater overuse was mainly caused by the winter wheat and summer maize double cropping system (WW-SM) because the evapotranspiration (ET) of the double cropping system was approximate 850–900 mm (Liu et al., 2002; Shen et al., 2013; Zhang et al., 2013a,b) while the annual precipitation was between 487 mm and 520 mm with a high variation from 300 mm to 1000 mm (Sun et al., 2010; Cao et al., 2014). Most of the precipitation occurred in the maize season

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(July–September) and water deficit mainly occurred in the winter wheat season (Sun et al., 2006, 2010; Iqbal et al., 2014). Usually, winter wheat is sown at the beginning of October and harvested in the middle of June in the following year; summer maize is sown immediately after wheat harvest and harvested at the end of September. Therefore, the contradiction between production and water consumption for the double cropping system has been attracting the increasing attentions due to the food security and water security (Zhao et al., 2015; Xiao et al., 2017).

The previous studies mainly focused on water-saving technologies in winter wheat season (Ma et al., 2013; Zhang et al., 2013a,b; Sun et al., 2006, 2015). The different irrigation schedules were developed based on the different objectives such as the minimum irrigation schedule (MI) and the critical irrigation schedule (CI). Straw mulch and different tillage have been used to reduce the soil evaporation. All of the technologies have improved the water use efficiency (WUE). Meanwhile, China has developed the police for the crop rotation and fallow systems in the groundwater funnel area, heavy metal polluted area, and the severely degraded area. The policy mainly recommended to reduce the winter wheat sowing area and to develop the crops whose water consumption could meet the precipitation. However, the NCP also played an important role for the food supply especially for the winter wheat and maize. The field experiments and the simulations had been done to investigate the effects of different crops and cropping systems on the water use, groundwater, water use efficiency and economic benefit (Sun et al., 2011; Meng et al., 2012; Gao et al., 2015; Yang et al., 2015a,b; Luo et al., 2018). Several studies have investigated yield and water use when one season of winter wheat in the rotation has been changed to a fallow (e.g., Liu et al., 2008; Meng et al., 2012). The possibility of using winter wheat – summer maize – spring maize rotation (three crops at two years, WW-SM-sM) and the monoculture system such as continuous spring maize, winter wheat (WW), and summer maize (SM) (one crop a year) replacing the winter wheat and summer maize double cropping system had been studied to reduce the groundwater use. Xiao et al., (2017) found that the annual grain yield under the triple cropping system was only 13% less than that under the double cropping system. Meng et al. (2012) found that 35% and 61% of irrigation water and 16% (4.9 t/ha) and 31% (9.2 t/ha) grain yield were reduced in WW-SM cropping system and continuous spring maize cropping systems compared to the WW-SM cropping system through a six years field study. These results show that optimal cropping system is a WW-SM-sM system with three crops in two years which could reduce water use while maintaining similar net economic benefits compared with conventional system (Ma et al., 2016). This cropping system is therefore under consideration as the preferred option to achieve the goal of sustainable use of groundwater in this region (Meng et al., 2012). However, there also need 190 mm and 94 mm for the triple cropping system and monoculture system, respectively.

Transpiration (T) through crops is regarded as a beneficial depletion, but soil evaporation (E) is considered as the nonbeneficial depletion which is not only from bare soils but also from cropped fields (Wallace, 2000; Droogers and Bastiaanssen, 2002). In the NCP, the ratio of E/ET and T/ET accounted for about 30% and 70% for winter wheat and summer maize seasons, respectively (Liu et al., 2002; Sun et al., 2006). However, there are few studies showed the soil evaporation during the fallow season. Quantify the E and T at the different cropping system and different irrigation schedules is necessary for the water management.

Groundwater table was mainly determined by the agricultural water consumption in this region where the ratio of agricultural water consumption to total water consumption was about 70%. The groundwater table decline rate was about 1.0 m per year in Luancheng station (Fang et al., 2010) and over the whole North China Plain (World Bank, 2005). Many research showed that the change of groundwater table was affected by the different irrigation schedule and cropping system (Sun et al., 2011, 2016; Yang et al., 2015a,b). Chen et al. (2010) investigated that higher irrigation levels with efforts to meet crop water demand of both wheat and maize would lead to further decline of groundwater table up to 1.5 m/year using APSIM model. However, few studies were conducted combined with the irrigation schedule and cropping system.

Despite those important results, there are few researches to investigate the effects of different cropping system under the different irrigation schedules on grain yield, water consumption, and groundwater table changes. Therefore, the objectives were (1) to quantify the ET, T, E of four different cropping systems under four irrigation schedules, (2) to evaluate the grain yield and water use efficiencies based on the different scales under different cropping system and irrigation schedules, (3) to estimate the effects on groundwater table change of four different cropping systems and irrigation schedules.

2. Materials and methods

2.1. Study site

Field data were collected at the Luancheng Agro-ecological experimental station (LC, 37°53′N, 114° 41′E, 50 m elevation). LC is located close to Shijiazhuang City which is the typical representative for the agricultural production in the NCP. The average annual temperature is 11.5 ℃, with a minimum of −5.6 ℃ in January and a maximum of 26.7 ℃ in July. The average annual precipitation is 487 mm, 70% of which occurred between July and September. The soil is classified as silt loam and the detailed information including the bulk density, hydraulic parameters were shown in Table 1.

2.2. Simulation of different cropping systems under different irrigation schedules

In order to investigate the effects of different cropping systems under different irrigation schedules on water consumption, groundwater level and the water use efficiency, a calibrated APSIM model was used to simulate the grain production, E and T during 1982–2013 under 16 scenarios. The purposes of each simulation were explained in Table 2.

The calibration of APSIM was based on the experimental results from the same site. The detailed calibration processes were showed in Sun et al., (2015). The calibration for the triple cropping system and

Table 1
Soil characteristics in different soil layers at the study site.

Depth (cm)	Texture	Bulk density (g/cm^3)	Saturated volumetric water content (V/V)	Drained upper limit (v/v)	15 bar lower limit (v/v)
0–25	Loam	1.30	0.457	0.344	0.100
25–40	Loam	1.41	0.395	0.336	0.126
40–60	Loam	1.46	0.342	0.329	0.137
60–85	Loam	1.49	0.365	0.329	0.140
85–120	Silty clay loam	1.44	0.332	0.318	0.143
120–165	Clay loam	1.45	0.360	0.321	0.125
165–200	Silty clay loam	1.54	0.390	0.380	0.130