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Evaluating water conservation effects due to cropping system optimization on the Beijing-Tianjin-Hebei plain, China

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ABSTRACT

Irrigation of the conventional double cropping system of winter wheat and summer maize has caused serious problems regarding water resources and the environment on the Beijing-Tianjin-Hebei plain (HP), China. Reducing or replacing high water consumption crops (such as winter wheat) is the most impactful way to effectively save water in the HP region. In this study, crop coefficient and vegetation remote sensing data were used to estimate evapotranspiration (ET_a) for winter wheat and summer maize on the HP from 2009 to 2013. For early maize, ET_a and yield were based on the results from the APSIM (Agricultural Production System Simulator) crop model, which had been calibrated and validated using field experimental data. The effects on groundwater conservation and grain yield were estimated at the regional scale for the conventional winter wheat (WW) and summer maize (SM) double cropping system (Y_1M_2) and three alternative cropping systems: three harvests in two years system (Y_2M_3, 1st year: WW-SM; 2nd year: early maize), four harvests in three years system (Y_3M_4, 1st year: WW-SM; the next two years: early maize), as well as a continuous early maize monoculture system (Y_1M_1). The results showed that: (1) Relative to Y_1M_2, the water savings in each alternative cropping system exceeded 50% of the groundwater overdraft on the HP. The evapotranspirations of Y_2M_3, Y_3M_4 and Y_1M_1 decreased by 14%, 19% and 29% over that of Y_1M_2 (740 mm), respectively. The economic water use efficiencies (WUE_e) of the alternative cropping systems were 7% –16% greater than that of Y_1M_2. The groundwater drop by Y_1M_2 (0.59 m year^{-1}) was higher than that by Y_2M_3 (0.20 m year^{-1}) and Y_3M_4 (0.07 m year^{-1}), and the drop by Y_1M_1 was negative, indicating a groundwater rise of 0.20 m. The groundwater overdraft in Y_1M_2 was 160 mm (3.83 billion m^3), and the alternative cropping systems were more sustainable, with groundwater overdrafts that were less than the recharge value of 128 mm on the HP. (2) In comparison with Y_1M_2, the total yield was reduced by 2.28, 3.04 and 4.56 billion kg a^{-1} (or 7.7%, 10.2% and 15.3%) for Y_2M_3, Y_3M_4 and Y_1M_1, respectively, which accounted for < 15% of the regional total or < 1% of the national total. It is important to note that the yield loss of the alternative cropping systems was below the net grain export amount in Hebei province, so the grain supply and demand could be roughly balanced. (3) In summary, Y_2M_3 is a preferred alternative cropping system over Y_1M_2 in the near future because of the advantages of high WUE_e, economic return, mitigated groundwater level decline and balance between wheat supply and demand on the HP. Y_1M_1, which had the least water use and highest WUE_e and economic return, is an option for the most serious groundwater overdraft area despite a contradiction between the traditional dietary habit and complete abandonment of wheat. Y_3M_4 is recommended as the transitional cropping system between Y_2M_3 and Y_1M_1. The method in this study is applicable to relevant regional research, and the results can be of use to the government when formulating policies on cropping systems and groundwater management.

1. Introduction

The Beijing-Tianjin-Hebei plain (HP) is located in the northern part of the North China Plain and provides > 5.3% of the national grain yield, whereas its water resources are < 0.6% of the national total (2009–2013) under a highly intensive winter wheat and summer maize double cropping system (Y_1M_2). Water shortages are widespread and threaten the development of the economy and agriculture.

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Groundwater has long been the most important water source for irrigation in the region. Due to the continuous pumping of groundwater for socio-economic use, the HP is now characterized by serious groundwater overexploitation and poor water environments (Yuan and Shen, 2013; Sun et al., 2010, 2015; van Oort et al., 2016). The groundwater level at the piedmont plain has declined from approximately 10 m below the ground surface in the 1970s (Shen et al., 2002; Zhang et al., 2003; Zhang et al., 2011b) to approximately 48 m today. 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). A series of environmental problems have subsequently been produced. Most rivers have dried up, natural wetlands have gradually atrophied, and a groundwater depression cone of 50,000 km^2, the largest recorded worldwide, has formed in this area (Hu et al., 2005). The water environment on the HP has become most vulnerable in China and even in the world (Wang et al., 2015).

Groundwater level drops primarily occurred during the winter wheat season due to the extraction of groundwater for irrigation, which is the primary means to bridge the large gap between crop water demand and precipitation in that season. Water consumption of well-watered winter wheat is approximately 430 mm (Zhang et al., 2011a), but the precipitation is < 150 mm (1963–2013), and the water deficit is approximately 280 mm. Generally 4–5 irrigations of 60–80 mm each are applied during the winter wheat season to maintain high yields (Sun et al., 2010). Because groundwater is almost the only source for irrigation (Xiao and Tao, 2014), winter wheat irrigation has been the most important factor for the groundwater drawdown (Yang et al., 2002, 2006; Xu et al., 2005; Sun et al., 2006; Gao et al., 2015).

Many studies have focused on water-saving agriculture. Some conventional water-saving methods such as drip irrigation, straw mulching, and critical period irrigation have been tested in agricultural production in past decades and have improved water use efficiency. However, total water consumption has remained high given the continuous increase in yield, and the groundwater level has continued to decline. As a consequence, the government has carried out a scheme to comprehensively treat groundwater overexploitation. In 2014, a subsidy of 7500 Chinese Yuan per hm^2 was implemented to reduce winter wheat acreage. In 2016, Central Document No. 1 emphasized limiting high water consumption crops on the North China Plain and moderately reducing the sowed area of winter wheat in the groundwater overdraft region. Researchers have also suggested reducing high water consumption crops for the sake of sustainability. Sun et al. (2015) simulated crop water consumption using the APSIM (Agricultural Production System Simulator) model and suggested that an alternative cropping systems with less water consumption is inevitable on the North China Plain. Kendy et al. (2004) reported that reducing crop evapotranspiration is the only means to lower groundwater consumption and that this could be accomplished by reducing the crop area on the HP. Curtailing high water-consuming crops (winter wheat) is urgently needed to alleviate or reverse declining groundwater for sustainability on the HP.

The feasibility of reducing or replacing the high water consumption crops on the HP has been investigated. It was confirmed that evapotranspiration and groundwater use were both lessened when Y_1M_2 was replaced once or more times by maize, millet, sorghum, soybeans, peanuts or sweet potatoes (Holst et al., 2014; Yang et al., 2015). Among those crops, maize is special because its water constraint risk is less than those of the other crops (An et al., 2016), its yield and yield gap are high (Meng et al., 2013), and the crop water demand during the maize growing period matches precipitation well, for example. Studies on optimizing cropping systems have therefore mainly focused on continuous maize monoculture systems and a two-year system of winter wheat/summer maize-spring maize (WW/SM-M). Data from field experiments and simulations have shown that the net groundwater use for continuous spring maize ranged from 94 to 139 mm $year^{-1}$ (Sun et al., 2011; Meng et al., 2012; Gao et al., 2015) and was 16 mm $year^{-1}$ for continuous early maize, both of them were below the estimated recharge value of 150 mm $year^{-1}$ and could almost achieve groundwater use balance (Xiao et al., 2017). A continuous maize monoculture system therefore appears to be the best choice for sustainable development (Sun et al., 2011), albeit with a high grain yield loss of 26%–31% (Meng et al., 2012; Gao et al., 2015; Xiao et al., 2017). Regarding WW/SM-M, annual groundwater use was reduced by 19%–45% compared to Y_1M_2 (Sun et al., 2011; Meng et al., 2012; Gao et al., 2015). The grain yield loss was only approximately 16% and the net economic returns had no much difference with that for Y_1M_2 (Sun et al., 2011; Meng et al., 2012). In view of grain yield and environmental effects, WW/SM-M was a relatively appropriate alternative cropping system for Y_1M_2 due to its considerable effect on water conservation and minor yield loss (Meng et al., 2012; Gao et al., 2015).

Despite those important results, research has been mainly based on field or site data, and there are few data to quantify the effects of alternative cropping systems on a regional scale. In this study, we used crop coefficient and vegetation remote sensing data to estimate evapotranspiration (ET_a) for winter wheat and summer maize on the HP, and combined field experiments, the APSIM model and summer maize data to calculate ET_a for early maize to research crop water consumption and grain yields for different cropping systems in the HP region. The objectives were (1) to estimate the ET_a, groundwater drops and economic water use efficiencies of different cropping systems on a regional scale, (2) to evaluate the effects on groundwater sustainability, food supply and economic benefits for three alternative cropping systems in comparison with the conventional double cropping system, and to discuss the preferred alternative cropping system to the conventional double cropping system in the HP region.

2. Materials and methods

2.1. Study area and experimental station

The HP region (36°03′ – 40°29′ N, 114°13′ – 119°27′ E), including the plain region of Beijing, Tianjin Municipalities and Hebei province, faces the Bohai Sea, backs onto Mt. Taihang and Mt. Yan, and covers an area of approximately 9.5 × 10^4 km^2 (Fig. 1). The climate is of a

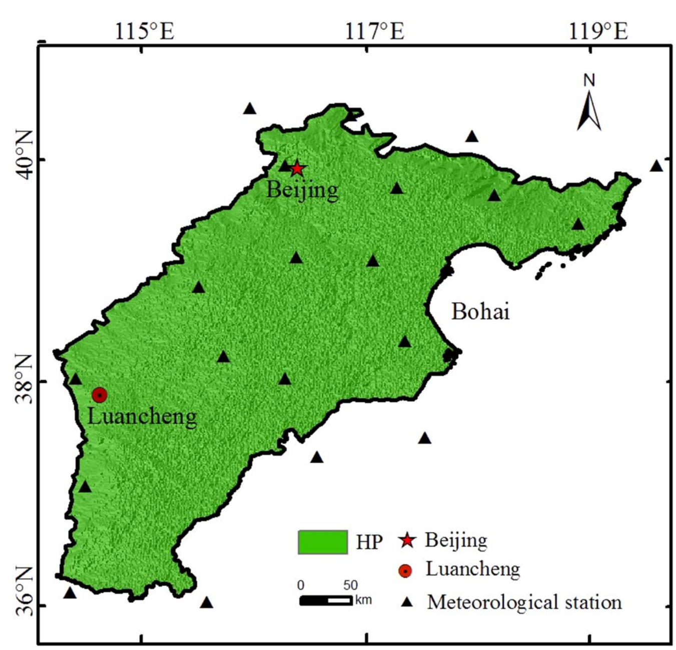

Fig. 1. Distributions of the Beijing-Tianjin-Hebei plain (HP), meteorological stations and field experimental station (Luancheng station).