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Deficit irrigation enhances contribution of shallow groundwater to crop water consumption in arid area

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ABSTRACT

Agricultural water conservation is important in arid and semi-arid areas where water resources are deficient and agriculture irrigation accounts for a high proportion of water use. Thus, efficient deficit irrigation methods, which the supplied water is less than potential evapotranspiration have been developed. In semi-arid areas, groundwater can contribute to crop's water consumption but less is known about impact of deficit irrigation on the contribution. We conducted, therefore, a two-year field experiments with deficit flood irrigation for maize in an arid district with shallow groundwater in China. Four irrigation practices were tested with water applied at approximately 82.5%, 75%, 67.5% and 60% of the 540 mm potential evapotranspiration (PET) in 2014 and the 500 mm in 2013 over the crop growing season. We found that the upward flux between soil water and groundwater varied from 5 mm with input water of 488 mm to 60 mm with input water of 353 mm. The yield of maize decreased by only 15% from 10.0 to 8.5 t/ha for the WS treatment (irrigated at 60% of PET) compared with the WH treatment (irrigated at 82.5% of PET) due to more groundwater contribution to the crop growing with less irrigation. As a consequence, the water use efficiency (WUE), defined as quotient of the yield and plant evapotranspiration was not significantly different among different irrigation treatments. However, the irrigation water use efficiency (IWUE), which is the yield per unit of water applied, increased significantly with the decreasing amount of water applied due to the contribution of upward fluxes. The implication is that deficit irrigation enhances the contribution of groundwater to crop water use and will not produce an obvious reduction of yield within a stable shallow groundwater level.

1. Introduction

Worldwide, irrigated agriculture accounts for approximately 70% of the world's freshwater withdrawals and produces 40% of the food (Ayars et al., 2006). With water becoming scarce especially in semi-arid countries, pressure is mounting to produce more food with less water (Khouri et al., 2011; Wright and Cadiero, 2011). In addition, insufficient and unreliable water supply in less developed countries are often the main cause of poverty and hunger (Ringler and Zhu, 2015).

In China, one of the most water-short countries in the world, irrigation and food supply are intrinsically linked. Seventy percent of the food required for 1.3 billion people is produced on irrigated land. In addition, rapid development of urbanization and industrialization will use more water in the future and then the already decreasing resources require agriculture to produce more food with less water. Therefore, improving the irrigation efficiency in China while maintaining its original yield is an important challenge and a priority for Chinese government (Meng et al., 2013; Long et al., 2003).

Deficit irrigation has been shown to reduce evapotranspiration in regions with deep groundwater (Zhang et al., 2004; Fereres and Soriano, 2007) and in several cases without reducing the crop yield (Jaimez et al., 1999; Kirnak et al., 2002; Kirda et al., 2005). Also, lots of studies (Kang et al., 2002; Sun et al., 2006; Mojaddam et al., 2011) have shown that water use efficiency WUE (i.e., the ratio of crop yield and the amount of water irrigated) can be improved by apply-

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ing less irrigation water. These studies, however, usually consider the crop-soil system and neglect the water for crop evapotranspiration from groundwater in the shallow groundwater regions.

Generally, with the recharging of excess irrigation water in the irrigated land with flooding irrigation practice, many irrigation areas with shallow groundwater appeared. In such districts, groundwater upflow can play an important role in contributing to crop water use and then the vertical water flux in groundwater tables needs to be quantified (Yang et al., 2007). Fluxes in a groundwater table depend on several factors such as groundwater table depth, soil hydraulic properties, crop growth stage, weather and irrigation. Several studies that have quantified the amount of water derived from groundwater found that 20%-40% of the evapotranspiration can be met by capillary rise from water tables at depths of 0.70–1.50 m (Ragab et al., 1988; Khandker 1994; Ayars and Schoneman, 2006; Gowing et al., 2009; Fan and Miguez-Macho, 2010; Gao et al., 2015). Based on a lysimeter experiment, Yang et al. (1999) reported that the contribution of groundwater to maize was 16% with groundwater depth of 0.7–1.3 m. Similarly, Babajimopoulos et al. (2007) reported that 18% of the water transpiration originated from a mean groundwater of 0.58 m. For a long term and regional scale, Chen et al. (2016) reported that the contribution of groundwater to evapotranspiration in regions has an obvious increasing trend with reduction of water diversion, accounting for 20% in 2013, which is doubled compared with that in 1980. Furthermore, Huo et al. (2012a,b) found a linear relationship between groundwater contribution and groundwater depth for a lysimeter experiment with water table depths between 1.5 m to 3.5 m.

Recently, some empirical equations and numerical models have been used to quantify the contribution of groundwater to crop water consumption at shallow groundwater areas (Sepaskhah et al., 2003; Raes and Deproost, 2003; Liu et al., 2006). Torres and Hanks (1989) reported that the contribution of water table to evapotranspiration simulated by WATABLE model varied from 92% to 9% for fine sandy loam at 50 cm to 150 cm. Sepaskhah et al. (2003) found that a linear descending relationship between water table contribution and groundwater depth. A number of studies including experimental and model work have proved that shallow groundwater can contribute to part of the water use of crops and enhance crop yield. To our knowledge, however, few studies describes the impact of different irrigation amount on the contribution of shallow groundwater to crop water consumption.

Therefore, the general objective of the study is to (1) study the variation of upward capillary flux under deficit irrigation; (2) investigate the impact of deficit irrigation on the evapotranspiration and water productivity of maize in shallow groundwater areas; (3) investigate the contribution of groundwater to crop water consumption and the impact of deficit irrigation on the contribution of groundwater in shallow groundwater areas.

2. Materials and methods

2.1. Study area

Field experiments were conducted in 2013 and 2014 at the experimental farm Shuguang (Fig. 1) in the 12000 km^2 Hetao irrigation district with severe water scarcity and high groundwater tables (Yang et al., 2009), which is located at an elevation of 1040 m in the north-west of Inner Mongolia in China. The district has a typical arid and semi-arid continental climate. Mean annual rainfall is 136–222 mm per year, and potential evaporation is 1940–2400 mm per year. Winters are cold with minimal snow cover and summers are hot. The soil starts to freeze around the middle of November. The surface thaws out in March and soils are fully thawed out at the end of May. The Yellow River at the south of Hetao irrigation district is the main source of irrigation water (Fig. 1). Maize and sunflower are main crops. The 12000 km^2 Hetao irrigation district has an annual water consumption of about 48 × 10^8 m^3. In recent years, agricultural water-saving (deficit irrigation) has been implemented with the reduced irrigation water from the Yellow River and the expanding irrigated command area, (Li et al., 2004).

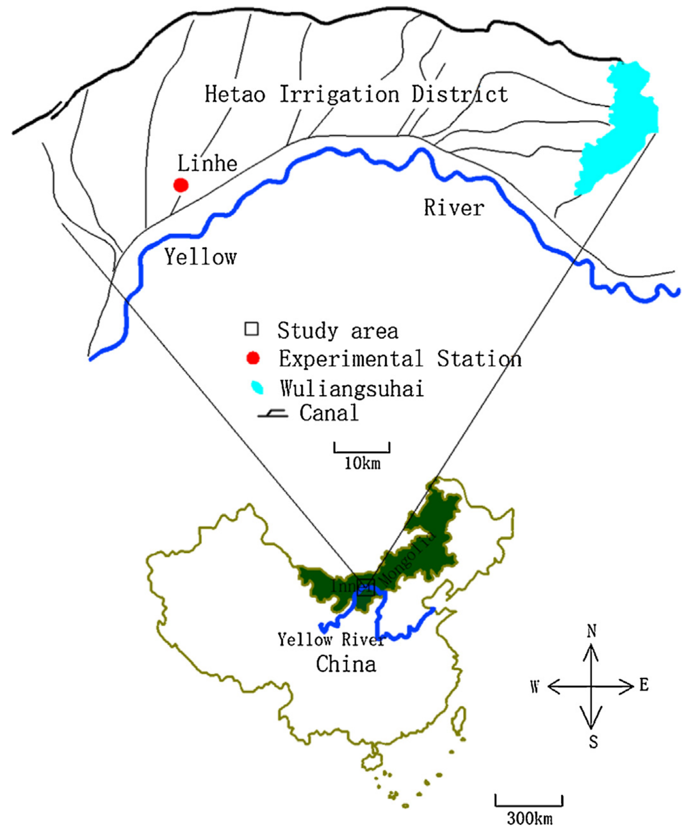

Fig. 1. Location of the study area.

The location of the irrigation experiments at the Shuguang experimental station is depicted in Fig. 1. The top 60 cm soil is a sandy loam soil. The sand content increases from 36% at the surface to 91% at 1 m (Table 1). The soil bulk density of 1.45 g/cm^3 and field capacity between 0.17 and 0.20 cm^3/cm^3 were determined on undisturbed soil cores using the methods described by Grossmann and Reinsch (2002) (Table 1). The groundwater table is at a depth of 2.5 m during the summer and at 1.8 m in the fall after irrigation water for salt leaching is applied.

2.2. Measurements

2.2.1. Weather and groundwater conditions

The meteorological weather station (HOBO U30) on the Shuguang experimental site collected the precipitation, wind speed, temperature and humidity from April 20th to September 10th. The number of sunshine hours was obtained from the China Meteorological Data Sharing Service System. During the measurement period the temperature ranged from 14 to 28 °C in 2013 and from 13 to 27 °C in 2014 (Table S1 in the Supplementary materials). Mean wind speed was 2.0 m/s in both years.

2.2.2. Water table depth

An automatic groundwater level recorder (HOBO U20) was used to measure groundwater depth at the boundary of the experimental plot from April 20th to September 10th. During the measurement period, groundwater depth was 1.1 m in May 2013, when soil had