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Research paper

Assessing the performance of different irrigation systems on winter wheat under limited water supply

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A B S T R A C T

The rapid decline of groundwater table is threatening sustainable irrigation agricultural development in the North China Plain (NCP). Optimized irrigation scheduling and water-saving irrigation technologies need to be developed to reduce irrigation water use and maintain the grain production potential for the region. This study was conducted at Luancheng experimental station in the NCP during 2012–2015 to evaluate the effects of different irrigation methods (basin irrigation, BI; tube-sprinkler irrigation, SI; pillow irrigation, PI and drip irrigation, DI) with various irrigation amount/frequency on yield, economic returns and water use efficiency (WUE) of winter wheat. Under the same limited irrigation amount (90 mm/season), two irrigation applications (45 mm/application) conducted using DI significantly increased the yield and WUE as compared with the BI using one single application. Increasing the seasonal irrigation amount to 160 mm, the increase in the application frequency by reducing the irrigation amount per application didn't significantly affect the yield using either PI or SI. Results showed that soil water depletion (SWD) contributed 40–60% of the seasonal evapotranspiration (ET) under limited water supply. The smaller root length density (RLD) in deep layers of the soil restricted the soil water uptake by the crop. Therefore, increasing irrigation frequency would maintain the top soil layers with higher soil water contents where RLD was greater that improved crop water use and yield under limited water supply. However, when irrigation water was plentiful, micro-irrigation methods did not increase yields. Due to the high cost in installation of the three micro-irrigation systems, their net income was reduced by 30% as compared with the BI method. The economic water productivity ratio (EWPR) was only 3–4 for the three micro-irrigation systems, much less than the basin irrigation method, which had an average value of 16. Currently, the basin irrigation method is more economic for growing winter wheat in the NCP.

1. Introduction

Winter wheat (*Triticum aestivum* L.) is one of the main crops in the North China Plain (NCP). It accounts for more than half of all winter wheat production in China (Sun et al., 2006). The rainfall during the growing season was about 60–150 mm. However, the consumptive water use by wheat is about 430–470 mm. In order to obtain higher grain yield, supplemental irrigation is essential (Zhang et al., 2003; Sun et al., 2011). Farmers in this region generally irrigate winter wheat three or four times each season (Zhang et al., 2017). Consequently, the groundwater table are dropping at an average rate of about 1–1.5 m/year due to over-pumping (Chen et al., 2010), which is threatening the sustainable development of irrigation agriculture in this region. To cope with the shortage of irrigation water resources, suitable irrigation strategies and water-saving irrigation technologies need to be produced.

Deficit irrigation, defined as the application of water below full crop-water requirements (Fereres and Soriano, 2007), has been promoted in many countries in an attempt to minimize irrigation water use (Fereres and Soriano, 2007; Tari, 2016). Peake et al. (2016) reported that deficit irrigation has greater economic water productivity under water limited conditions. This irrigation strategies could increase water productivity in the ranges of 10%–50% (Jensen et al., 2014). Large soil water holding capacity, high soil water contents at sowing and deep root system were important factors for the application of deficit irrigation (Stockle and James,1989; Lobell and Ortiz-Monasterio, 2006; Peake et al., 2008; Peake et al., 2016). Zhang et al. (2013) reported that a single irrigation at jointing stage could reduce irrigation water use by 120–140 mm as compared with full irrigation treatment with yield penalties of 14%

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for winter wheat in the NCP. Ali et al. (2007) showed that deficit irrigation saved 135 mm water but with 16% yield decrease as compared with the full water supply treatment of wheat in Bangladesh. The yield decrease of spring wheat under reduced irrigation was mainly related to climatic conditions, soil properties and timing of irrigation (Lobell and Ortiz-Monasterio, 2006).

Optimizing the irrigation strategies is another aspect to efficiently utilize the limited irrigation water (Rodrigues and Pereira, 2009). Some studies indicated that frequent application of water in small quantities can increase water use efficiency (WUE) (e.g. Enciso et al., 2003). Rawlins (1973) suggested that the water holding capacity of the soil become less important with the increase in irrigation frequency. Other studies have shown that increasing irrigation frequencies with small quantities per application could maintain higher grain yield of maize (*Zea mays* L.), with a reduction in yield observed with decreasing irrigation frequency in Loess Plateau of Northwest China (Wang et al., 2014). Bian et al. (2016) indicated that 60 mm of water applied at jointing and heading stages for winter wheat achieved higher grain yield than a single application of 120 mm at jointing stage. Sezen et al. (2006) showed that irrigation intervals of 3–6 days (18–22 mm) obtained higher WUE, irrigation water use efficiency (IWUE) and grain yield of bell pepper at a Arikli silty–clay–loam soil conditions. Muhumed et al. (2014) reported that above-ground biomass and yield components of sweet corn increased with the increase in irrigation frequency.

Unfortunately, traditional irrigation methods such as flooding irrigation may not easily control the irrigation amount per application (e.g. Sezen et al., 2006), and alternate irrigation methods might be required to improve the IWUE for field grown crops, such as winter wheat. Micro-irrigation can precisely control the irrigation application and are popular in orchards, vegetable growing and wide-row planted crops (e.g. Pereira et al., 2012; Bhunia et al., 2015; Gerçek et al., 2017). Drip irrigation is one of the major micro-irrigation methods, allowing accurate application of irrigation in small amount directly to the root zone (Bhunia et al., 2015). Increasing the frequencies by drip irrigation could maintain a high soil matric potential in the root rhizosphere, accelerating crop growth, decreasing deep percolation, reducing soil evaporation and saving irrigation water (Qin et al., 2016; Jensen et al., 2014). Jensen et al. (2014) reported that drip irrigation can reduce the loss of irrigation water in conveyance, and saved 30–40% water compared to basin irrigation. Muhumed et al. (2014) indicated that above-ground biomass and yield components of sweet corn were increased with the increase in drip irrigation frequency.

Other irrigation methods such as pillow irrigation and tube-sprinkler irrigation are also being used in growing crops. Pillow irrigation, which uses plastic tubes with holes on the tubes and the tubes are placed between two rows of the crop, can directly deliver water to the crop. The diameters of tubes are varied based on plant row spacing, and the tube after irrigation can cover the row spacing as mulch material. Plastic tube was pierced with holes of 1-mm diameter. Hole spacing varies between 50 and 100 cm depending on crop species (ek et al., 2009a, 2017;). Pillow irrigation has the benefits of plastic mulching and drip irrigation. This method can also restrict weed growth and improve grain yield as well as WUE of hot pepper under limited water supply (Gerçek et al., 2009b). For the application of the micro-sprinkler irrigation to the densely planted crops, such as winter wheat, a modified micro-sprinkler irrigation is becoming popular in China This method uses a thin tube placed on the soil surface with holes on it. Pressurized water will come out from the holes acting as sprinkler. Liu and Kang (2006) reported that the air temperature and vapor pressure deficit of winter wheat in sprinkler-irrigated treatment was lower than that under surface irrigation treatment in NCP. However, due to the higher cost in installation and maintenance, those micro-irrigation systems are not widely used on the cereal crops in the NCP currently.

Micro-irrigations can save water as compared with flood irrigation due to the reduction in water loss from evaporation, deep percolation as well as during water delivery (Namara et al., 2007; Maisiri et al., 2005). With the increase in irrigation water shortage, water-saving irrigation methods would become more important in future. However, their wide use in crops is still limited, due to the high investment and maintenance cost of the irrigation system and the lower economic returns of the crops (Paredes et al., 2014). Hanson et al. (1997) suggested that savings from reduced water costs of lettuce were not enough to offset the equipment costs of drip irrigation system. Dağdelen et al. (2009) indicated that drip irrigation method saved 177 mm water, but lead to 34.0% reduction in the net income of cotton. However, Namara et al. (2007) found that micro-irrigation technologies can increase economic returns of banana and peanut when compared to flood irrigation in India. Selection of a suitable irrigation method would depend on the specific conditions of water resources, crop types and management requirements.

Therefore, the objectives of this research are as follows: 1) To assess the performance of basin irrigation, tube-sprinkler irrigation, drip irrigation and pillow irrigation methods on grain yield and WUE of winter wheat, and 2) to evaluate the economic benefits of different irrigation methods.

2. Material and methods

2.1. Study site and the growing condition of the crop

The experiment was conducted during 2012–2013, 2013–2014 and 2014–2015, three growing seasons of winter wheat, at Luancheng experimental station (37°53′N, 114°40′N; elevation 50 m) in the North China Plain (NCP). Winter wheat (grown from October to earlier June) and summer maize (grown from earlier June to the end of September) form the annual double cropping system. The mean annual precipitation is 473 mm, with around 30% of the precipitation falling during the winter wheat season. The soil is loam with average field capacity at 36% (v/v) and wilting point at 13% (v/v) for the top 2 m of the soil profile. The groundwater table was 40 m below soil surface; and the soil and irrigation water have no salinity problems. Soil nutrient contents were 18 g/kg for organic matter, 80 mg/kg for available N, 110 mg/kg for available K and 15 mg/kg for available P for the top tillage layer. Detailed soil physical characteristics at the experimental site can be found in Zhang et al. (2016).

Winter wheat was sown in October after maize was harvested and the maize straw was chopped and incorporated into the top soil layer. The same winter wheat cultivar "KN199" was used for the three seasons. Winter wheat was planted following the local practice with four rows closely together; and between two four-close-rows there was a wide row spacing of 30 cm. The four close rows had row spacing around 12 cm. The four rows took 0.6 cm width averagely. Seeding rate was 300 viable seeds/m^2 and sowing was done with a seeding machine. Before planting, diammonium phosphate (DAP) at 300 kg/ha, urea at 150 kg/ha and potassium chloride at 150 kg/ha were broadcast and incorporated into the soil. An additional 225 kg/ha of urea was top-dressed at jointing stage in early April, either with an irrigation or with an rainfall event. The fertilizer amount followed the local practices.

2.2. Treatments for irrigation methods and irrigation amounts

Four irrigation methods: basin irrigation (BI), tube-sprinkler irrigation (SI), drip irrigation (DI) and pillow irrigation (PI) were tested. BI is the local irrigation method widely used by the local farmers. The study for the BI was included in a long-term irrigation