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Impact of irrigation volume and water salinity on winter wheat productivity and soil salinity distribution

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ABSTRACT

Sustainable development of agriculture in the North China Plain is severely restricted by a shortage of fresh water. Saline water used for irrigation can increase crop yields as well as the risk of soil salinization. Therefore, to identify safe and simple ways of using saline water in this region, field experiments were conducted from 2011 to 2013 to evaluate the effect of irrigation volume and water salinity on winter wheat productivity and soil salinity distribution. A total of twelve treatments including four levels of irrigation volume (0.8*E*, 1.0*E*, 1.2*E* and 1.4*E*) and three levels of water salinity (3.3, 5, and 6.8 dS m^{-1}) (S1, S2 and S3), were arranged in a randomized split-plot design with three replicates of each treatment. *E* is the total net pan evaporation that occurred after the irrigation. The results indicated that soil salinity increased at the harvest time of winter wheat under all of the treatments compared with initial conditions, particularly in the upper soil layers (0–40 cm). However, these impacts were eliminated by rainfall in summer and autumn. The effect of irrigation water salinity on yield was significant in the 2011/2012 growing season and non-significant in the 2012/2013 growing season ($p < 0.05$). Quadratic relationships were found between grain yield and irrigation volume for three water salinity levels in both growing seasons. The effects of irrigation volume on total water use (TWU), water productivity (WP) and irrigation water productivity (WP_{irrig}) were significant. The interaction effects of irrigation volume and water salinity on grain yield, TWU, WP, WP_{irrig} and soil salinity were statistically non-significant. The optimal irrigation volume per application was 0.98*E*, 0.98*E* and 0.92*E* for water salinities of S1, S2 and S3, respectively, by which more than 96% of the maximum yield and WP can be achieved.

1. Introduction

Winter wheat (*Triticum aestivum* L.) is one of the major crops in the North China Plain (NCP), and its yield production levels depend largely on irrigation due to low precipitation during the winter wheat growing period (Pang et al., 2010; Liu et al., 2013; Iqbal et al., 2014). Previous studies have shown that precipitation during the wheat growing season varies from 100 to 180 mm, while the water demand of wheat is approximately 400–500 mm (Liu et al., 2002; Li et al., 2007, 2010). Therefore, more than 70% of irrigation water resources are allocated for winter wheat to ensure maximum production in this area (Iqbal et al., 2014). The shortage of fresh water is becoming the most limiting factor for winter wheat production in recent decades (Chen et al., 2003; Sun et al., 2010; Liu et al., 2013). At the same time, many areas in the NCP contain saline water with a salt content ranging from 2 to 5 g l^{-1}. As a result, farmers are forced to explore the possibility of utilizing saline water for irrigation due to the scarcity of fresh water (MWR, 1998; Pang et al., 2010).

The effect of water salinity both on the crop yield and on the environment (particularly in regard to soil salinization) should be taken into account when saline waters are used for irrigation. Several researchers have demonstrated the use of saline water in wheat with pot or field experiments (Murtaza et al., 2006; Wang et al., 2007; Ould Ahmed et al., 2007; Chauhan et al., 2008; Singh et al., 2009; Pang et al., 2010; Jiang et al., 2012). Sharma and Rao (1998) reported that the mean yield reduction of wheat grown in a sandy loam soil in India was 4.2, 9.7, 16.3 and 22.2% at irrigation water salinity of 6, 9, 12 and 18.8 dS m^{-1}, respectively. These authors also indicated that increased soil salinity and sodicity were eliminated by the subsurface drainage during the ensuing monsoon periods. Chauhan et al. (2008) revealed that saline water with electrical conductivity ranging between 8 and 12 dS m^{-1} could be used to supplement at least two irrigations per year to obtain 90% or more of the optimum yield. These studies primarily focused on the impacts of saline water on crop yield and water consumption, rather than its impacts on soil salinity. However, wheat is a

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moderately salt-tolerant crop (Mass and Hoffman, 1977) with a tolerance limit of 6 dS m^{-1}, although wheat production decreases by approximately 7% for each 1 dS m^{-1} increase in the electrical conductivity of the soil's saturation extract (EC_e). The threshold value is the maximum average salt concentration in the root zone at which crop yield is not significantly reduced. Soil resource health and crop yield are two variables of great interest when using saline water for crop production (Verma et al., 2012). Therefore, the effects of saline water on crop production and soil salinity should be studied simultaneously.

Good irrigation management practices are required to improve crop yields and water use. Numerous studies on optimizing irrigation schedules to conserve water and boost crop yield have been conducted (Kijne et al., 2003; Nasseri and Fallahi, 2007; Nagaz et al., 2012; Zhang et al., 2013). Soil and plant water status are normally used as indicators to guide irrigation, but these measurements require the use of professional equipment, and thus are inaccessible for most farmers (Jones, 2004; Liu et al., 2013). Recent studies have shown that pan evaporation can be used as a simple and easy method for determining irrigation scheduling (Ricardo and Heber, 1995; Yuan et al., 2003, 2004; Şimşek et al., 2004; Ould Ahmed et al., 2007; Çetin and Uygan, 2008; Wang et al., 2009; Liu et al., 2011, 2013). For example, Liu et al. (2011) used a Chinese 20-cm pan evaporation to determine the sprinkler irrigation regimes for winter wheat and found that a relatively high yield and water use efficiency (WUE) were achieved by using a coefficient of 0.63 to multiply the net evaporation. Liu et al. (2013) reported that the optimal irrigation per application could be determined by using a coefficient of 1.25 to multiply the net pan evaporation, calculated by using a E601 pan (which has an evaporation area of 3000 cm^2 of free water) for winter wheat. Ould Ahmed et al. (2007) indicated daily irrigation at 100% pan evaporation is the most appropriate saline water irrigation management option for sorghum using a pot experiment. Management of saline water for irrigation is traditionally based on the application of excess water to maintain minimum root zone salinity and consequently minimize salinity-caused yield reduction (Ayers and Westcot, 1985). However, when the irrigation volume is increased, more total salts are added to soil. In addition, more water does not necessarily correspond to maximum yield and water use efficiency when using saline water irrigation (Russo and Bakker, 1987; Amer, 2010). Thus, in this study, the pan evaporation method was used to optimize the saline water irrigation in a field experiment.

The objectives of this study were (1) to demonstrate the soil salinity distribution under different irrigation volume and water salinity levels, (2) to evaluate grain yield and water productivity of winter wheat under different irrigation volumes and water salinities and (3) to optimize the irrigation regime under different water salinities by using pan evaporation.

2. Materials and methods

2.1. Study site climate and soil physical properties

Field experiments were conducted during the winter wheat growing seasons over two years (2011/2012) and (2012/2013) in Fengqiu State Key Agro-Ecological Experimental Station (35°01′N, 114°32′E), Henan Province, China.

The 30-year mean annual temperature in the area was 13.9°C, the annual precipitation ranged from 355 to 800 mm and the mean annual rainfall was 615 mm (Ding et al., 2010). The monsoon climate dominates the region with more than 70% of the annual precipitation occurs from July to September. Irrigation may therefore be required to optimize growth of winter wheat, particularly during dry years. The precipitation amount was 185 and 45 mm for the 2011/2012 and 2012/2013 growing seasons, respectively. Soil physical properties at the experimental site are listed in Table 1.

2.2. Experimental design, irrigation treatments, and soil water content and salinity measurements

Winter wheat (Xinmai-19) was sown on 3 October 2011 and harvested on 8 June 2012 in the 2011/2012 growing season. In the 2012/2013 growing season, winter wheat was sown on 3 October 2012 and harvested on 10 June 2013. The experiment was laid out in a split-plot within a randomized complete block design with three replicates of each treatment. Each plot measured 1 m × 1 m and was bordered by cement curbs to minimize the effects of lateral water and salt movement between plots. Irrigation was performed with three levels of water salinity: 3.3 dS m^{-1} (S1), 5 dS m^{-1} (S2) and 6.8 dS m^{-1} (S3) and four levels of irrigation volume (ranging from below to above the seasonal crop water requirement). The irrigation volume applied was based on the evaporation from an uncovered, 20-cm diameter pan (Model ADM7, China) positioned 0–5 cm above the crop canopy (Liu et al., 2011). Pan evaporation (E_{pan}) was measured at 08:00 am daily. After the measurement, the pan was cleaned and refilled with 20 mm fresh water according to the measurement standard (Ministry of Water Resources and Electric Power People's Republic of China, 1988). E_{pan} was calculated as:

$$E_{pan} = 20 + P - W_{left} \quad (1)$$

where W_{left} is the water depth in the pan at the time of measurement, and P is the precipitation between two measurements.

The volume of water applied to the four treatments was the total net evaporation E ($E_{pan} - P$) that occurred after the previous irrigation multiplied by four set different numbers: 0.8, 1.0, 1.2 and 1.4. The first irrigation was performed on March 15 in 2012 and on February 23 in 2013. For the first irrigation, fresh water was applied at equal irrigation depth (80 mm) to all plots. The greater fresh water volume at the first irrigation was due mainly to the low soil water content after a long winter period and application of urea. Once cumulative pan E reached approximately 40 mm, all plots were irrigated with the designated irrigation volumes (Table 2). Flood irrigation was applied to the plots using a water meter to record the water used. There were five irrigation events in the first season and eight irrigation events in the second season due to lower precipitation and higher pan evaporation in the second than in the first season (Fig. 1).

Standard amounts of fertilizer were applied in both years with the same amounts. Nutrient supply was applied following local practices that consisted of providing nitrogen (N) in the form of ammonium nitrate, P_2O_5 and K_2O at a rate of ($N:P_2O_5:K_2O$ = 32:4:4%). A total of 500 kg ha^{-1} was applied as base before sowing. Urea was applied at a rate of 300 kg ha^{-1} with the first irrigation water in all treatments during the winter wheat reviving stage.

The soil water content was measured with a neutron probe (Model L520, Jiangsu Academy of Agricultural Sciences, China) at 20-cm intervals along the 120 cm soil profile every 7–10 days. Additional measurements were taken before and after each irrigation or heavy rain event. Soil samples were taken before sowing and after harvesting in each plot to measure electrical conductivity ($EC_{1:5}$). Soil was sampled with a 4 cm auger from six depths (0–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm). Samples were air-dried and ground to pass through a mesh of 2 mm size, and analyzed for $EC_{1:5}$. Then, $EC_{1:5}$ values were converted to the electrical conductivity of saturated paste (EC_e) based on previous research in this area (Li et al., 1996):

$$EC_e = -0.724 + 8.24 \times EC_{1:5} \quad R^2 = 0.994 \quad (2)$$