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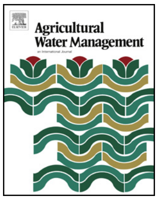

Impact of saline water irrigation on water use efficiency and soil salt accumulation for spring maize in arid regions of China

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ABSTRACT

Saline water irrigation represents the future of agriculture in the arid regions of northwestern China. Therefore, saline water irrigation experiments for spring maize were performed for 3 years from 2009 to 2011 in arid regions of northwestern China, and the impact of irrigation with saline water at different concentrations on the water use efficiency and soil salt accumulation was investigated. A SWAP model was calibrated and verified using field experiment data. The relationships of the salt concentration of the irrigation water with the yield and water use efficiency of spring maize were simulated using the SWAP model. Furthermore, the salt transport across the soil layers was quantitatively analyzed. The results showed the following: (1) irrigation with water containing low concentrations of saline (<3 g/L) for 3 consecutive years combined with a single application of fresh spring water before sowing every year did not cause significant changes in the yield of spring maize. (2) Saline water irrigation for 3 consecutive years resulted in an increase in the salt accumulation at a soil depth of 0–100 cm in 2011. This finding indicated that spring irrigation did not completely leach the salt introduced by saline water irrigation. (3) The SWAP simulation indicated that the yield of spring maize declined by 622 kg/ha for every 1 g/L increase in the salt concentration. When the salt concentration of the irrigation water was less than 3 g/L, the yield of the spring maize was reduced by less than 10%, whereas salt concentrations above 3 g/L decreased the yield much more significantly. A simulation over 10 consecutive years of saline water irrigation showed that the spring maize yields of T3, T6 and T9 will reduce by 8%, 33% and 52%, respectively, compared with the yield in 2009. (4) Despite the differences in the salt concentration of irrigation water, the salt residue in the 0–100 cm soil layer due to irrigation with 3 g/L, 6 g/L and 9 g/L saline water accounted for approximately 60% of the total salt in the irrigation water in 2011. The remaining 40% of the salt leached to the soil layer below 100 cm. In conclusion, irrigation with saline water at concentrations below 3 g/L will reduce the yield by no more than 10% compared with fresh water irrigation, but long-term saline water irrigation will result in significant yield losses, even for low concentrations of salt. Thus, the accumulation of salt in the soil after many years of saline water irrigation needs to be addressed by using a proper irrigation schedule in order to ensure the sustainability of saline water irrigation.

1. Introduction

The Shiyang River basin in northwestern China is a typical inland basin that experiences little precipitation and an arid climate, which results in water shortages and environmental deterioration (Kang et al., 2004). Agricultural practices are the largest consumers of water—approximately 2.4 billion m^3 water is used for irrigation every year, which accounts for 85.7% of the total water use in the Shiyang River basin. Irrigation constitutes the primary source of water for agricultural development, but the vast quantity of agricultural water not only places heavy demands on stream ecological water but also severely overexploits local groundwater. Although fresh water sources are scarce, shallow saline groundwater resources are abundant in the Shiyang River basin. Thus, the use of saline water for irrigation may be preferable to decreasing the

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irrigation area in this region and has consequently received considerable attention in water-deficient areas (Sharma et al., 1993; Chauhan et al., 2008; Jiang et al., 2012). In the Middle East, e.g., Israel, Iraq and Kuwait, saline water irrigation has preceded extensive use of saline water irrigation. Based on experience with saline water irrigation in Israel, saline water irrigation is more suitable for light and medium soil textures, but appropriate amounts of leaching water should be employed (Pasternak and De Malach, 1995). Saline water irrigation practices have been implemented in multiple regions of the southwestern United States, and the irrigation of cotton with 1.5 ~ 5 g/L saline water produced cotton yields that are equal to or exceed those obtained with fresh water irrigation. However, these yields required that the cotton seedlings be irrigated with fresh water (Dutt et al., 1984). The use of poor quality groundwater in agriculture can ameliorate the demand for fresh water (Droogers et al., 2000; Yang-Ren et al., 2007; Kang et al., 2010; Xu et al., 2013), and saline water can even be used to supplement shortages in good quality water in arid areas (Chauhan et al., 2008). Some studies have investigated the influence of saline water irrigation on crop physiological characteristics. Katerji et al. (1996) indicated the leaf water potential, photosynthetic rate, transpiration rate, and stomata conductance of maize all decreased in response to saline water irrigation. Van Hoorn et al. (1993) obtained a similar conclusion for the effect of saline water on wheat. Moreover, Katerji et al. (2003) showed that the water use efficiency (WUE) of salt-tolerant crops did not change, but the WUE of salt- sensitive crops markedly decreased as the saline concentration increased because their yield decreased more than their transpiration. Saline water irrigation is widely thought to reduce crop root water uptake because the salt accumulation in the root zone soil and the yield under saline water irrigation are lower than those under fresh water irrigation (Lamsal et al., 1999; Katerji et al., 2000). Soil salt accumulation is another cause for concern. Sharma and Rao (1998) conducted a saline water irrigation field experiment on sandy loam soil for seven consecutive years and found that monsoon rains and a subsurface drainage system prevented soil degradation. Jiang et al. (2011) simulated water-salt transport based on field experiments in an arid region of China, and found that the salt concentration at a depth of 65 cm continuously increased starting at the middle stage of the wheat growth period. In monsoon regions, adequate precipitation can effectively leach the salts from the soil (Verma et al., 2012), but the ability of once annual fresh water irrigation before sowing to leach salts introduced saline water irrigation requires further investigation.

Field experiments are a conventional method to verify the effect of saline water irrigation, and many researchers have such experiments. However, long-term experiments are required to reach sound conclusions and place high demands on manpower, financial resources, and other infrastructure when employing conventional techniques. Alternatively, limited field experimental data and appropriate mathematical models can be utilized to determine the most appropriate options (Verma et al., 2014). A number of models have been used to obtain short- and long-term descriptions of salt and water transport under different climatic, drainage, and crop conditions (Martin et al., 1984; Majeed et al., 1994; Singh and Singh, 1996; Bakker et al., 2010; Jiang et al., 2011). The soil–water–atmosphere–plant (SWAP) model has been widely used because it can simulate physical, chemical, and biological processes at the field scale level and accommodate long-term simulations with multiple crops per year (Castrignano et al., 1998; Tedeschi and Menenti, 2002; Eitzinger et al., 2004; Schahbazian et al., 2007; Domínguez et al., 2011; Jiang et al., 2011; Verma et al., 2012). Consequently, the SWAP model has been used to simulate the crop yield and salinity in soil profiles for different locations and crops within and below the crop root zone (Hoffman et al., 1979; Letey and Dinar, 1986; Maas and Poss, 1989; Ayars et al., 1993; Sharma et al., 1994; Datta et al., 1998; Singh et al., 2006; Ma et al., 2011; van Dam et al., 2008).

The objectives of this study were to (1) compare the impact of 3 consecutive years of different levels of saline water irrigation on the spring maize yield, WUE and salt accumulation in soil; (2) study the relationship between the salinity of irrigation water and spring maize yield by more of the scene simulation using calibrated SWAP model; and (3) quantitatively evaluate the migration of salt in different soils layer by SWAP model.

2. Material and method

2.1. Climate summary

Experiments were carried out at the agricultural water conservation and irrigation experiment station in the Shiyanghe River Basin from 2009 to 2011. Daily rainfall, maximum temperature and minimum temperature data for the spring maize growth stage were obtain from automatic weather station located 50 m from the field experiment site, as shown in Fig. 1. The precipitation during the spring maize growth stage in 2009, 2010 and 2011 were 69 mm, 82 mm and 119 mm, respectively. The multi-year average precipitation during the spring maize growth stage was 90 mm, which indicated that 2009 was a dry year and 2011 was a wet year. The average air temperatures in 2009, 2010 and 2011 were 19.4 °C, 18.2 °C and 17.8 °C, respectively. Pan evaporation data were not obtained during the spring maize growth stage due to the lack of appropriate equipment, but the multi-year mean water surface evaporation in the entire year was 2000 mm.

2.2. Field experiment

2.2.1. Experimental area

Shiyanghe River Basin is located in the east of Hexi Corridor of Gansu Province, Northwest China (101°41′–104°10′east longitude, 36°29′–39°27′north latitude), covering an area of 41.6 thousand km^2. Shiyanghe River Basin belongs to typical inland arid climate with ample sunshine and large temperature difference between day and night. This region has intense evaporation and small rainfall, belonging to typical desert oasis region with annual mean precipitation of 164 mm and annual mean water surface evaporation of 2000 mm. The natural conditions of the experiment station are representative of the inland arid regions in Northwest China.

2.2.2. Experimental design

Experiments were carried out in plots with concrete liners, each plot covering an area of 6.67 m^2 (3.33 m × 2 m). The physical and chemical properties of each soil layer above 100 cm are listed in Table 1. Four levels of salt concentration were set up. T0, T3, T6 and T9 represented salt concentration of 0.07 g/L (fresh water), 3 g/L (low level), 6 g/L (medium level) and 9 g/L (high level), respectively. Each treatment of saline water irrigation had 3 replicates. The saline water for irrigation was prepared according to the contents of different ions in saline water in local regions (mass ratio of NaCl, $MgSO_4$ and $CaSO_4$ 2:2:1). Total irrigation volume in the whole growth period of spring maize was 285 mm, divided into 4 irrigation treatments with 60 mm, 75 mm, 60 mm and 90 mm, respectively. Spring irrigation was performed once at the volume of about 90 mm half a month before sowing every year for the purpose of salt leaching and soil water conservation. The time of sowing, time of irrigation and time of harvest are shown in Table 2.

2.2.3. Measurements

The soil samples were taken before and after irrigation using soil auger during the growth period of spring maize at the depth of 0–10 cm, 10–20 cm, 20–40 cm, 40–60 cm, 60–80 cm and