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Optimum water and nitrogen supply regulates root distribution and produces high grain yields in spring wheat (*Triticum aestivum* L.) under permanent raised bed tillage in arid northwest China

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ABSTRACT

Shortages in water, energy and human resources, low water productivity, soil degradation, and environmental pollution in northwestern China are compelling farmers to develop and adopt sustainable conservation technologies. While the effect of permanent raised beds with furrow irrigation (PRBF) on soil fertility, crop yields and water use efficiency under different soil and climatic conditions has been studied extensively, few experiments have investigated the regulation of irrigation and nitrogen (N). A two-year field experiment, conducted in arid northwestern China, assessed the effects of nitrogen and irrigation rates on grain yield, root growth, root distribution, soil nitrate-nitrogen (NO_3–N) distribution, and water and N use efficiencies in spring wheat under PRBF tillage. The experiment followed a completely randomized split-plot design with three irrigation amounts—one-third conventional irrigated [1200 $m^3\ ha^{-1}$ ($I_{0.33}$)], two-thirds conventional irrigated [2400 $m^3\ ha^{-1}$ ($I_{0.67}$)], and conventional irrigated [3600 $m^3\ ha^{-1}$ ($I_{1.0}$)]—as the main-plot treatments, and four nitrogen levels—unfertilized [0 kg ha^{-1} N (N_0)], one-third conventional unfertilized [90 kg ha^{-1} N ($N_{0.33}$)], two-thirds conventional unfertilized [180 kg ha^{-1} N ($N_{0.67}$)], and conventional fertilized [270 kg ha^{-1} N ($N_{1.0}$)]—as the sub-plot treatments.We identified a significant interaction between irrigation and N application rate. The response of root length density (RLD) and its distribution to the N treatments also depended on the irrigation amount. When conventionally irrigated (3600 $m^3\ ha^{-1}$), N fertilizer was the main factor limiting spring wheat root growth; N application at 270 kg ha^{-1} produced the highest RLD values (1.273 and 1.374 cm cm^{-3}) in 2014 and 2015, respectively. At lesser irrigation amounts (1200 and 2400 $m^3\ ha^{-1}$), N fertilizer had little effect, with the contribution of water more important to spring wheat root growth; N application at 180 kg ha^{-1} produced maximum RLD values (1.335 and 1.545 cm cm^{-3}) in the 2400 $m^3\ ha^{-1}$ irrigation treatment in 2014 and 2015, respectively, and N application at 90 kg ha^{-1} produced maximum RLD values (1.042 and 1.163 cm cm^{-3}) in the 1200 $m^3\ ha^{-1}$ irrigation treatment in 2014 and 2015, respectively. The $I_{0.67}N_{0.67}$ treatment produced the highest yields (5022 and 6124 kg ha^{-1}) and RLD values (1.223 and 1.554 cm cm^{-3}) in 2014 and 2015, respectively, and the same treatment had a relatively wide distribution of RLD at 20–60 cm. The NO_3–N concentration from 0 to 120 cm increased with N fertilization and decreased with irrigation amount. The results showed that the $I_{0.67}N_{0.67}$ treatment, with one-third less N and irrigation water than traditional rates ($I_{1.0}N_{1.0}$), produced equivalent grain yields, had relatively low N losses, and had the highest 20–60 cm root distribution. In the PRBF irrigation system, the $I_{0.67}N_{0.67}$ treatment appears to be the most promising strategy for producing a high percentage of roots in deep soil layers and increasing grain yields, and water and N use efficiencies.

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1. Introduction

Wheat is a major staple food crop, providing 20% of the protein and 21% of the food calories to more than 4.5 billion people in 94 developing countries (Vigani et al., 2013). In arid areas of northwestern China, especially in the Hexi Corridor of Gansu Province, the average precipitation is less than 150 mm, with more than 60% occurring after spring wheat harvest (Huang et al., 2012). Water and nitrogen (N) are significant but limited inputs for realizing high wheat productivity. Water shortages have been increasing each year in this area, mainly due to climate change and increased water use, which is threatening the sustainability of wheat production. There is an urgent need to produce more wheat per unit area worldwide for food security; many farmers are using unreasonable levels of irrigation and excessive nitrogen supplementation, reaching more than 360 mm and 270 kg ha^{-1} N, respectively, in an attempt to increase wheat yields in spring wheat. These practices lead to excessive withdrawal of underground water (Ma et al., 2005), higher production costs (Xing and Zhu, 2000), pollution of soil and underground water (Du et al., 2011), gaseous N emissions (e.g., N_2O) (Trost et al., 2016), and lower water and N fertilizer use efficiencies (Wang et al., 2010). Increasing water and N fertilizer use efficiencies should improve grain yields in wheat while minimizing environmental damage (Coventry et al., 2011). Most farmers in this area adopt traditional tillage with flood irrigation practices, with corresponding low water use efficiencies. For instance, in Israel, 1 m^3 of irrigation water produces on average 2.32 kg of grain, but < 1 kg in China (Kang and Li, 1997). Flood irrigation practices with conventional flat planting can also result in non-uniform distributions of water and fertilizer in the seed zone (Ma et al., 2016), and soil erosion and degradation (Saha and Ghosh, 2013; Huang, 2007). Consequently, there is an urgent need to adopt water-saving conservation tillage and to regulate irrigation and N application for sustainable agricultural production in the area. Permanent raised beds with furrow irrigation (PRBF) offer additional advantages including zero or reduced tillage, water conservation (Jat et al., 2013), reduced weed infestations (Farooq and Cheema, 2014), less crop lodging (Mulvaney et al., 2014), reduced production, labor and machinery costs (He et al., 2008), improved grain yields (He et al., 2008), and improved soil structure with increased soil carbon by confining traffic to the furrows and retaining residues (Ma et al., 2016).

In China, the application of N and irrigation to cropping systems has had a remarkable effect on the nitrate-nitrogen (NO_3–-N) content in soils. In agricultural areas, NO_3–-N is accumulating in the groundwater with increasing N fertilizer application rates (Xing and Zhu, 2000; Follett and Delgado, 2002). In northern China, Zhang et al. (1996) reported a significant positive correlation between NO_3–-N concentrations in well water and N application rates in cropping environments. Excess irrigation is a major factor causing soil NO_3–-N to leach downwards in arable land (Wang et al., 2010).

Wheat growth and yield are affected by the absorption of water and nutrients in the root system (Caires et al., 2016). A PRBF system under zero-tillage with crop residue retention has significant nutrient and root growth stratification; some studies have suggested that PRBF is associated with higher RLD in the topmost layer (0–20 cm) (Sandhu et al., 2012; Ma et al., 2016). Moderate soil water levels can significantly increase root weight density in deep soil layers (Wang et al., 2014). Nitrogen application can improve the root system to facilitate water and nutrient absorption (Sandhu et al., 2012).

Compared with conventional practices, optimizing N and water application could promote the absorption of soil nitrogen and water by roots, i.e., increasing water and fertilizer use efficiencies, without decreasing grain yield (Xu et al., 2016b; Rasmussen et al., 2015). Further study is needed on how to regulate root density, improve deep root penetration, and increase the percentage of deep roots in a PRBF system using irrigation and nitrogen management to play the ‘safety net’ and ‘nutrition pump’, the nutrients and water may be intercepted by the roots and decrease NO_3–-N leaching (Cannell et al., 1996; Peng et al., 2015).

The available information on PRBF with spring wheat under different N fertilizer and irrigation rates in arid northwest China is scant. Thus, strategies are needed for the efficient utilization of water and N under PRBF to improve grain yields in spring wheat.

The objective of this study was to investigate the effect of different irrigation and N application rates on root growth, grain yield, soil NO_3–-N content, and water and N use efficiencies on spring wheat in a PRBF system. The overall aim was to identify the optimum N fertilizer and irrigation rates to simultaneously improve water and N use efficiencies and productivity in spring wheat.

2. Materials and methods

2.1. Research site description

A four-year field experiment was conducted at the Gansu Academy of Agricultural Sciences (GAAS) water-saving research station (38°85′ N, 100°81′ E) in Zhang-ye city, Gansu province, China, from 2012 to 2015. This site is located in the Hexi Corridor of northwest China, with an elevation of 1200–1700 m above sea level. The experimental site is dry and hot in summer, cold and dry in winter, with very low and erratic rainfall (Fig. 1). The average annual air temperature is 7.38 °C, average annual rainfall is 172 mm (1958–2015) and mean annual evaporation is 1972 mm (Fig. 1). About 70% of the precipitation occurs

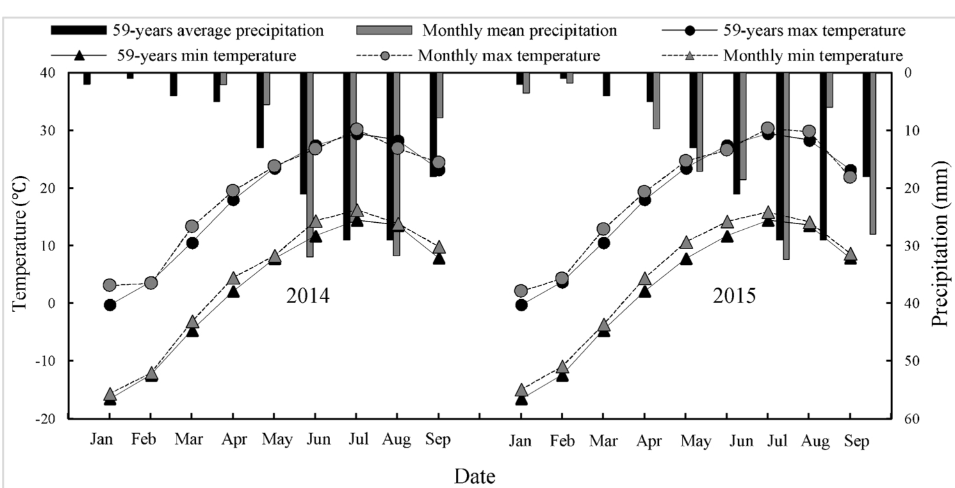

Fig. 1. Monthly temperatures (min and max) and precipitation during across two growing seasons (2014 and 2015) and the 58-year average for Zhang-ye city, China.