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Nitrogen fertilization improved water-use efficiency of winter wheat through increasing water use during vegetative rather than grain filling

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ABSTRACT

Water availability is a major constraint for wheat production in many semiarid regions of the world, including the Loess Plateau of China, and thus improving the water use efficiency (WUE) becomes a main research target. The impact of nitrogen (N) fertilizer on root growth, water use and WUE were examined for winter wheat grown in a semiarid farm on the Loess Plateau of China. A four-growing season field study (2011–2015) at the Changwu Agri-ecological Station, Changwu, Shaanxi, China with four rates of N fertilizer (0, 60, 120 and 180 kg N ha^{-1}) were conducted to determine soil water balance, root growth, yield and WUE in each growing season. Soil water content at final harvest in each growing season was lower and evapotranspiration (ETg) was higher under N supply than under non-N fertilization. N supply increased root growth and root length density (RLD) in deeper layers of the soil profile (80–140 cm), and improved water uptake, above-ground biomass and WUEb during vegetative growth stage. Grain yield under 60, 120 and 180 kg N ha^{-1}, increased by 12.8, 25.4 and 34.8%, respectively, with corresponding improvements in WUEg of 5.1, 13.8 and 29.3%, respectively, when compared to the non-N treatment. Our results demonstrated that N applications improved dryland winter wheat WUEg by increasing deep root growth and water use during vegetative.

1. Introduction

On the Loess Plateau of China, more than half of the precipitation is received during the fallow season from July to September (Wang et al., 2011). The precipitation storage efficiency (PSE), expressed as soil water accumulation divided by precipitation received during fallow periods, is approximately 35–40% (Shangguan et al., 2002). Therefore, maximizing water productivity is a major target in this region and will have a great impact at local and regional scales. Grain yield and water use efficiency (WUE) in wheat are primarily limited by the soil water deficit during the spring growth and through the grain-filling because of the high evaporation and the erratic distribution of rainfall. High wheat grain yields are often achieved by using N fertilizer and this practice has markedly increased in China to the point that a controversial environmental concern has been brought to grain production (Zhu and Chen, 2002). It is considered that high N fertilization will not be sufficient in the long-term maintenance of high grain yields and WUE because of the potential depletion of soil water under high N supply (Fan et al., 2005; Huang et al., 2003; Liu et al., 2013; Wang et al., 2011). The understanding of the mechanisms that control water use and WUE under N fertilization is critical for the efficient use of water in semiarid regions of the world, including the Loess Plateau of China.

One of the ways for efficient water use improvement by a crop is through increasing the depth of the root system, since in most dryland environments crops do not use all the water available in the soil profile due to restrictions to root growth (Turner, 2004). The growth and distribution of the crop root system is affected

Abbreviations: DM, dry matter; DMR, pre-anthesis DM remobilization; CDMR, the contribution of pre-anthesis DM remobilization to grain; RD, root diameter; RDW, root dry weight; RLD, root length density; RML, root mass per length; PSE, precipitation storage efficiency.

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by factors, such as cultivar, soil properties, timing and amount of irrigation and fertilization and tillage management (Huang et al., 2012; Outoukarte et al., 2010; Wang et al., 2014). For instance, fertilizer application stimulates deeper root growth in winter wheat, enabling access to more stored soil water and reducing the risk of water deficit (Read et al., 1982; Wang et al., 2011). A larger root system can also lead to increases in evapotranspiration (ET) through increases in the extraction of stored soil water (Cooper et al., 1987) and if the soil water is not sufficient, then highly fertilized crops may experience greater water deficit late in the season, limiting grain yield and WUE (Fan et al., 2005; Frederick and Camberato, 1995; Huang et al., 2003). Alternatively, if the crop has a poor developed root system, grain yield can be also limited because of insufficient capture of soil water by the roots (Johnson and Davis, 1980). For instance, a grain yield of 0.84 Mg ha^{-1} resulted from plots in which the soil water extraction was limited to a depth of 0.9 m in the soil profile, leaving 72 mm of available soil water in the 2.1 m of the soil. In contrast, a high yield of 2.3 Mg ha^{-1}, resulted when only 25 mm of available soil water was left in the 2.1 m profile because crops captured more water from deeper soil layers (Johnson and Davis, 1980). The role of roots system in acquiring N and water have increasingly gained focus in recent years (Fang et al., 2017; Palta and Watt, 2009; Palta et al., 2011; Wang et al., 2014), with valuable results for improving crop yields and the efficiency of water and N use.

On the Loess Plateau of China, limited and erratic rainfall is the primary water resource for rainfed wheat production, and no other water resources are available (Liu et al., 2013). Additionally, in most cases, the limited water resources are used inefficiently by crops; therefore, improving the efficient use of rainfall is a primary target in this region. An ideotype of root architecture seems to be important for improving the capture of water and nitrogen (Palta and Watt, 2009). However, the effects of N fertilization on the soil water balance, grain yield and WUE need to be assessed for wheat grown in a region with limited and erratic rainfall, before a root architecture is designed. The aims of this study were (i) to determine the effect of N application rate on the spatial distribution of the root system and its relationship with WUE and grain yield, and (ii) to evaluate the sustainability of obtaining high grain yield under high rates of N fertilizer. A field study was conducted during four consecutive growing seasons (2011–2015) and the N fertilizer rates of 0, 60, 120 and 180 kg N ha^{-1} were applied to a wheat crop in each growing season. It was hypothesized that (i) N application to winter wheat increase root length density (RLD) in deeper layers of the soil profile, increasing water use and grain yield, and (ii) high N application rates increasing grain yield and WUE adversely deplete the soil water and organic C.

2. Materials and methods

2.1. Experimental site

A four-growing season's field study was conducted at the Changwu Agri-ecological Station of the Loess Plateau (107°44.703′E, 35°12.787′N) in Changwu County, Shaanxi Province, China during 2011–2015 growing seasons. The site is located in a warm temperate zone with a continental monsoon climate with a long-term average rainfall of 570 mm (1984–2010) with more than half falling from July to September. The mean frost free period is 194 days and an annual water-surface evaporation demand of 1552 mm. The experimental site is 1220 m above sea level and has a slope of 0.07%. The soils are Cumuli-Ustic Isohumosols, according to the Chinese Soil Taxonomy (Gong, 1999), containing 37% clay, 59% silt, and 4% sand, the dominant clay mineral in this region is I/S mixed-layer mineral (approximately 69%). The pH measured in a suspension of soil in 0.01 M $CaCl_2$, is 8.4 in 0–20 cm soil layer. The field capacity is about 0.287 cm^3 cm^{-3}and the wilting point 0.098 cm^3 cm^{-3} (Chen et al., 2015a; Kang et al., 2000; Wang et al., 2013). The soil total N, organic matter content, available phosphorus, available potassium and bulk density at 0–20 cm depth were 0.93 g kg^{-1}, 14.1 g kg^{-1}, 16.3 mg kg^{-1}, 138.7 mg kg^{-1} and 1.3 g cm^{-3}, respectively.

2.2. Experimental design and crop management

The traditional practice in the region is to apply all N fertilizer before sowing as the base fertilizer. However, the late N amendment has been proposed as a strategy to achieve an improvement in grain yield in recent years because it stimulates photosynthate use in the growth processes and delays senescence of the photosynthetic apparatus (Fuertes-Mendizábal et al., 2010). So, we optimized this pattern using late N fertilizer application in this study. The four N treatments were as follows:

1. No N applied (N_0)
2. 60 kg N ha^{-1} (N_{60})
3. 120 kg N ha^{-1} (N_{120})
4. 180 kg N ha^{-1} (N_{180})

For treatments of N60, N120, N180, 36, 72 and 108 kg N ha^{-1}, urea was broadcast at planting as base fertilizer and an additional 24, 48 and 72 kg N ha^{-1} were broadcast at flag leaf visible stage (i.e. from April 20 to May 2) when there was some rainfall, respectively. Superphosphate was the P source and was broadcast at a rate of 120 kg P_2O_5 ha^{-1} at planting. The experimental plots were 12 m × 5 m (25 rows) and each N treatment was replicated four times for a total of 16 plots in each growing season. The plots with the different N application were arranged in a randomized complete block design and located in the same location for the four growing seasons. Winter wheat (cv. Changhan 58, a high-yielding cultivar) was sown at the rate of 150 kg ha^{-1} using a no-till disk drill with 20−cm row spacing. Wheat crops were sown in late September and harvest in late June of four consecutive growing seasons (2011–2015), all residual straw was removed after harvest for each growing season.

2.3. Sampling and measurements

The dates of the developmental stages (phenostages) for anthesis and physiological maturity (flag leaves turned yellow; Hanft and Wych 1982) were recorded for each plot in each N treatment. Daily observations were made and the phenostage noted when 50% of the plants in each plot had achieved the particular stage. Phenostages were defined using the Zadoks' scale of cereal development (Zadoks et al., 1974). Comparisons between the two phenostages were made in days after sowing (DAS).

Rainfall was recorded daily at the experimental station. In addition, daily records of wet and dry bulb temperature, windspeed, and class-A pan evaporation were obtained from an automatic weather station located 500 m away from the experimental plots. Annual rainfall, fallow rainfall and growth-season rainfall were also calculated according to the periods of winter wheat growth in the region. The drought index (DI) for annual rainfall was used to assess variations and status in rainfall among the four growing seasons and calculated using the following equation (Fan et al., 2005; Guo et al., 2012):

$$DI = (Ar - M)/\sigma \quad (1)$$

Where Ar is the annual rainfall (the sum of fallow rainfall and seasonal rainfall), M is the average annual rainfall, and s is the standard deviation for annual rainfall. DI is used to distinguish among the wet