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Root development and water uptake in winter wheat under different irrigation methods and scheduling for North China

Shiva K. Jha[a,b], Yang Gao[a], Hao Liu[a], Zhongdong Huang[a], Guangshuai Wang[a,b], Yueping Liang[a,b], Aiwang Duan[a,*]

[a] *Key Laboratory of Crop Water Use and Regulation, Ministry of Agriculture Farmland Irrigation Research Institute, Chinese Academy of Agricultural Sciences, Xinxiang, Henan 453003, PR China*
[b] *Graduate School of Chinese Academy of Agricultural Sciences (GSCAAS), Beijing 100081, PR China*

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ABSTRACT

A field experiment was conducted on winter wheat (*Triticum aestivum* L.) during 2013–2014 and 2014–2015 to study the root distribution profile and soil water dynamics under the main currently used irrigation methods in the North China Plain (NCP). The WinRHIZO system and the HYDRUS-1D model were used to identify a promising irrigation schedule. In this two-factor experiment, three irrigation methods, i.e., sprinkler irrigation (SI), surface drip irrigation (SDI) and surface flooding (SF), were scheduled to irrigate the crop as soon as the soil water content decreased to 70%, 60% and 50% of the field capacity. The results showed that both the irrigation method and irrigation schedule influenced root development, the profile root distribution pattern and the profile root water uptake (RWU). The soil surface temperature fluctuated very rapidly depending on the irrigation method and scheduling system used, whereas profile soil temperature fluctuations became more consistent with depth. The RWU was higher in the upper soil layer (0–60 cm) for all irrigation methods for frequently irrigated treatments, and the maximum was observed in SDI compared to SI and SF due to the higher root length density (RLD) in the top soil under SDI. On the other hand, the RWU was higher in SF at a deep soil profile below 60 cm, where it had a higher RLD compared to that of SI and SDI. SDI at 60% of FC not only improved water uptake but also resulted in better water productivity and produced the highest grain yield (9.53 t/ha). The simulated RWU and soil water dynamics presented in this paper will be helpful to improve winter wheat production in the NCP and can be used as a reference for further research on water management practices.

1. Introduction

Sustainable management of the regional groundwater in North China, where more than 70% of fresh water is used in agriculture, is a major challenge (Du et al., 2015). This is why severe groundwater level decreases (0.5–3 m/year) were found by Currell et al. (2012) throughout the North China plain (NCP) in the last three to four decades. Liu et al. (2002) and Sun et al. (2006) stated that winter precipitation ranges from 50 mm in dry to 150 mm in wet years in areas where the water requirement for winter wheat production is estimated to be 300–450 mm. Thus, maximizing the water productivity of winter wheat is the current basic need for NCP farmers. This can be achieved by proper soil water management practices. Selecting water management practices without knowing the soil water dynamics and water uptake by the crop makes it nearly impossible to support an efficient winter wheat production system that includes root development (Ritchie, 1981; Samson and Sinclair, 1994). Less attention has been paid to studies of root morphology because roots occur beneath the soil surface and require tedious measurements (Ephrath et al., 1999; McMichael and Taylor, 1987). Roots are anchors and function as entry points for the uptake of water and mineral nutrients for crops. Roots also serve as sensors of water stress and have many synthetic functions of shoot cells (Kramer and Boyer, 1995). Thus, a better understanding of root morphological growth and root water uptake (RWU) patterns in the soil profile is very important for successful crop growth and maximum grain production (Coelho and Or, 1999; Roose and Fowler, 2004; Samson and Sinclair, 1994). Zuo et al. (2004) collected wheat

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* Corresponding author at: Farmland Irrigation Research Institute, Chinese Academy o Agricultural Sciences, No. 380 Hongli Road, Xinxiang, Henan 453003, PR China.
E-mail address: duanaiwang@aliyun.com (A. Duan).

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root length density (RLD) information from several studies and concluded that RLD is an important parameter to model water and nutrient movement in the vadose zone as well as to study soil-root-shoot-atmosphere interactions. Carvalho and Foulkes (2013) also concluded that the RLD (cm/cm^3) is the most suitable parameter to describe water uptake by plant roots compared with other root traits. Thin roots have a relatively high specific root length (SRL) or length: dry weight ratio, whereas the fine root system functions as the principal pathway for water and nutrient absorption (Eissenstat, 1992). This author further concluded that water and nutrient uptake increases are more likely to occur with greater root length than root mass and provided evidence that a higher SRL tended to lead to greater plasticity in root growth and a greater physiological capacity but shorter root longevity and less mycorrhizal dependency. Various techniques have been developed to monitor root dynamics under field conditions where excavation techniques, including soil cores, have long been considered to provide the most reliable estimates of root morphology (Samson and Sinclair, 1994).

Many researchers have correlated root growth and water uptake under different soil moisture regimes (Carvalho and Foulkes, 2013; Coelho and Or, 1999). The amount of soil water absorbed by plant roots not only depends on the physical characteristics of the soil but also has a greater influence on profile root growth features (Yang et al., 2006). Non-irrigated plants have thicker roots, fewer roots near the soil surface, and more roots at deeper depths (Rowse, 1974). The RWU is distributed over the root zone according to the spatial root distribution and is controlled by climatic demand, the spatial distribution of soil water availability and root density (Albasha et al., 2015; Šimůnek and Hopmans, 2009). Li et al. (2014) concluded that the RWU rate of maize increased after rainfall or irrigation. Xue et al. (2003) found that winter wheat roots continued to grow up to a depth of 2 m until the booting stage and concluded that the RWU rate decreased as available soil water decreased. The root sampling results presented by Zhang et al. (2004) showed that winter wheat has a profile root system with an average maximum rooting depth of 2 m, and most of the root system is concentrated in the upper 40 cm of soil, which is why the roots in the top layer of soil play an important role in soil water uptake. Kmoch et al. (1957) mentioned that the root development of winter wheat was influenced by soil moisture. These authors found that a dense network of roots developed in the soil when the soil moisture tension was above 15 atmospheres, and they observed roots at a depth of 13 feet under favorable moisture conditions. Maximum root growth in the subsoil significantly improved the soil water supply to the crop by shifting root growth downward during the growing period due to water depletion in the surface soil (Torreano and Morris, 1998). On the other hand, soil temperature affects the growth, initiation, branching, orientation, direction of growth, and root turnover of root system components (Kaspar and Bland, 1992). These authors showed that as the temperature increases, roots grow faster and reach a maximum growth rate at approximately 30 °C for maize and pecans, above which the rate begins to decrease. The soil temperature profile distribution is greatly affected by the irrigation method and undoubtedly influences root water uptake directly or indirectly (Lv et al., 2013a).

Coelho and Or (1999) emphasized that for irrigation scheduling, it is necessary to consider the effect of the RWU rate on soil water dynamics. Li et al. (2010) compared three irrigation schedules applied during the jointing, heading and milking stages of winter wheat and concluded that single irrigation event applied during the jointing stage caused an increase in root length density in a >30 cm deep soil profile compared to 2 or 3 irrigation events during other growth stages. Lv et al. (2010) concluded that the irrigation method influences winter wheat root development and the water uptake profile, even for the same irrigation schedule. These authors found that root uptake in the upper zone of the soil profile increased with increases in irrigation frequency. An experiment performed by Camposeo and Rubino (2003) on autumn sown sugar beet clearly illustrated that the applied irrigation frequencies significantly affected RWU. These authors concluded that the root length density along the soil profile decreased more than 76% by decreasing the irrigation frequency. Above and below ground biomass is more severely limited by water stress than by nutrient stress (Fabião et al., 1995), whereas root initiation decreases with increasing depth (Torreano and Morris, 1998) if adequate water can be accessed by the surface roots. Although there are numerous fractional studies on the effect of irrigation method (Lv et al., 2010) or irrigation frequency (Li et al., 2010; Shao et al., 2009; Xue et al., 2003) on root growth or water uptake, a combined approach of irrigation method and scheduling system with water management practices applied to an entire farmer's field to understand the overall soil water dynamics and their influencing parameters has not been attempted.

Thus, the objectives of this field-based winter wheat experiment with a promoting irrigation method and feasible irrigation schedule were to (i) measure the root morphological growth, (ii) study the effects of soil moisture and temperature and (iii) estimate soil water dynamics in the root zone under surface drip irrigation (SDI), sprinkler irrigation (SI) and surface flooding (SF), with irrigation at 50%, 60% and 70% of FC. The results of this study will provide references for further research and the farmers of the NCP to design a practical and environmentally friendly irrigation system by selecting an appropriate irrigation method with a proper irrigation schedule.

2. Materials and methods

2.1. Experimental site

Field research was conducted at the experimental station of the Farmland Irrigation Research Institute (FIRI) of the Chinese Academy of Agricultural Science (CAAS), located in Qiliying, Xinxiang City of Henan Province in North China (35°08′N, 113°45′E and 81 m altitude). The experimental site has underground pipelines connected to pumps with pressure regulators to supply ground water as source of irrigation water at a desired pressure head and a weather station is located in very close proximity to the experimental plots. The seasonal precipitation from mid-October to early June ranges from 60 to 200 mm, with seasonal water consumption of approximately 450–500 mm (Sun et al., 2006; Zhang et al., 2002) and a mean seasonal air temperature that varies between 10 and 12 °C.

2.2. Soil specification, tillage and harvesting

The soil characteristics, such as the physical and hydraulic parameters, were investigated before the irrigation treatments started and are presented in Table 1 for different root zone depths. The average contents of the available soil nutrients, i.e., nitrogen (N), phosphorous (P), and potassium (K), at the experimental site were 40.20, 11.90, and 100.51 mg kg^{-1}, respectively. The pH and electrical conductivity (EC) of the soil were 8.51 and 257.6 μs cm^{-1}, respectively, whereas the soil organic matter content was 1.64 g kg^{-1}.

Seed beds were prepared by plowing to a depth of 20 cm using a tractor drawn rotary cultivator; larger soil clods were smoothed using a harrow to ensure a completely flat bed. The equal amount of basal fertilizer dose was N: 120 kg ha^{-1} (50% of total N), applied as ammonium nitrate, P: 90 kg ha^{-1}, applied as calcium superphosphate, and K: 30 kg ha^{-1}, applied as potassium sulfate in all treatments (Gao et al., 2014). The remaining 50% of N (120 kg ha^{-1}),