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Nitrogen use by winter wheat and changes in soil nitrate nitrogen levels with supplemental irrigation based on measurement of moisture content in various soil layers

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ABSTRACT

In northern China, water sources are one of most limiting factors for agricultural development, particularly for winter wheat. Optimizing supplemental irrigation (SI) to achieve the ideal soil moisture content and nutrient uptake by plants is therefore highly important in this region. The present study investigated how various SI regimes affect nitrogen use in winter wheat and alter soil nitrate nitrogen (NO_3—N) content under field conditions. The soil relative water content (SRWC) of the 0–20 cm (D20), 0–40 cm (D40) and 0–60 cm (D60) soil layers was raised to 70% by supplemental irrigation at jointing and anthesis, and a non-irrigated, rain-fed (R-F) condition served as the control. The highest grain yields of 9648.4 kg ha^{-1} in 2011–2012 and 10,032.2 kg ha^{-1} in 2012–2013 were obtained in D40, which had higher nitrogen use efficiency (NUE) than R-F, D20 and D60. NUE was positively correlated with nitrogen translocation efficiency (NtE) and nitrogen fertilizer productivity (NfP) but not with nitrogen uptake efficiency (NupE). These results indicated that optimizing the SI regime improved NUE primarily by increasing nitrogen uptake and translocation and thereby raising NtE and NfP. The soil NO_3—N content was lower in D40 than in R-F, D20 and D60 in the 0–200 cm soil layers, indicating that NO_3—N leaching was the lowest in D40. Thus, the optimal SI regime, which consisted of irrigating SRWC in the 0–40 cm soil layer to 70% at jointing and anthesis, reduced NO_3—N leaching and increased NUE and NfP in winter wheat.

1. Introduction

The Shandong province of Northern China has 344 m^3 of water resources per capita, which is less than 1/6 of the national average and 1/25 of the global average (Qin et al., 2010). Piao et al. (2010) reported that climate change has significant impact on water resources in China. Moreover, due to low availability of water per capita and unbalanced distribution of water resources during the winter wheat growth season (Deng et al., 2006), water is a major factor restricting the production of winter wheat in this region. For this reason, water-saving irrigation regimes are commonly used in these areas (Sun et al., 2006; Zhang et al., 2013). Shao et al. (2011) reported that jointing and anthesis are the critical growth stages of winter wheat. However, studies on supplemental irrigation (SI) after measuring soil moisture content in different soil layers is rare in this region.

Nitrogen (N) is one of the main plant nutrients affecting plant growth (Sadras and Lawson, 2013). Water limitation substantially restricts total N uptake by crops (Haefele et al., 2008). In addition, irrigation is the main factor affecting nitrogen uptake, translocation, distribution and accumulation in winter wheat (Albina et al., 2013). Jin et al. (2009) applied irrigation water at wintering, turning-green, jointing, heading and filling stages of winter wheat at the rate of 60 mm each time in a warm temperate monsoon environment. The amount of N accumulation amount in grains at maturity under single (jointing) or double (jointing and filling) was higher than that of other conditions. However, the amount of N translocation from vegetative organs to grains under four irrigation times (wintering, turning-green, jointing and filling) was higher, at 3.2 mg per plant, than that under two

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irrigation times. In another experiment, soil moisture content in the root of wheat was irrigated to 33%, 66% and 100% of full irrigation. The amount of N uptake in wheat receiving 100% of full irrigation was lower by 9 kg ha^{-1}, compared to those receiving 66% of full irrigation, indicating that increasing amount of irrigation water, total N uptake decreased in wheat (Garabet et al., 1998). However, in a Mediterranean environment, 100% full irrigation and 50% of full irrigation resulted in N accumulation in grains at maturity of 84.6 and 73.0 kg ha^{-1}, respectively. The total N uptake amount in wheat plants receiving 100% of full irrigation was higher by 15.0 kg ha^{-1}, compared with that in those receiving 50% of full irrigation (Rossella et al., 2010). Therefore, optimizing SI regime could improve nitrogen uptake and translocation in winter wheat.

Behera and Panda (2009) noted that increased irrigation enhanced the leaching of soil nitrate–nitrogen (NO_3—N), but no significant differences were observed in nitrogen uptake and accumulation of winter wheat. NO_3—N leaching below 1.0 m of soil depth is the main pathway by which N is loss in the rotation system (Liu et al., 2003). Johnson-Beebout et al. (2009) and Adrienn et al. (2012) showed that appropriate water management reduced N loss and improved N uptake. Therefore, optimization of SI regime is necessary to reduce soil NO_3—N leaching.

Nitrogen use has been studied extensively in continuous-flood and limited-irrigation conditions in winter wheat (Devkota et al., 2013; Oweis et al., 2004; Krishna et al., 2013). In Northern China, at an application rate of 192 kg ha^{-1} of N, no significant difference in nitrogen use efficiency (NUE) was found between those receiving irrigation once at jointing and irrigation twice at jointing and anthesis. However, nitrogen fertilizer productivity (NFP) in the latter group was higher by 5.72 kg kg^{-1}, compared to the former group (Zang et al., 2012). In another study, irrigation was done to achieve soil moisture content at 0–120 cm depth of 30%, 60% and 100% in a semi-arid environment of India. Nitrogen use efficiency (NUE) in soil receiving 100% of full irrigation was higher by 8.08 kg kg^{-1} than that in soil receiving only 30% of full irrigation (Pradhan et al., 2013). Cossani et al. (2012) found that water and nitrogen availabilities resulted in a wide range of NUE, from 2.9 kg kg^{-1} to 33.9 kg kg^{-1}, the highest NUE was obtained for bread wheat (33.9 kg kg^{-1}) with 136 mm of irrigation water, whereas N-uptake efficiency increased by 14% with 400 mm of irrigation water. However, information on nitrogen use and NUE of winter wheat in response to SI by measuring soil moisture content in various layers is limited.

In the present study, the soil moisture contents of the 0–20, 0–40 and 0–60 cm soil layers were measured prior to SI. The soil moisture in each measured layer was raised to 70% of field capacity by irrigation at jointing and anthesis. The objectives of this study were: (1) to determine the effect of the different SI regimes on nitrogen translocation and uptake; (2) to evaluate the dynamics of soil NO_3—N content and total N content and (3) to recommend an optimal SI regime for improving the grain yield, NUE and nitrogen harvest index (NHI) for winter wheat.

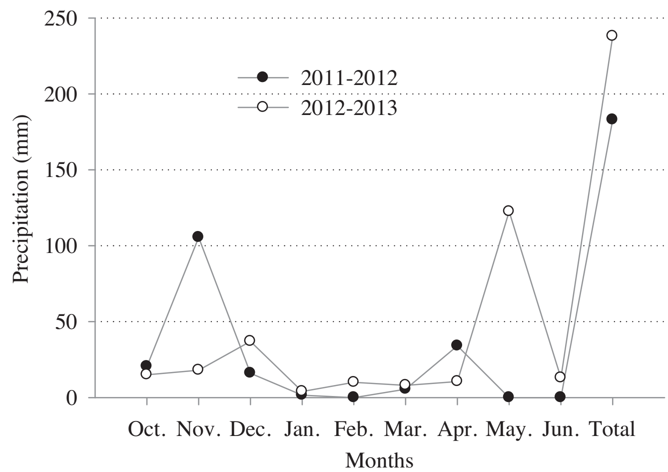

Fig. 1. Precipitation in the growth seasons of winter wheat in 2011–2012 and 2012–2013.

2. Materials and methods

2.1. Experimental site

The experiment was carried out from 2011 to 2013 under field conditions in the village of Shijiawangzi (35°40′09′N, 116°41′43′E, 55 m above sea level), Yanzhou, Shandong Province, Northern China. The area has a warm temperate semi-humid continental monsoon climate with annual average temperature of 13.6 °C, annual precipitation ranging from 480 to 850 mm and a groundwater depth of 25 m (Wang et al., 2013). The agrotype of the filed was loam. The nutrient conditions of the 0–20 cm soil layer before sowing are presented in Table 1. Precipitation during the 2011–2012 and 2012–2013 growth seasons are shown in Fig. 1. The field capacity and soil bulk density of the 0–20, 20–40 and 40–60 cm soil layers before sowing are presented in Table 2.

Winter wheat 'Jimai 22' was planted on 12 October, 2011 and 9 October, 2012 and harvested on 12 June, 2012 and 14 June, 2013, respectively. At the sowing stage, 105 kg N ha^{-1}, 150 kg P_2O_5 ha^{-1} and 150 kg K_2O ha^{-1} were applied to the soil as urea, diammonium phosphate and potassium chloride, respectively. At the jointing stage or Z31 (when the first node is detectable) (Zadoks et al., 1974), 135 kg N ha^{-1} was applied to the soil by ditching. At the trefoil stage, 180 plants m^{-2} remained.

2.2. Experimental design

The experiment consisted of four treatment conditions, each with three replicates, in a randomized design. The soil water content (SWC) was measured at depths of 0–20 cm (D20), 0–40 cm (D40) and 0–60 cm (D60). Using a previously reported irrigation formula (Cuenca, 1989; Jalal et al., 2012), the soil relative water content (SRWC) of each soil layer was raised to 70% at the jointing/Z31 (first node detectable) and anthesis/Z61 stages (beginning of

Table 1
Nutrient condition of 0–20 cm soil layers before sowing in 2011–2012 and 2012–2013.

Soil nutrient	Years	
	2011–2012	2012–2013
Organic matter (%)	1.4	1.5
Total nitrogen (g kg^{-1})	1.2	1.1
Available nitrogen (mg kg^{-1})	142.3	143.6
Available phosphorous (mg kg^{-1})	31.0	34.5
Available potassium (mg kg^{-1})	112.6	118.5

Table 2
Field capacity and soil bulk density of 0–60 cm soil layers before sowing in 2011–2012 and 2012–2013.

Years	Soil layers (cm)	0–20	20–40	40–60
2011–2012	Field capacity (%)	29.68	23.50	25.65
	Soil bulk density (g cm^{-3})	1.40	1.59	1.52
2012–2013	Field capacity (%)	30.90	23.86	27.17
	Soil bulk density (g cm^{-3})	1.39	1.58	1.50