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Crop rotation and N application rate affecting the performance of winter wheat under deficit irrigation

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ABSTRACT

Deficit irrigation to winter wheat is gradually adopted in the North China Plain (NCP) for conservation of groundwater resources. N application to winter wheat should be decided based on the irrigation water availability. Under deficit irrigation, yield of winter wheat was also related to the water use characters of its previous crops. Field studies were conducted from 2013 to 2016 at Luancheng station in the NCP to evaluate the addition of soybean to the conventional annual double cropping system (winter wheat-summer maize) and reducing N input on the performance of winter wheat under deficit irrigation. Summer maize was either replaced by soybean or inter-planted with soybean. The subsequent winter wheat was applied with six nitrogen rates (0, 135, 216, 270, 324 and 405 kg/ha) with one irrigation or two irrigation applications. The results showed that the average seasonal water use of single soybean (SS), intercropping of maize and soybean (IMS) and single maize (SM) was 359.1 mm, 336.3 mm and 309.6 mm from 2013 to 2016, respectively. The inclusion of soybean as single or inter-planted crop increased the water use during the summer rainy season, which was related to the increase in leaf area index. As compared with the SM, the soil water stored in the 2 m soil profile at the summer crops harvesting was reduced by 24.7 mm and 94.7 mm in 2014, 15.9 mm and 95.6 mm in 2015, respectively, for the IMS and SS, respectively. Due to the dependent of winter wheat on the stored soil water before sowing, the reduction in pre-season soil water content significantly decreased the yield by 1005.4–1878.0 kg/ha. Yield of winter wheat didn't respond to the increase in N application when N rate was over 135 kg/ha. The local N application rate at 270 kg/ha could be reduced up to 50% without apparent effects on crop productivity under deficit irrigation scheduling. The results indicated that for diminishing the reduction in yield of winter wheat under limited water supply, its previous crop with less water use in summer season should be selected. Yield of winter wheat could be maintained with half of its normal N application under limited water supply.

1. Introduction

The North China Plain (NCP) is one of the most important grain production bases in China, where the prevailing winter wheat and summer maize double cropping system produced about 60% of the wheat and 45% of the maize nationally (National Bureau of Statistics, 2015). High inputs in nitrogen and irrigation have played key roles in the high-yielding of this double cropping system (Zhang et al., 2017). However, excessive nitrogen application and over-irrigation have been endangering ecological environment, which impeded the sustainable development of cereal production in NCP (Huang et al., 2018; Li et al., 2017; Rattan et al., 2017; Sánchez-Martín et al., 2017; Shibata et al., 2017; Zhao et al., 2017). Due to the exhausted groundwater resources and lowered aquifer, deficit irrigation is now widely applied to winter wheat which grows during the dry season and depends greatly on the stored soil water before planting (Zhang et al., 2013). Due to the importance of winter wheat for the national food security, it is important to maintain the production of winter wheat. Therefore, the summer crop before winter wheat season could be changed to conserve soil water for winter wheat use (Nielsen et al., 2011). The soil water status determines the nitrogen availability to crops. Crop responses to nitrogen fertilizer were generally reduced with the reduction in irrigation (Cosentino et al., 2014; Gonzalez-Dugo et al., 2010; Saeed et al., 2017). Therefore, it is necessary to decide the N application based on the water availability to crops for improving the nitrogen use efficiency (NUE).

Methods of improving NUE included adopting the high N use efficiency cultivar, choosing the right fertilizer type and the proper fertilization method, and so on (Cui et al., 2008; Di Gioia et al., 2017; Fox

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et al., 2017; McAllister et al., 2016; Nelson et al., 2014; Rajala et al., 2016). Combining legume by intercropping or rotation in cereal production was taken as one of environment-friendly methods (Amossé et al., 2014; Manevski et al., 2015; Oberson et al., 2013; Peoples et al., 2017; Plaza-Bonilla et al., 2017). As the main protein and oil crop, soybean is usually planted as mono-crop or intercropped crop with others. The addition of soybean into the annual double-cropping system of winter wheat and summer maize in the NCP may reduce the nitrogen fertilizer input. Another aspect is that due to the water shortage problems in the NCP, winter wheat is now applied with deficit irrigation practices, the addition of soybean might interfere with the annual water balance. How the inclusion of soybean into the annual double cropping system of winter wheat and maize affecting the performance of its following crop, winter wheat, needs further elaborating.

Deficit irrigation, which was defined as the supplied water use below the crop's evapotranspiration (ET) (Expósito and Berbel, 2017; Gheysari et al., 2017; Munitz et al., 2017), was widely applied to winter wheat in the NCP (Deng et al., 2006; Zhang et al., 2017). Deficit irrigation scheduling has been developed to winter wheat that could decrease irrigation water use by around 40% and increase water use efficiency (WUE) by 10% with small yield penalty (Sun et al., 2014; Zhang et al., 2006, 2008). Under deficit irrigation, the increase in the contribution of soil water depletion to the total ET of wheat could diminish the yield reduction (Fang et al., 2017; Sun et al., 2014; Zhang et al., 2006, 2013). Therefore, the distribution of the root system in the soil profile will affect the soil water availability to the crop (Dodd et al., 2011; Draye et al., 2010; Hodgkinson et al., 2017; Pinto and Reynolds, 2015). Maximizing the rooting depth would improve the crop performance under water stress condition (Zhang et al., 2004). Selecting crops with aggressive root system as the previous crop can improve the yield of the following crop because that the "bio-drilling" of the previous crop's root system can help the roots of the following crop to grow in deeper soil profile to extract more soil water, and the deceased roots in the soil of former crop can supply channels and nutrients for the root growth of subsequent crop (Calonego and Rosolem, 2010; Han et al., 2016; Perkons et al., 2014).

The water use of previous crop could also affect the soil water availability to its following crops. After analyzing the six-year water dynamics of the inclusion of fall-winter cover crop into a maize-soybean rotation in the Argentine Pampas, Restovich et al. (2012) concluded that the yield of main crop would be affected by its previous cover crop in exceptionally dry seasons due to the soil water extraction. Nevertheless, the effects on soil water equilibrium by preceding crops were not all adverse for the following crops, which were related to the soil water consumption by the previous crops (Badaruddin and Meyer,1989; Anderson, 2005; Nielsen and Vigil, 2005).

Nitrogen and water usually have interactive effects on crop growth. The increase in nitrogen concentration in leaf can improve the photosynthesis rate by accelerating the Rubisco activity and electron transport activity at a low stomatal conductance of crop with a water scarcity (Field et al., 1983). Higher soil NO_3^- content can regulate the aquaporin to improve the hydraulic conductivity of root system to relieve the water stress of crop (Aroca et al., 2012). Nitrogen can also stimulate the distribution of root along the deeper profile to extract more soil water for crop use (Pala et al., 2007; Shen et al., 2013).The application of nitrogen fertilizer has the potential to improve crop production under water stress condition. However, the benefit of N application will change with the soil water conditions. Thus, it is important to have the optimized N rate corresponding with the limited water supply condition for the purposes of improving both NUE and WUE.

Therefore, the objectives of this study were to: (i) evaluate the changes in the water use by summer crops with introducing legume (soybean) to replace maize or intercropped with maize and their effects on the performances of the following winter wheat under deficit irrigation; (ii) evaluate the effects of N application on the yield, NUE and WUE of winter wheat under deficit irrigation; (iii) optimize N application to winter wheat under deficit irrigation based on the yield response of winter wheat to different N rates as well as the economic output.

2. Materials and methods

2.1. Experimental site

The study was conducted from 2013 to 2016 (three continuous annual rotation cycles of summer maize and winter wheat) at Luancheng Agro-Eco-Experimental Station of the Chinese Academy of Sciences, which is located in the northern part of the NCP at the base of Mt. Taihang (37°53′N, 114°41′E, 50 m above sea level). The soil at the station, belongs to Gleysol, is a moderately well-drained loamy soil with a deep profile that is considered highly suitable for grain production. The average water holding capacity and the wilting point of 0–200 cm soil profile are 36% (v/v) and 13% (v/v), respectively, and soil nutrient contents for the top 0–20 cm tillage soil layer were: 2.1 g/kg for organic matter, 0.11 g/kg for total N, 92 mg/kg for available N, 21 mg/kg for available P and 80 mg/kg for available K. The main cropping system for the region is the annual double–crop rotation of winter wheat and summer maize. Rainfall mostly falls in the summer season, the maize growing season, with amount around 350 mm (from middle of June to end of Sep.). During winter wheat growing season (from October to early June next year), rainfall is around 120 mm, far less than the water requirements of this crop (around 450 mm). Irrigation is important for high yielding of this crop.

2.2. Experimental design

The study was carried out using a factorial field experiment in a split-plot randomized complete block design with four replicates. A field with area of 15 m × 180 m divided into three parts were used for the three planting patterns in summer season, which were single maize (SM), single soybean (SS), intercropping of maize and soybean (IMS), respectively. After harvesting winter wheat, maize and soybean were planted. The varieties of maize, soybean and wheat were Zhendan958, Lindou10 and Shixin828, respectively. The row spacing and the plant spacing of single maize were 60 cm, 28.57 cm, respectively, and that of single soybean were 40 cm, 16 cm, respectively. The summer maize in intercropping pattern was planted with wide row of 160 cm and narrow row of 40 cm and plant space of 19.35 cm, 3 lines soybeans were intercropped in the wide row of summer maize with a 40 cm row spacing and a 16 cm plant spacing, a 40 cm space row was between plants of maize and soybean. After planting, maize and soybean were immediately irrigated with 80 mm water to ensure emergence due to the top 50 cm soil profile was very dry after harvesting of winter wheat. The irrigation was conducted by connecting a plastic tube with the low-pressure water transportation pipelines and a flow meter was connected with the outlet from the pipelines to record the water used for each plot. A top application of 375 kg/ha urea (N content at 46%) was broadcasted during the early growth period of summer crops with a rainfall event. At the end of September, the maize cobs and the soybean of above-ground part were harvested manually, the straw of maize were chopped and incorporated into the top soil layer.

The three blocks each with area of 15 m × 60 m were used for the six nitrogen gradient treatments to winter wheat with zero N (0% N), the normal N rate (100% N) as the local practice (270 kg N/ha), increase of 20% (120% N) and 50% (150% N) over the normal rate and reduction of 20% (80% N) and 50% (50% N) over the normal rate. The six N treatments were randomly arranged in the blocks in winter wheat season. Each treatment was replicated four times, and each replication having area of 30 m^2 (5 m × 6 m). The detailed N applications of different treatments were described in Table 1. Once the plots were decided for different treatments, they were treated the same during the