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# Micro-irrigation improves grain yield and resource use efficiency by co-locating the roots and N-fertilizer distribution of winter wheat in the North China Plain

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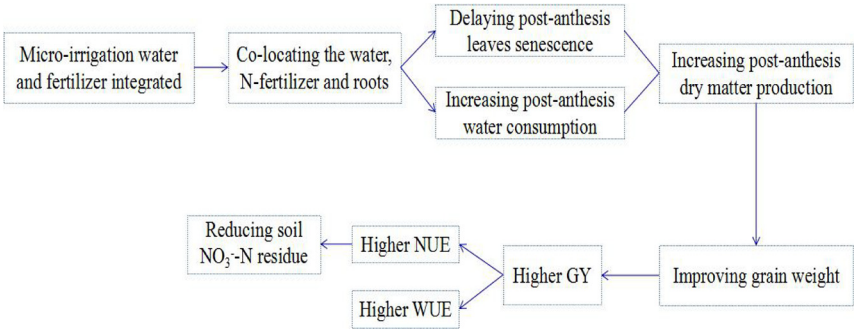
## HIGHLIGHTS

- MI significantly increased yield and water and nitrogen use efficiency compared to TI.
- MI significantly promoted matter production post-anthesis, leading to higher yield.
- MI optimized water consumption structure thus increased WUE.
- MI co-located the roots, water, and $NO_3^-$-N distribution in soil thus increased NUE.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Water use efficiency (WUE) and nitrogen fertilizer use efficiency (NUE) of winter wheat are urgently needed to further improve in the North China Plain (NCP). In this study, a 3-year field experiment was conducted during the 2014–2017 growing seasons to clarify the effect of traditional flood irrigation (TI), surface drip irrigation (DI), and micro-sprinkling irrigation (MSI) on grain yield, WUE, and NUE of winter wheat. Across the 3 years, grain yield of DI and MSI improved by 9.79% and 14.1%, WUE of DI and MSI increased by 12.3% and 17.7%, and NUE of DI and MSI increased by 9.77% and 14.0%, respectively compared with those of TI. Wheat subjected to the micro-irrigation treatments (DI and MSI) had higher chlorophyll content in flag leaves 10 days post-anthesis; this postponed senescence of the flag leaves, which increased dry matter accumulation post-anthesis, and increased 1000-grain weight and grain yield. The micro-irrigation treatments reduced pre-anthesis water consumption but increased post-anthesis water consumption and ensured the water supply in the top soil layer at the critical stage, thus increasing WUE. Root length density (RLD) of TI in the 0–80-cm soil layer was significantly higher than that of micro-irrigation, whereas micro-irrigation had higher RLD than TI below the 80-cm soil layer, which promoted the absorption and utilization of water and nitrogen in deep soil. The micro-irrigation treatments increased total nitrogen accumulation of the plants, reduced soil nitrate nitrogen ($NO_3^-$-N) content at maturity, ensured the nitrogen supply in the top soil layer, thus increasing NUE. Overall, micro-irrigation with water and fertilizer as an integrated pattern significantly improved grain yield, WUE, and NUE of winter wheat in the

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NCP by co-locating the root, water, and N-fertilizer distribution and reducing $NO_3^-$-N accumulation in deep soil. The best treatment was micro-sprinkling irrigation.



## 1. Introduction

The North China Plain (NCP) is one of the most important agricultural production areas in China, as it covers about 25% of the total farmland and provides 71% of the whole country's winter wheat production (National Bureau of Statistics of China, 2015). However, the shortage of groundwater resources caused by years of agricultural production in this region has become an important factor restricting sustainable development of agriculture (Sun et al., 2015; Oort et al., 2016). Water consumption for winter wheat is approximately 400–500 mm, while annual rainfall mainly occurs in summer, and only about 150–180 mm precipitation occurs during the winter wheat growing season (Liu et al., 2011; Yuan et al., 2015). As this volume does not match the demand of wheat growth, thus, the wheat production is mainly based on groundwater irrigation in the NCP. Water-saving irrigation has made great progress in this area to alleviate the severe problem of overexploitation of groundwater. It has optimized the farmers' irrigation practices from the former four to six times to two to three times, and also greatly increased water use efficiency (WUE) (Zhang et al., 2015; Zhang et al., 2011). However, successive crop production in previous years under water-saving irrigation still resulted in a further decline in the groundwater table and had a serious impact on the region's eco-environment (Hu et al., 2010; Sun et al., 2010; Yang et al., 2010). New highly efficient production methods need to be further studied to improve WUE and promote environmentally friendly agriculture.

Optimizing irrigation is an important means to improve grain yield and WUE of winter wheat. Studies have shown that ensuring a water supply during the critical growth period and a moderate water deficit during the non-critical period of wheat can significantly improve WUE by adjusting the population structure and achieve higher utilization efficiency of irrigation water (Wang, 2017). However, the prevailing irrigation method in the NCP is flood irrigation. It is difficult to improve WUE further under traditional flood irrigation conditions. In recent years, new irrigation methods, such as drip and sprinkler irrigation, have been applied gradually to field crops. These irrigation patterns significantly improve WUE, particularly in the area of groundwater deficit (Liu et al., 2011; Man et al., 2014). Compared with traditional irrigation method, using drip irrigation significantly reduced the irrigation water required by a corn crop by 35%–55%, increasing grain yield and WUE (Lamm and Trooien, 2003; Sui et al., 2018). Similarly, researchers have also reported that suitable sprinkler irrigation improves wheat grain yield and resource use efficiency (Mon et al., 2016). Micro-sprinkling irrigation is a new irrigation method that has been developed in recent years through the development of drip and sprinkler irrigation (Man et al., 2014). Our previous studies reported that, compared with traditional flooding irrigation (applied at jointing and anthesis with 60 mm each time), micro-sprinkling irrigation and integrating water and nitrogen fertilizer with optimal irrigation frequency (applied at jointing, booting, anthesis and grain filling with 30 mm each time) obtained higher grain yield and water use efficiency; and we also found that, under the optimal irrigation frequency, the nitrogen application rate of 195 kg $ha^{-1}$ had higher grain yield, WUE and NUE than those of 135 kg N $ha^{-1}$ and 240 kg N $ha^{-1}$ (Zhang et al., 2016; Li et al., 2016). However, research on the mechanism behind the high yield and efficiency associated with this irrigation method is insufficient, and further research and discussion are needed.

The root system of winter wheat is the most important functional organ for plants to capture available water and nutrients from the soil (Bengough et al., 2011). Roots play a critical role in the plant–soil ecosystem and significantly affect crop growth and grain yield (Zhang et al., 2009; C. Wang et al., 2014). Root vertical distribution of winter wheat in soil is closely related to the utilization of soil water and nitrogen, and the management of water and nitrogen has a great influence on the distribution of the root system (C. Wang et al., 2014; Feng et al., 2017). A reasonable root distribution significantly increases N use efficiency and reduces the loss of nitrogen fertilizer and the negative effects on the environment (Rasmussen et al., 2015). Zhang et al. (2006) reported that wheat is a deep root crop, in which maximum root length can reach to 2 m in the soil profile. Root growth can be regulated by optimizing irrigation, and the appropriate soil water deficit promotes the spread of roots into deeper soil layers, increasing the absorption and utilization of deep soil moisture to improve WUE (Li et al., 2010; Xu et al., 2016). However, the upper profile of soil is the main root distribution area, and the 0–40-cm soil layer accounts for 87.4% of the total root quantity (C. Wang et al., 2014). Co-locating the water and nitrogen applications with root distribution in the soil profile can greatly affect WUE and NUE.

Traditional fertilization by farmers in the NCP always involves a combination of a base fertilizer at sowing and a top dressing by broadcasting fertilization (the prevailing fertilization method in the NCP) before irrigation at the regreening to jointing stage of winter wheat. Smiciklas and Below (1992) reported that N fertilizer is rapidly transformed to nitrate-nitrogen ($NO_3^-$-N) through nitrification in good aerated or strongly calcareous soils. Soil $NO_3^-$-N leaching below the 1.0 m depth of soil is the main pathway of N loss (Liu et al., 2003). Loss may reach half the amount of fertilizer applied due to poor synchrony between N-fertilizer supply and crop demand (Guarda et al., 2004; Shi et al., 2012). Fertilization and irrigation are the main causes of nitrogen leaching, usually occurring after irrigation, especially when excessive irrigated water is applied (Gheysari et al., 2009; Wang et al., 2015). And nitrogen may migrate out of the main root distribution area when the crop cannot make full use of nitrogen in the soil, which can cause $NO_3^-$-N leaching into the deep soil layer and pollution of groundwater, as well as an increase in greenhouse gas emission (Zhang et al., 2018). It is difficult to achieve better co-location among the root system, fertilizer, and water supply when using traditional production practices, which restrict further improvements in WUE and NUE. Integrating water and fertilizer with micro-irrigation is expected to achieve irrigation water and nitrogen fertilizer supply coincident with the main root distribution area, ensure water and nitrogen supply during the critical growth period in the upper soil, reduce the risk of soil nitrate leaching into deeper soil layers, increase dry matter (DM) production post-anthesis, promote plant nitrogen absorption, and improve WUE and NUE.

To confirm this hypothesis, a 3-year field experiment was conducted to identify the effects of different irrigation patterns on (1) grain yield of winter wheat, accumulation of DM, the contribution ratio of DM to grain yield and the harvest index (HI), (2) water consumption, WUE, and soil water content during the critical growth stage and the distribution characteristics of the root system, and (3) soil $NO_3^-$-N content during the critical growth period, nitrogen accumulation, and NUE. We also expect to clarify the mechanism of micro-irrigation improving the yield, WUE, and NUE of winter wheat after integrating water and fertilize in the NCP and provide a theoretical basis for applying micro-irrigation technology.

## 2. Materials and methods

### 2.1. Experimental site

The experiments were conducted at Wuqiao Experimental Station of the China Agricultural University (Hebei Province, China; 116.3°E,