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RESEARCH ARTICLE

A simulation of winter wheat crop responses to irrigation management using CERES-Wheat model in the North China Plain

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Abstract
To improve efficiency in the use of water resources in water-limited environments such as the North China Plain (NCP), where winter wheat is a major and groundwater-consuming crop, the application of water-saving irrigation strategies must be considered as a method for the sustainable development of water resources. The initial objective of this study was to evaluate and validate the ability of the CERES-Wheat model simulation to predict the winter wheat grain yield, biomass yield and water use efficiency (WUE) responses to different irrigation management methods in the NCP. The results from evaluation and validation analyses were compared to observed data from 8 field experiments, and the results indicated that the model can accurately predict these parameters. The modified CERES-Wheat model was then used to simulate the development and growth of winter wheat under different irrigation treatments ranging from rainfed to four irrigation applications (full irrigation) using historical weather data from crop seasons over 33 years (1981–2014). The data were classified into three types according to seasonal precipitation: <100 mm, 100–140 mm, and >140 mm. Our results showed that the grain and biomass yield, harvest index (HI) and WUE responses to irrigation management were influenced by precipitation among years, whereby yield increased with higher precipitation. Scenario simulation analysis also showed that two irrigation applications of 75 mm each at the jointing stage and anthesis stage (T3) resulted in the highest grain yield and WUE among the irrigation treatments. Meanwhile, productivity in this treatment remained stable through different precipitation levels among years. One irrigation at the jointing stage (T1) improved grain yield compared to the rainfed treatment and resulted in yield values near those of T3, especially when precipitation was higher. These results indicate that T3 is the most suitable irrigation strategy under variable precipitation regimes for stable yield of winter wheat with maximum water savings in the NCP. The application of one irrigation at the jointing stage may also serve as an alternative irrigation strategy for further reducing irrigation for sustainable water resources management in this area.

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1. Introduction

Winter wheat is one of the most important food crops in the North China Plain (NCP) (Mueller *et al.* 2012). Approximately one-third of the total arable land in the NCP is currently used for winter wheat cultivation (CAYN 2013). In the NCP, the growth and yield of winter wheat is mainly determined by water availability from precipitation and irrigation. The average precipitation during the winter wheat growing season (October–June) in this area is approximately 117 mm, which is less than the water requirements for achieving the maximum grain yield and water use efficiency (WUE) for winter wheat. Irrigation is thus critical for maintaining high wheat production (Chen *et al.* 2015). Traditional high-yielding irrigation strategies are usually based on the full water requirements at different growth stages in winter wheat. Previous studies have reported three to five or more irrigation strategies to maintain wheat yield (Zhang *et al.* 2005). Through studies over the course of many years, cultivation systems with water-saving, fertilizer-saving, high-yielding and simplified management have been developed for winter wheat, and the WUE has improved by 20% compared to the traditional high-yielding technology (Wang *et al.* 2006).

Underground water is the major source of irrigation water in the NCP. Large-scale irrigation in this region began in the 1970s, and since the adoption of this practice, the extraction of groundwater increasingly exceeds depletion of groundwater table. As a result, groundwater levels are continuously decreasing (Fang *et al.* 2010; Piao *et al.* 2010). Although more efficient irrigation technologies have been introduced over the past 40 years, these developments have not slowed the depletion of underground water (Ma *et al.* 2015). Studies have shown that the groundwater table in the NCP is declining at a rate of 0.8 m yr^{-1}, and this has led to a serious underground water crisis in the area (Chen *et al.* 2003; Han *et al.* 2016). On the other hand, precipitation in NCP has exhibited a long-term trend of decline (Piao *et al.* 2010). The groundwater resource crisis has led to an urgent need for a reduction of irrigation to maintain agricultural sustainability in the area (Fang *et al.* 2010). In the future, irrigation strategies will emphasize maximizing the productivity per unit of water used rather than the productivity per unit of crop area (Fereres and Soriano 2007).

Reduction of the overall application of irrigation water to conserve water resources is possible through deficit irrigation (Guo *et al.* 2014). Deficit irrigation is defined as the application of irrigation water in volumes less than the full evapotranspiration (ET) requirement of the crop (Geerts and Raes 2009). Irrigation only at certain stages of crop growth is a strategy that has been widely utilized in areas where water resources are limited (Kang 2004). In the NCP, deficit irrigation can be applied to wheat crop at specific growth stages to mitigate the adverse effects of water stress on plants (Zhang *et al.* 2013). For example, Kang (2002) reported that irrigation below the full potential ET requirement did not necessarily reduce the winter wheat yield. Determining the critical growth stages for applying the limited water available for irrigation will be crucial for reducing the impact of water shortage on wheat grain yield while maintaining economic returns. Precipitation is also a critical factor affecting wheat production in the NCP because it directly affects irrigation requirements and water balance in wheat (Sun *et al.* 2010).

The CERES-Wheat model is a cropping system model that is a component of the Decision Support System for Agrotechnology Transfer, popularly known as DSSAT (Jones *et al.* 2003; Hoogenboom *et al.* 2004). High performance has been reported for CERES-Wheat in simulating wheat growth and yield in response to environmental factors and management under a wide range of soil and climatic conditions (Arora *et al.* 2007; He *et al.* 2013; Ji *et al.* 2014; Mavromatis 2014; Yu *et al.* 2014; Dokoohaki 2015; Ahmed *et al.* 2016; Attia *et al.* 2016). The objectives of this study were to: (1) calibrate the CERES-Wheat model to accurately predict the winter wheat grain and biomass yield, harvest index (HI), and WUE responses to different irrigation scheduling practices using long-term weather datasets available for NCP; (2) simulate the development and growth of winter wheat under different irrigation treatments using historical weather data from 33 years (1981–2014) with crop seasons that were classified into three types according to seasonal precipitation; and (3) discuss the possibility of further reducing irrigation by optimizing the irrigation strategies for sustainable groundwater management.

2. Materials and methods

2.1. Model description

In this study, we used CERES-Wheat, a component of the DSSAT Cropping System Model v4.6 (Hoogenboom *et al.* 2015) that can simulate the growth and development