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Optimized single irrigation can achieve high corn yield and water use efficiency in the Corn Belt of Northeast China

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ABSTRACT

Decreasing the corn (*Zea mays* L.) gap between the potential yield and farm yield and reducing the risk of grain yield of drought are very important for corn production in the Corn Belt of Northeast China (CBNC). To achieve a high and stable corn yield, the effects of supplementary irrigation on yield, water use efficiency (WUE) and irrigation water use efficiency (IWUE) were studied using a modelling approach. The Root Zone Water Quality Model 2 was parameterized and evaluated using two years of experimental data in aeolian sandy soil and black soil. The evaluated model was then used to investigate responses to various irrigation strategies (rainfed, full irrigation and 12 single irrigation scenarios) using long-term weather data from 1980 to 2012. Full irrigation guarantees a high and stable corn grain yield (12.92 Mg ha^{-1} and has a coefficient of variation (CV) of 14.8% in aeolian sandy soil; 12.30 kg Ma^{-1} and CV of 11.1% in black soil), but has a low water use efficiency (19.92 and 21.81 kg ha^{-1} mm^{-1}) and a low irrigation water use efficiency (10.01 and 11.03 kg ha^{-1} mm^{-1}). A single irrigation can increase corn yields by 3–35% for aeolian sandy soil and 5–35% for black soil over different irrigation dates compared with no irrigation. The most suitable single irrigation date was during late June to early July for aeolian sandy soil (yield = 10.73 Mg ha^{-1} and WUE = 27.94 kg ha^{-1} mm^{-1}) and early to mid-July for black soil (yield = 11.20 Mg ha^{-1} and WUE = 27.70 kg ha^{-1} mm^{-1}). The lowest yield risk of falling short of the yield goal of 8, 9, and 10 Mg ha^{-1} were 9.1%, 18.2%, and 33.33% in aeolian sandy soil and 3.0%, 15.25, and 21.2% in black soil when an optimized single irrigation was applied in late June or early July, respectively. Therefore, an optimized single irrigation should be applied in late June to early July with the irrigation amount to refill soil water storage of root zone to field capacity in CBNC.

1. Introduction

The Corn Belt of Northeast China (CBNC) includes the Heilongjiang, Jilin and Liaoning provinces, which accounts for about 35% of total corn production and 31% of national corn growing area (National Bureau of Statistics of China, NBSC, 2014). It is main corn commodity grain base with above 80% commodity rate. In CBNC, corn yield have steadily increased since the 1980s (Chen et al., 2011; Liu et al., 2012) due to the improved management and cultivars (Chen et al., 2012; Chen et al., 2013; Lv et al., 2015). However, farm yields were, on average, only 51% of the potential yields (Yang et al., 2007). An opportunity was provided to significantly increase corn production by effective irrigation, fertilization, herbicide, and planting density (Liu et al., 2012). Corn production in the CBNC is mainly rainfed. The drought resulted in a large corn yield reduction in 10 of 24 years from 1990 to 2013 (NBSC, 1991–2014) due to annual and seasonal fluctuations of precipitation (Liu et al., 2013; Lu et al., 2014). The rate of yield reduction ranged from 1.8% to 24.5%. The irrigation might be an effective way to reduce the gap between the potential yield and farmer yield and decrease the risk of the drought. And the optimized irrigation strategy should also be studied for high corn yield and high water use efficiency (WUE) under the condition of the local limited water resources.

Irrigation schedules can be classified as full and deficit irrigation, based on plant, soil, and climate conditions (Martin et al., 1990). Full irrigation could achieve an elevated and stable corn yield, but it would increase the related equipment and labor cost (Guo et al., 2010; Finger 2012). Crop water requirements vary greatly during different growing stages. To avoid water stress during critical growth stages, supplementary irrigation may increase the yield and water use efficiency (WUE) when water resources are restricted or the cost is excessive (Iqbal et al., 2014; Zhang et al., 2007).

Abbreviations: CBNC, the corn belt of Northeast China; ET, evapotranspiration; ET0, reference crop evapotranspiration; IWUE, irrigation water use efficiency; LAI, leaf area index; RZWQM2, Root Zone Water Quality Model 2; WUE, water use efficiency.

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Hergert et al. (1993) showed that the corn yield of 5.6, 10.1 and 11.8 Mg ha^{-1} for rainfed, supplementary irrigation, and full irrigation, respectively, and marginal returns of 31 kg ha^{-1} mm^{-1} of water applied for supplementary irrigation and 11 kg ha^{-1} mm^{-1} for full irrigation. Zhang et al. (2006) reported that supplementary irrigation could increase WUE of corn compared with full irrigation. Some research has shown that scheduling irrigation based on crop responses to water stress at different growth stages can improve WUE (Wang et al., 2002; Zhang et al., 2004a,b; Fang et al., 2007). Li et al. (2005) showed that the full irrigation and the 4 times supplemental irrigation treatments of corn increased yields 49.0 and 43.9% compared to the rainfed control based on 2-years experiments in the semi-arid western area of Jilin province, respectively. However, crop production and WUE generally have a high variation in response to irrigation across seasons and regions, mainly due to varying annual rainfall, soil type, and other agronomic practices (Wang et al., 2002; Zwart and Bastiaanssen, 2004). The creation of a practical and simple irrigation schedule is necessary in this region. Agricultural system models are useful tools in the evaluation of actual irrigation efficiency and crop yield responses to irrigation strategies in a given location when soil and daily weather data are available (Grassini et al., 2011; Hartkamp et al., 1999; Mo et al., 2005). Therefore, the objectives of our study were to use an agricultural system modeling approach to: (1) evaluate the grain yield, WUE, and irrigation water use efficiency (IWUE) of corn under different irrigation strategies and (2) explore optimal irrigation strategy for corn in the CBNC for the purpose of increasing water use efficiency using long-term (1980–2012) weather data.

2. Materials and methods

2.1. Study site, soil, and climate data

The study was conducted from 2011 to 2012 in Lishu county, Jilin Province, in the center of the CBNC, which produced 2,099,025 tons corn grain and the yield of 9.89 Mg ha^{-1}. Lishu is representative of the high corn production zone in CBNC (Lv et al., 2015). Corn is planted in approximately 87.8% of the total crop area in Lishu. Lishu county is located in the North Temperate Zone which is characterized by a semi-humid temperate monsoon climate. The mean annual temperature (1980–2012) is 5.9 °C, annual sunshine is 2679 h, frost-free period is 142 d each year, annual cumulative temperature (>10 °C) is 3078 °C, annual precipitation is 573 mm (65% of which occurs from June to August). It represents the climate characteristics of a warm moist summer and a cool dry winter with annual precipitation of 400–600 mm and annual cumulative temperature (>10 °C) of 2000–3200 °C in most of CBNC (Qian et al., 2007).

All typical soils for corn production in CBNC can be found in Lishu county. Two contrasting soil types were selected for this study: an aeolian sandy soil (43°21′18″N, 124°7′46″E) and a fine-textured black soil (43°19′5″N, 124°14′55″E). Aeolian sandy soil is a frigid, Typic Haplustoll with sandy loam texture that has been formed from aeolian deposits. Black soil is a fine-silty, mixed, superactive, mesic Cryrendoll with a silty clay loam texture in the 0–35 cm soil range that has been formed from alluvial deposits. The key properties of these soils are summarized in Table 1.

2.2. Measurements and analyses

Crop and soil data measured from two field experiments were used to test the model. In aeolian sandy soil, the rainfed treatment was conducted in both 2011 (AR2011) and 2012 (AR2012) and the irrigation treatment was conducted only in 2011 (AI2011). In black soil, the rainfed treatment was conducted in both 2011 (BR2011) and 2012 (BR2012). There were three replications in each treatment and plot size was 7.2 m wide by 14 m long with a 1.5 m buffer zone between plots. The widely used corn variety in local corn production is XianYu335 with moderate sensitive to water deficit (Zhang et al., 2012, 2014). Seeds were planted manually at a depth of 5 cm with a density of 60,000 plants ha^{-1} on 11 May 2011 and 8 May 2012 for aeolian sandy soil, and on 9 May 2011 and 7 May 2012 for black soil. Compound fertilizer was applied at 90 kg N ha^{-1}, 39 kg P ha^{-1}, and 75 kg K ha^{-1} before seeding. Urea was applied at 187 kg N ha^{-1} at the corn jointing stage as the local applied levels of fertilizer management. Post-emergence herbicide with the active ingredient glyphosate was used to control weed during from V2 to V4 growth stages and the pesticide with the active ingredient cypermethrin was used to control the pest. The corn was harvested on 24 September 2011 and 23 September 2012.

Corn growth stages from VE to R6 were recorded (Ritchie et al., 1982). The aboveground biomass and leaf area index (LAI) of plants were sampled by hand over an area of 1 m^2 in each plot for 5–9 times during corn growing period Leaf area index was calculated according to the total amount of leaf area per sampling area. Leaf area was calculated using leaf length × maximum width × 0.75 (Montgomery, 1911), and measurements were taken with a ruler. Grain yields were sampled from a subplot of 20 m^2. Soil water content was measured using Time Domain Reflectometry (TRIME-PICO IPH, IMKO) down to 140 cm depth at 20 cm intervals, approximately every seven days. Evapotranspiration (ET) was estimated based on soil water balance (ET = rainfall + irrigation − increases in soil water storage − drainage − runoff) (Allen et al., 1998). Runoff was 0 in this study. Drainage was estimated from the excess water beyond field capacity for each irrigation and rainfall event.

During the entire corn growing season (May–September) the mean precipitation was 458 mm from 1980 to 2012, with a range of 198–776 mm with a coefficient of variation (CV) of 28.5%. The rainfall years were classified as dry when $Z < -0.524$, normal when $-0.524 \leq Z \leq 0.524$, and wet when $Z > 0.524$ according to the China Z index from Wu et al. (2001) and the classification system form Cheng (2013). The mean reference crop evapotranspiration (ET0) was 688 mm, with a range of 620–762 mm, and a CV of 4.6% (Fig. 1). The monthly mean precipitation during the corn growing season ranged from 47 to 154 mm and the CV ranged from 43.1% to 86.5% (Fig. 2). The monthly ET0 mean ranged from 118 to 149 mm and the CV ranged from 7.0% to 10.8% (Fig. 2). The value of mean precipitation was lower than the value of ET0 in each month in the dry year. Normal year had the similar value of precipitation and ET0 in July and August, respectively. The value of precipitation was higher relative to ET0 in July and August in the wet year, respectively. But there was a larger variation in precipitation than in ET0 in various rainfall year types.

For our modeling study, daily meteorological data, including daily mean, maximum and minimum temperatures, precipitation, relative humidity, average wind speed, and sunshine hours from 1980 to 2012, were obtained directly from the Lishu County weather station. Daily solar radiation was calculated from daily sunshine hours using the Angstrom equation (Allen et al., 1998).

2.3. RZWQM2 model and its parameterization

The Root Zone Water Quality Model 2 (RZWQM2) is a comprehensive agricultural system model with the capacity to integrate and synthesize biological, physical, and chemical processes in order to simulate the impacts of water, agricultural chemicals, and crop management practices on crop production and water quality (Ahuja et al., 2000a,b). The RZWQM2 therefore been used to assess crop production at various locations worldwide (Hu et al., 2006; Saseendran et al., 2007, 2010; Fang et al., 2010). A configuration of the RZWQM version 2.50 was used, which included modules of soil and water routines, crop growth, and management. The Green