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Responses of winter wheat (*Triticum aestivum* L.) evapotranspiration and yield to sprinkler irrigation regimes

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ABSTRACT

The North China Plain (NCP) is one of the main productive regions for winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) in China. However, water-saving irrigation technologies (WSITs), such as sprinkler irrigation technology and improved surface irrigation technology, and water management practices, such as irrigation scheduling have been adopted to improve field-level water use efficiency especially in winter wheat growing season, due to the water scarcity and continuous increase of water in industry and domestic life in the NCP. As one of the WSITs, sprinkler irrigation has been increasingly used in the NCP during the past 20 years. In this paper, a three-year field experiment was conducted to investigate the responses of volumetric soil water content (SWC), winter wheat yield, evapotranspiration (ET), water use efficiency (WUE) and irrigation water use efficiency (IWUE) to sprinkler irrigation regimes based on the evaporation from an uncovered, 20-cm diameter pan located 0–5 cm above the crop canopy in order to develop an appropriate sprinkler irrigation scheduling for winter wheat in the NCP. Results indicated that the temporal variations in SWC for irrigation treatments in the 0–60-cm soil layer were considerably larger than what occurred at deeper depths, whereas temporal variations in SWC for non-irrigation treatments were large throughout the 0–120-cm soil layer. Crop leaf area index, dry biomass, 1000-grains weight and yield were negatively affected by water stress for those treatments with irrigation depth less than 0.50*E*, where *E* is the net evaporation (which includes rainfall) from the 20-cm diameter pan. While irrigation with a depth over 1.0*E* also had negative effect on 1000-grains weight and yield. The seasonal ET of winter wheat was in a range of 206–499 mm during the three years experiments. Relatively high yield, WUE and IWUE were found for the irrigation depth of 0.63*E*. Therefore, for winter wheat in the NCP the recommended amount of irrigation to apply for each event is the total 0.63*E* that occurred after the previous irrigation provided total *E* is in a range of 30–40 mm.

1. Introduction

Continual improvement in agricultural production is essential to achieve goals of national food security and poverty reduction in China (Khan et al., 2009). Due to the excellent thermal conditions and flat terrain, the North China Plain (NCP) has become one of the primary food production regions in China (Zhang et al., 2008). In 2007, the production of wheat, corn, cotton and peanut in the NCP accounted for 60.7%, 44.5%, 35.3% and 64.3% of the corresponding total production in China, respectively (National Bureau of Statistics of China, 2008).

Water scarcity and increasing crop water requirements limit wheat production in the NCP (Zhang et al., 2003; Zhang et al., 2004). The annual precipitation in this region is about 500–600 mm, of which more than 70% occurs between June and September (Zhang et al., 2004). About 30% of annual precipitation (150–180 mm), distributed between October and June, does not satisfy seasonal water demand of 400–500 mm for winter wheat (Liu et al., 2002; Zhang et al., 2003; Li et al., 2008). Therefore, irrigation provides more than 60% of seasonal water use by winter wheat (Zhang et al., 2004). As a consequence of over-pumping groundwater for agricultural irrigation, the depth to groundwater has increased by about 1 m per year over the last 20 years (Li et al., 2008), over an area of about 40,000 km^2 in the NCP (Chen et al., 2000). Land subsidence, caused by over pumping groundwater, has resulted in an economic loss

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Table 1
Soil physical properties.

Soil depths (cm)	Soil particle percent (%)			Soil classification[a]	Soil bulk density[b] ($g\,cm^{-3}$)	Field capacity[c] ($cm^3\,cm^{-3}$)
	Sand (>0.05 mm)	Silt (0.05–0.002 mm)	Clay (<0.002 mm)			
0–25	20	54	26	Silty clay loam	1.35	0.298
25–40	26	42	32	Clay loam	1.56	0.325
40–80	18	56	26	Silt loam	1.41	0.317
80–125	28	56	16	Silt loam	1.41	0.373
125–180	4	42	54	Silty clay	1.38	0.366

To assure that the water content of the entire soil profile exceeded field capacity after it was irrigated, the soil water content within 0–200-cm soil layer in the basin was determined by thermo-gravimetric method and then used for determining the irrigation depth before the measurement of field capacity.

[a] Soil classification was determined using the soil particle percent based on USDA textural soil classification system.

[b] Soil bulk density was in situ measured using thin-wall-metal tubes with known volume at a prepared soil pit.

[c] Field capacity was in situ measured in the middle point of a 3 m × 3 m basin 2 days after the basin was over irrigated and covered with a plastic sheet to prevent soil surface evaporation.

(He et al., 2009) of 332.8 billion Chinese Yuan (about 47.5 billion US dollars).

Provided the area of cropped land does not increase, increasing water use efficiency is one of the most important ways to increase crop production, save water and protect the environment. The Chinese government has promoted the use of water-saving technologies and has also provided financial support for infrastructure, both of which have created notable impacts on food security (Li, 2006). In the past 20 years, use of sprinkler irrigation has developed fast due to its higher water distribution uniformity as compared to surface irrigation (Nogués and Herrero, 2003; Kahlown et al., 2007; O'Neill et al., 2008). The area of sprinkler irrigation in the NCP has increased from 440×10^3 ha in 1990 to 2750×10^3 ha in 2005, accounting for 50% of the total area with sprinkler irrigation in China.

A reasonable irrigation scheduling is a key factor to help farmers increase crop yield and save water, especially in water deprived regions. The water consumption patterns and the corresponding scheduling of sprinkler irrigation for different variety of crops have been studied in the NCP during the past 20 years. However, most sprinkler irrigation scheduling is determined on the basis of surface irrigation with relatively large irrigation depth and intervals (Li et al., 2003; Liu et al., 2008). Under these conditions, winter wheat is irrigated two to four times with 40–60 mm per irrigation during a season. In general, soil water content and/or soil water potential are used as criteria to determine irrigation depths and intervals (Liu and Kang, 2006; Cooley et al., 2007; Z. Sun et al., 2006). However, in practice it is still difficult for farmers to use such criteria. Liu and Kang (2007) proposed a relatively simple method for winter wheat irrigation based on the evaporation from an uncovered, 20-cm diameter pan located 0–5 cm above crop canopy. With this method, a relationship between daily crop evapotranspiration and pan evaporation, plant height and leaf area index was developed and later used to schedule irrigation. The advantages of this method are its relative simplicity and low cost of measurement.

However, this methodology was developed under a condition with a suitable soil water range for winter wheat. Whether it is suitable for inadequate soil water conditions deserved further investigation. The objectives of this paper are to evaluate modifications of the pan evaporation method to manage sprinkler irrigation and to adapt it to schedule irrigation of winter wheat (*Triticum aestivum* L.) in the NCP under water stress conditions.

2. Materials and methods

2.1. Experimental layout and irrigation system

Field experiments were conducted during three wheat seasons from October to June of 2005–2008 at Tongzhou Experimental Base for Water-saving Irrigation Research (TEB), Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China (39°36′N, 116°48′E, 20 m.a.s.l.). The mean daily temperature is 11.3 °C. The average rainfall is 550 mm, in which more than 70% of the precipitation occurs from July to September. Soil physical properties at the experimental site are listed in Table 1.

The wheat variety was Jingdong-8, commonly grown in this region. It was sown between the 10 and 20 October, at a row spacing of 0.15 m and sowing rate of 338 $kg\,ha^{-1}$. Harvest occurred on 18 June. Cultivation practices, including fertilizer application, controls of pests, crop diseases and weeds were similar to the normal practices in this region.

The experimental layout (Fig. 1) provided for four sprinkler irrigation treatments, each replicated four times, and one treatment that was not irrigated. For the sprinkler irrigation treatments, each replicate subplot was an 8-m × 8-m layout. There was a 3-m spacing between subplots. Each subplot was irrigated using four 90°-angle sprinklers (Nlgo 80B2, Israel) with a discharge of 0.50–0.67 $m^3\,h^{-1}$, wetted diameter of 17 m, working pressure of 0.15–0.20 MPa and irrigation intensity of 31.0 $mm\,h^{-1}$. A flow-meter and a pressure-regulated valve were installed at the head of the irrigation system to measure the applied water and to control the system pressure. Uniformity of irrigation water distribution under this four square layout was measured three times by using containers with 15 cm in diameter and 7 cm in depth placed along the two diagonals at intervals of 1 m before each measurement. The coefficient of uniformity, computed using Christiansen method (Christiansen, 1942), ranged from 0.85 to 0.93 under low wind conditions (less than 2.0 $m\,s^{-1}$), which is higher than the Chinese standard CU value of 0.75 in the "Technical Specification of Sprinkler Engineering" (2007).

2.2. Irrigation management

Each season there were four sprinkler irrigation treatments where the total applied water ranged from less than, to more than the crop water requirement. The amount applied was based on the evaporation from the uncovered, 20-cm diameter pan (Model ADM7, China) positioned 0–5 cm above the crop canopy (Liu and Kang, 2007), and located as shown in Fig. 1. The pan evaporation (E_{pan}) was measured at 08:00 am daily. After the measurement, the pan was cleaned and refilled with 20-mm fresh water according to the measurement standard (Ministry of Water Resources and Electric Power, People's Republic of China, 1988). E_{pan} was calculated as:

$$E_{pan} = 20 + P - W_{left} \quad (1)$$

where W_{left} is the water depth in the pan at the time of measurement, P is the precipitation between two measurements. The pan was covered during the period of each irrigation, and then the pan was uncovered again immediately after each irrigation.