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Responses of yield and water use efficiency to irrigation amount decided by pan evaporation for winter wheat

Xiuwei Liu[a,b], Liwei Shao[a], Hongyong Sun[a], Suying Chen[a], Xiying Zhang[a,*]

[a] Key Laboratory of Agricultural Water Resources, The Center for Agricultural Resources Research, Institute of Genetics and Developmental Biology, The Chinese Academy of Sciences, 286 Huaizhong Road, Shijiazhuang 050021, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China

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ABSTRACT

In the North China Plain (NCP), the yield production of winter wheat (*Triticum aestivum* L.) plays an important role in food security for the nation. Irrigation is the key to boosting the crop yield. Although many irrigation strategies have been established, simple and easy methods are still required to guide local farmers to irrigation applications. The current study was intended to evaluate winter wheat performance under different irrigation amounts as determined by the difference between pan evaporation (E_p, type of E601) and rainfall multiplied by different coefficients from 0.5 up to 1.5 in increments of 0.25. The study was carried out during 2008–2012, four growing seasons of winter wheat. The results showed that the treatment with coefficient 1.25 produced the maximum yield in three out of the four seasons, and water use efficiency (WUE) was generally decreased with the increase in irrigation amount. Seasonal weather conditions had substantial effects on winter wheat responses to irrigation. A quadratic relationship was found between crop evapotranspiration (ET) and crop yield. The crop response factor (K_y) was related to relative ET and sometime negative K_y was got which indicated the negative effects of full irrigation on the yield of winter wheat under the specific climatic condition of NCP. Drainage from the root zone was increased with the increase in the irrigation amount during rainy seasons. The optimized irrigation per application could be determined using a coefficient of 1.25 for winter wheat for maximum yield. The coefficient could be further reduced for WUE improvement and for reducing nitrate leaching.

1. Introduction

Winter wheat (*Triticum aestivum* L.) is one of the major crops in the North China Plain (NCP). However, water shortage is becoming the most important limiting factor for wheat production in this area. It is essential to develop the most suitable irrigation scheduling scheme to produce optimum plant yields under limited water supplies for different ecological regions (Uçan et al., 2007). Yield increases in intensive farming practices mostly depend on the timely and adequate application of required irrigation water (Ertek et al., 2006). Numerous studies on optimizing the irrigation scheduling to conserve water and to boost crop yield have been carried out (e.g., Nasseri and Fallahi, 2007; Uçan et al., 2007; Zhang et al., 2008).

Optimized irrigation scheduling has usually been based on crop growth stages, or soil moisture, or both. In recent years, there have been a wide range of proposed novel approaches to scheduling irrigation on the basis of sensing the plant response to water deficits rather than directly sensing the soil moisture status (Jones, 2004). Some investigators used a crop water stress index (Alderfasi and Nielsen, 2001), stem water potential (Lampinen et al., 2001), and leaf water potential (O'Toole and Cruz, 1980) as indicators. All of these indicators of soil and plant water status can be measured using certain equipment. However, the measured results need some interpretation to effectively guide irrigation (Jones, 2004). Convenient and easy methods are necessary for farmers' use. Many studies showed that pan evaporation can be used in irrigation scheduling as a simple and easy method.

Pan evaporation (E_p) is one of the most prevalent climatic measurements from natural and managed ecosystems (Wang et al., 2009). Because E_p is closely related to reference evapotranspiration (ET_0) when appropriate pan coefficients are used, it has been successfully applied to the irrigation scheduling of cucumber (Wang et al., 2009), tomato (Çetin and Uygan, 2008), watermelon (Şimşek et al., 2004), banana (Ricardo and Heber, 1995), potato (Yuan et al., 2003), and strawberries (Yuan et al., 2004). Liu and Kang (2007) found that the Chinese 20 cm pan evaporation was closely related to actual evapotranspiration and was used to decide the sprinkler irrigation regimes to winter wheat (Liu et al., 2011). The successful utilization of E_p as an indicator for irrigation depends on the

* Corresponding author. Tel.: +86 311 85871762; fax: +86 311 85815093.
E-mail address: xyzhang@sjziam.ac.cn (X. Zhang).

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threshold values of accumulated E_p as the timing for irrigation and the coefficient used to decide the irrigation amount. The purposes of this study were to compare the effects of different coefficients for deciding the irrigation amount per application on the performance of winter wheat under a fixed irrigation interval and their continued effects on the soil water balance during the following maize growing season. The results could provide references for irrigation management to winter wheat by a simple E_p method.

2. Materials and methods

2.1. Study site

The study was conducted at the Luancheng experimental station (37°53′ N and 114°41′E; elevation 50 m) in the NCP from 2008 to 2012, with four growing seasons of winter wheat. The station is located in a monsoon climatic zone. Winter wheat and summer maize are the two main crops forming the double cropping system in this region. The average annual precipitation is approximately 484 mm, with 70% of the precipitation falling in the summer from June to September, which is also the maize growing season (Zhang et al., 2011). The mean precipitation during the winter wheat growing season was approximately 137 mm, which is far less than the water requirements for the crop. Irrigation is essential for high yields of this crop. The soil is Chao soil (light loam), and detailed soil characteristics can be found in Zhang et al. (2012).

The daily climatic factors, including rainfall, temperature, relative humidity, sunshine duration, radiation and wind speed, were monitored from a weather station approximately 50 m away from the experimental site. The type E601 pan has an evaporation area of 3000 cm^2 of free water and is surrounded by a ring of water to minimize edge effects, and it was installed inside the station to record the daily E_p. A standard Chinese 20-cm-diameter pan was also used to establish the relationship of the E601 with the 20-cm pan.

2.2. Irrigation treatments

Winter wheat was sown around the 10th of October and harvested around the 10th of June in the next year. Fertilization was applied as follows: before planting, diammonium phosphate (DAP) at 300 kg/ha, urea at 150 kg/ha and potassium chloride at 150 kg/ha was incorporated into the topsoil; an additional 150 kg/ha of urea was top-dressed at the jointing stage. Pests, diseases and weeds were all effectively prevented and did not affect crop yield during the study period. Summer maize was sown manually after the harvest of winter wheat with a density 6 plants/m^2. Irrigation of 40 mm was applied to all the plots for seed germinating. Urea at 300 kg/ha was applied to maize around 9th leaf stage with a irrigation (60 mm) or when there was a rainfall event.

The soil moisture condition at sowing was maintained at approximately 85% of field capacity in the top 50 cm soil layer. The soil water supply plus rainfall from sowing to over-wintering was able to meet the water requirements of winter wheat. After the long winter dormancy period (from December to early March of the next year), irrigation began when winter wheat went into the rapid growing period. The irrigation frequency was set up at 15-day intervals, and the irrigation quantity of each application was decided by the following equation:

$$\mathrm{IA} = K \times (E_p - P) \quad (1)$$

where IA is the irrigation amount per application (mm), E_p is the accumulated evaporation from E601 for a 15-day period, P is the precipitation during the same duration, and K is the coefficient used to decide the irrigation amount. The difference of E_p and P provides the net evaporation value that should be considered for irrigation management. The K was set up at 0.5, 0.75, 1.0, 1.25 and 1.5, five values. Table 1 lists the irrigation amount under the five coefficient values for the four seasons.

The five treatments were repeated four times using small plots divided by 10-cm concrete walls down to 1.2 m to minimize the mutual effects of adjacent plots. The plot area was 2 m × 2 m. The treatments were arranged randomly. Flood irrigation was applied to the plots using a 2-in. tube and a water meter was installed at the inlet of the tube to record the water used. The plots were set up in a large field and the same crops were grown in the surrounding field to minimize the edge effects of the small plots.

2.3. Measurements

Three out of the four plots of each treatment were installed with an access tube down to 2 m at the center of the plots. Soil volumetric moisture was regularly measured at increments of 0.2 m using a neutron meter (IH-II, Cambridge) throughout the growing season every 10 or 15 days during both winter wheat and maize growing seasons. The top 20 cm soil moisture was regularly measured by a portable TDR sensor (MP-160, Meridian). At the end of each growing season, the whole plot area was harvested to determine the final grain yield as described by Zhang et al. (2008).

Crop evapotranspiration (ET) for an individual period or the whole growing season was calculated using the soil water balance equation as follows (Zhang et al., 2008):

$$\mathrm{ET} = \mathrm{SWD} + P + I - \mathrm{Wg} - D - R \quad (2)$$

where ET is the evapotranspiration (mm), P is the precipitation (mm), I is the irrigation (mm), D is the water drainage (mm), R is the surface runoff, SWD is the soil water depletion for a given soil depth, and Wg is the capillary rise. Runoff was not observed, and the capillary rise was negligible because the groundwater table was 40 m below the soil surface. Thus, $\mathrm{ET} = P + I + \mathrm{SWD} - D$ was used under this experimental condition.

Drainage from the root zone at time t was determined based on the Darcy's formula $D(t) = -k(dh/dz)$, where k is the hydraulic conductivity, dh is the difference in hydraulic potential, and dz is the depth interval at the bottom of the root zone profile. Soil water potential at 160 cm ($h160$) and 180 cm ($h180$) was used to calculate the water leaching from the bottom of the root zone in this study. Then D was calculated by $k(h160 - h180)/20$. The sum of the $D(t)$ during a growing season was the total drainage from the root zone profile. Soil water potential at a certain depth was the sum of the matric and gravitational potentials (osmotic and air pressure potentials were omitted). Soil matric potential was calculated from the soil volumetric water contents measured by the neutron probe based on soil water retention curves developed at the same site by Zhang et al. (2001). Soil hydraulic conductivity was calculated using an exponential relationship between k and soil volumetric water content (θ): $k = k_s \times \exp((-\alpha(\theta_s - \theta)/(\theta_s - \theta_d))$, where k_s is the saturated hydraulic conductivity, α is a dimensionless constant (here $\alpha = 14.5$), θ_s is the saturated volumetric moisture content and θ_d is the moisture content of dry soil (Kendy et al., 2003). The soil from 160 cm to 180 cm has similar hydraulic parameters, with $\theta_s = 0.42$ v/v, $\theta_d = 0.12$ v/v, $k_s = 0.003$ m/d.

Crop water use efficiency (WUE) was calculated as the crop yield (Y) divided by the total ET during the entire growing season:

$$\mathrm{WUE} = Y/\mathrm{ET} \quad (3)$$

The yield response factor, which links relative yield decrease to relative evapotranspiration deficit, can be described by the following equation (Stewart et al., 1977):

$$Y/Y_m = 1 - K_y(1 - \mathrm{ET_a}/\mathrm{ET_m}) \quad (4)$$

where Y_m and Y are the maximum and actual yields, $\mathrm{ET_m}$ and $\mathrm{ET_a}$ are the maximum and actual evapotranspiration, and K_y is a yield