Field Crops Research 166 (2014) 102–111

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

# Photosynthesis and winter wheat yield responses to supplemental irrigation based on measurement of water content in various soil layers

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ARTICLE INFO

*Article history:*
Received 14 April 2014
Received in revised form 1 June 2014
Accepted 1 June 2014
Available online 25 June 2014

*Keywords:*
Supplemental irrigation
Soil water content
Photosynthesis
Grain yield
Winter wheat

ABSTRACT

Optimisation of supplemental irrigation (SI) is necessary for achieving continual improvement in the yield of winter wheat in arid, semi-arid and semi-humid regions. However, finding efficient water-saving irrigation techniques based on soil water storage in different soil layers has been difficult. In this field experiment, three soil layers were tested for soil water content (SWC) prior to SI: 0–20 (D20), 0–40 (D40) and 0–60 cm (D60). The target relative soil water content of each tested soil layer was 70% field capacity at jointing and anthesis. The SWC of D40 was significantly lower than that of D20 in the 60–160 cm soil profiles and that of D60 in the 20–180 cm soil profiles at maturity, which indicates that the soil water consumption amount of D40 was higher than that of D20 and D60. The net photosynthesis rate ($P_n$), stomatal conductance ($G_s$), actual photochemical efficiency ($\Phi_{PSII}$) of photosystem II (PSII) and electron transport rate (ETR) of flag leaves in D40 were greater than those in D20 and D60. The highest grain yields of 9648.35 and 10032.17 kg ha$^{-1}$ were attained in D40 with a higher water use efficiency of 20.7 and 22.2 kg ha$^{-1}$ mm$^{-1}$ in 2011–2012 and 2012–2013, respectively. These results indicate that the optimised SI regime based on measuring the SWC in the 0–40 cm soil layers at jointing and anthesis increased the $P_n$, $G_s$, $\Phi_{PSII}$, yield and water use efficiency of winter wheat, which was related to the soil water consumption.



## 1. Introduction

The Huang-Huai-Hai Plain (3HP) is one of the most important food production bases in China, whose areas of cultivated land and grain yield account for 21% and 26%, respectively, of those of the entire country (Shan et al., 2011). The climate in the 3HP, which is located between 28°59′N–43°9′N and 110°1′E–124°21′E, is a warm-temperate continental monsoon type with an annual average temperature range of 3.1 °C in the north to 16.8 °C in the south (Shi et al., 2014). Since 1950, the 3HP has experienced a reduction in precipitation at an average rate of 2.92 mm year$^{-1}$ (Liu et al., 2010). In this region, evapotranspiration is approximately 400–500 mm during the winter wheat growing season (Li et al., 2012). Precipitation is approximately 100–180 mm, which is approximately 25–40% of the crop water requirement over the growing season (Zhang et al., 1999). Therefore, water-saving cultivation techniques for winter wheat in this region must be developed.

Supplemental irrigation (SI), which uses a limited amount of water when applied during critical crop growth stages, substantially improves yield and water use efficiency (WUE). SI is a highly efficient practice with great potential for increasing crop production and improving livelihoods in dry areas (Tavakkoli and Oweis, 2004; Oweis and Hachum, 2006). In northern Syria, Oweis et al. (2004) reported that the mean grain yield and total above-ground dry biomass of chickpea increased under two-thirds of full SI, which was applied when the soil water content (SWC) in the root zone decreased to 50% of field capacity. The same results were also reported by Ilbeyi et al. (2006) in Turkey. The soil water content above 50 cm of the soil profiles was significantly affected by the irrigation at jointing and heading (Li et al., 2012). The roots of winter wheat mainly absorbed the soil water in the 0–60 cm soil profiles (Li et al., 2010). However, there are few published studies about SI based on measuring soil water content in different soil layers.

Grain yield is directly related to the photosynthesis ability of leaves. Fang et al. (2006) reported that approximately more than 60% photosynthesis activity is produced by flag leaves and spikes during the late winter wheat growing stage. In addition, stomatal

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http://dx.doi.org/10.1016/j.fcr.2014.06.004
0378-4290/

conductance ($G_s$) that diminished carbon dioxide availability to mesophyll cell chloroplasts (Reynolds et al., 2000) affected the net photosynthesis rate ($P_n$). $G_s$ has been described as the main limiting factor affecting carbon dioxide assimilation in response to water stress (Lawlor and Cornic, 2002). This finding is in accordance with that of who found that the $P_n$ and gas exchange of intact Holm oak decreased as a result of increased stomatal limitation Karen et al. (2004). Under water stress, the maximum photochemical efficiency ($F_v/F_m$) of photosystem II (PSII) declined 0.2 (Sharma et al., 2012), and the coefficient of photochemical quenching (qP) decreased more than 60% (Zlatev, 2009). Thus, soil water markedly affects the photosynthesis and fluorescence characteristics of winter wheat (Shangguan et al., 2000; Wu and Bao, 2011). In this study, we measured SWC in three soil layers (0–20, 0–40, and 0–60 cm) and brought the SWC in each measured soil layer to 70% of field capacity by SI at jointing and anthesis. The objectives were (1) to clarify the effects of SI on the SWC and the water consumption of winter wheat, (2) to investigate the response of gas exchange and fluorescence parameters traits of flag leaves to the SI, and (3) to screen the optimised SI treatments for higher grain yield and water use efficiency of winter wheat.

## 2. Materials and methods

### 2.1. Experimental site

The experiment was conducted during the winter wheat growing seasons in 2011–2012 and 2012–2013 in Shijiawangzi village, Yanzhou, Shandong province, which is located in the centre of the Huang-Huai-Hai Plain of China (35°40′09″ N, 116°41′43″ E, 55 m above sea level). Wang et al. (2013) provided detailed information on the average temperature (13.6 °C), annual precipitation (621.2 mm), accumulated sunshine hours (2460.9 h), groundwater depth (25 m), and soil type (cinnamon) in this region. In the topsoil (0–20 cm) of the experimental plots, the organic matter content was 1.39%. The rates of rapidly available nitrogen, phosphorous, and potassium were 142.29, 31.01, and 112.60 mg kg$^{-1}$, respectively, and the total nitrogen content was 1.23 g kg$^{-1}$. The main physical characteristics of the soil are listed in Table 1, which shows the soil texture in this experimental field is loam. The precipitation levels during the winter wheat growing seasons are shown in Fig. 1.

### 2.2. Experimental design

Three soil layers were tested for soil water content (SWC) prior to supplemental irrigation (SI) to calculate the amount of SI by the equation described by Sidika et al. (2012): 0–20 (D20), 0–40 (D40) and 0–60 cm (D60). The target relative soil water content of each tested soil layer was 70% of field capacity (FC) at jointing and anthesis. FC was defined as the water content of a soil layer following saturation with water when free drainage is negligible. The amount of SI was calculated based on the pre-irrigation soil water content in each measured soil profile according to the following equation (Sidika et al., 2012):

$$I = 10 \times \gamma_{bd} \times D_h \times (\theta_t - \theta_n)$$

where $I$ (mm) is the amount of SI; $\gamma_{bd}$ (g cm$^{-3}$) is the soil bulk density; $D_h$ (cm) is the thickness of the soil profile measured for soil water content before irrigation; $\theta_t$ (%) is the target soil water content on a weight-basis after SI; $\theta_n$ (%) is the water content of the soil on a weight-basis before irrigation. $\theta_t$ was calculated as follows:

$$\theta_t = \theta_{max} \times \theta_{tr}$$

where $\theta_{max}$ (%) is the field capacity; $\theta_{tr}$ (%) is the target relative soil water content (in this study it is 70%).

Water was sprayed evenly onto the experimental plots under pressure. A flow meter was used to measure the amount of water applied. The actual relative soil water content in each measured soil profile after supplemental irrigation and the amount of SI under different treatments are shown in Table 2. A rain-fed treatment with no irrigation was set as a control.

Each experimental plot was 4 m × 4 m, and each treatment was replicated three times in randomised block designs. Between two adjacent irrigation plots, a 1.5 m wide unirrigated zone was maintained to minimise the effects of adjacent plots.

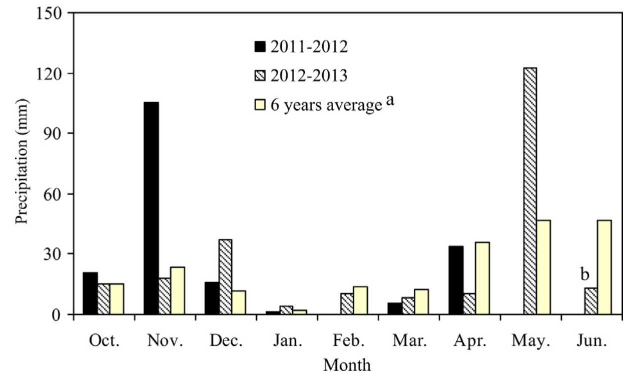


**Fig. 1.** Precipitation in the growing seasons of winter wheat in 2011–2012 and 2012–2013.
[a]The six years average of precipitation was 2007–2013.
[b]Precipitation for the whole month for six years average; however, for the experimental years, the precipitation values until harvest date.

**Table 1**
Main physical characteristics of the soil in the experimental plots.

| Soil layer (cm) | Soil mechanical composition (%) | | | Field capacity (%) | | Bulk density (g cm$^{-3}$) | |
|---|---|---|---|---|---|---|---|
| | <0.002 mm | 0.002–0.05 mm | 0.05–2 mm | 2011–2012 | 2012–2013 | 2011–2012 | 2012–2013 |
| 0–20 | 11.1 | 67.5 | 21.4 | 29.7 | 30.9 | 1.4 | 1.4 |
| 20–40 | 10.4 | 70.7 | 18.9 | 23.5 | 23.9 | 1.6 | 1.6 |
| 40–60 | 3.6 | 75.5 | 20.9 | 25.7 | 27.2 | 1.5 | 1.5 |
| 60–80 | 11.7 | 58.9 | 29.4 | 25.9 | 27.2 | 1.5 | 1.5 |
| 80–100 | 10.9 | 59.0 | 30.1 | 25.3 | 26.7 | 1.6 | 1.5 |
| 100–120 | 11.9 | 50.3 | 37.9 | 23.7 | 24.3 | 1.6 | 1.6 |
| 120–140 | 10.4 | 48.6 | 41.0 | 23.6 | 24.2 | 1.6 | 1.6 |
| 140–160 | 13.8 | 46.6 | 39.6 | 23.5 | 24.1 | 1.6 | 1.5 |
| 160–180 | 18.3 | 15.9 | 65.8 | 23.3 | 24.3 | 1.5 | 1.6 |
| 180–200 | 17.7 | 12.5 | 69.8 | 23.4 | 24.0 | 1.5 | 1.6 |