Biomass accumulation and radiation use efficiency of winter wheat under deficit irrigation regimes

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ABSTRACT

To better understand the potential for improving biomass accumulation and radiation use efficiency (RUE) of winter wheat under deficit irrigation regimes, in 2006–2007 and 2007–2008, an experiment was conducted at the Luancheng Experimental Station of Chinese Academy of Science to study the effects of deficit irrigation regimes on the photosynthetic active radiation (PAR), biomass accumulation, grain yield, and RUE of winter wheat. In this experiment, field experiment involving winter wheat with 1, 2 and 3 irrigation applications at sowing, jointing, or heading stages was conducted, and total irrigation water was all controlled at 120 mm. The results indicate that irrigation 2 or 3 times could help to increase the PAR capture ratio in the later growing season of winter wheat; this result was mainly due to the changes in the vertical distributions of leaf area index (LAI) and a significant increase of the LAI at 0–20 cm above the ground surface (LSD, $P < 0.05$). Compared with irrigation only once during the growing season of winter wheat, irrigation 2 times significantly (LSD, $P < 0.05$) increased aboveground dry matter at maturity; irrigation at sowing and heading or jointing and heading stages significantly (LSD, $P < 0.05$) improved the grain yield, and irrigation at jointing and heading stages provided the highest RUE (0.56 g/mol). Combining the grain yield and RUE, it can be concluded that irrigation at jointing and heading stages has higher grain yield and RUE, which will offer a sound measurement for developing deficit irrigation regimes in North China.

Keywords: leaf area index; PAR capture ratio; PAR reflection ratio; PAR penetration ratio; grain yield; winter wheat; deficit irrigation

The most important crops in North China are winter wheat and summer maize, and the winter wheat and summer maize double-cropping system was adopted (Li et al. 2007). The growing season of summer maize is the rainy season in North China (Quanqi et al. 2008) and during the growing season of winter wheat, the annual precipitation is approximately 200 mm; however, water use by the wheat plants can be 400–500 mm to obtain grain yield of approximately 6 to 7 t/ha. As a result, supplemental irrigation has become an important measure to obtain a stable yield of winter wheat.

In recent years, with the rapid expansion of wheat area to be irrigated, the excessive exploitation of groundwater resources for irrigation has been adopted. As a consequence, many environmental problems occurred. Xia et al. (2005) found that the groundwater table in North China is falling steadily at the rate of about 1 m/year. Hence, in order to develop the sustainable production of winter wheat, water use efficiency (WUE) should be improved, and the conventional flood irrigation is confronted with serious challenge. The major agricultural use of water is for irrigation,

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which is however affected by decreased supply. Therefore, innovations are needed to increase the use efficiency of water that is available. In recent years, some researchers found that deficit irrigation (less than full irrigation) could improve agricultural water use, and subsequent use of that water is possible for more efficient crop production. Xu et al. (2006) found that water deficit remarkably increased the N translocation ratio derived from soil and the contributions of N in various vegetative organs to grain N. Xue et al. (2003) noted that due to a relatively deep root system in rainfed crops, the higher grain yield in deficit irrigated crops compared to rainfed crops was not a result of rooting depth or root length density, but of increased harvest index, and higher water uptake rate during grain filling. Some researchers focus on efficient use of limited soil water and increasing crop water use efficiency (Zhang et al. 1999, Walter and Morio 2005, Ali et al. 2007, Elvio and Michele 2008, Saleh et al. 2008, Vazifedoust et al. 2008), others focus on the integrated effects of the cropping systems when combined with deficit irrigation applications on the water consumption and yield of winter wheat and summer maize in North China (Li et al. 2004, Fang et al. 2006b, Zhang et al. 2006, Li et al. 2007). The studies, however, have not reported on the integrated effects of the deficit irrigation on radiation use efficiency of winter wheat.

Under field conditions, crop growth is dependent on the ability of canopy to intercept incoming radiation, and convert it into biomass (Gifford et al. 1984). The deficit irrigation that limits winter wheat growth may act by restricting one or both of these processes, or sometimes through a combination of both. The fraction of the incoming PAR that is absorbed by the canopy mainly depends on the LAI and crop geometry (Plénet et al. 2000). Han et al. (2008) reported that the effects of variety and deficit irrigation on RUE and grain yield of winter wheat were due to the modifications of PAR in the winter wheat canopies. Li et al. (2008a) showed that in North China, furrow planting pattern should be used in combination with deficit irrigation to increase RUE and grain yield of winter wheat.

The objectives of this study were to determine: (i) the effect of deficit irrigation on the LAI vertical distribution of winter wheat, (ii) above-ground biomass accumulation and grain yield, and (iii) the effect of deficit irrigation on the RUE of winter wheat. In addition, irrigation with 120 mm at sowing, jointing, or heading stages of winter wheat was applied according to the previous studies by the authors in North China (Li et al. 2007, Li et al. 2008b).

MATERIAL AND METHODS

Experimental field. The study was carried out in 2006–2007 and 2007–2008 at LuanCheng Experimental Station of Chinese Academy of Science (114°40'E, 37°50'N). The plot comprised a loamy soil. The concentration of organic matter was 1.2%, the level of rapidly available phosphorous was 15 mg/kg, potassium was 150 mg/kg, nitrogen was 80 mg/kg, and field moisture capacity and wilting pointing were of 36.4% and 9.6% volume, respectively. The winter wheat variety used for the experiment was "kenong 9204". Agriculture in this area is intensified by a double cropping system of winter wheat and summer maize with high-yielding cultivars and high fertilizer and water inputs. The mean annual precipitation at the Station is 485 mm, of which approximately 70% falls from June to September, the growing season of summer maize; with the remainder falls from October to early June, i.e. the winter wheat growing season. Winter wheat was sown at the rate of 225 seeds/m^2 on October 12th, 2006 and October 17th, 2007. At the time of sowing, 30.0 g/m^2 of triple superphosphate, 30.0 g/m^2 of urea and 7.5 g/m^2 of potassium chloride were applied to the soil. The wheat plants were harvested on June 11th and June 12th in 2007 and 2008, respectively.

Experimental design. The experiments were conducted in triplicate using a randomized block design during 2006–2007 and 2007–2008. Previous studies by the authors suggest that irrigation ap-

Table 1. Treatments with the amount and growth stages of irrigation for winter wheat

Treatment	Amount/stages of each irrigation application
T1	120 mm/sowing
T2	120 mm/jointing
T3	120 mm/heading
T4	60 mm/sowing; 60 mm/jointing
T5	60 mm/sowing; 60 mm/heading
T6	60 mm/jointing; 60 mm/heading
T7	40 mm/sowing; 40 mm/jointing; 40 mm/heading

plication of 120 mm during the growing season of winter wheat could achieve reasonable grain yield and WUE (Li et al. 2007, Li et al. 2008b); according to these results, the following seven irrigation treatments were applied throughout the entire growing cycle of winter wheat (Table 1).

The water was supplied from the pump outlet to the plots using plastic pipes, and a flow meter was used to measure the amount of water applied. Between two irrigation plots, there was a 1.5 m wide zone without irrigation to minimize the effects of two adjacent plots.

Measurements

The LAI and above-ground biomass were estimated from jointing to harvest approximately once per week. After jointing stage, the LAI and the above-ground biomass were determined by sampling small plots consisting of 20 consecutive plants from the central rows, and the LAI above the ground surface of 0–20, 20–40, 40–60, and 60–80 cm were separated, respectively. Leaf area was calculated by the following equation (Fang et al. 2006a):

$$\text{Leaf area} = \text{leaf length} \times \text{leaf width} \times 0.78$$

In the above equation, the leaf length was the distance from leaf pillow to leaf finial, and the leaf width was measured at the widest part of the leaf. The sampling areas were spaced to avoid the effects of previous samplings. Dry matter was determined after drying at 80°C for 72 h.

In the later growing season of winter wheat, the PAR that was incident and transmitted to the ground surface was measured using a SunScan Canopy Analysis System (Delta T Devices Ltd., Cambridge UK). To measure the transmitted radiation, the line sensor was placed parallel to the row direction and near the winter wheat roots of each plot (Shi et al. 2005, Li et al. 2008a). The average of these measurements was considered as the radiation transmitted by the canopy.

The intercepted radiation was calculated as the ratio of the difference between the incident and transmitted radiation to the incident radiation, these values were obtained from instantaneous measurements obtained every hour between 8 a.m. and 8 p.m. on clear days. The incident radiation was measured hourly at the meteorological station near the experimental site.

The RUE was calculated by the following equation (Plénet et al. 2000):

$$\text{RUE} = (W_n - W_{n-1})/(\text{cPARa}_n - \text{cPARa}_{n-1})$$

where: W is the above-ground biomass measured at dates n and $n-1$; cPARa_n and cPARa_{n-1} are the cumulated amounts of PAR absorbed by the canopy at dates n and $n-1$.

Yield was measured at maturity corresponding to the central rows of each plot. Spike numbers per m^2, kernel numbers per spike, and thousand kernel weights were determined.

Analysis. The treatments were run as an analysis of variance (ANOVA). The ANOVA was performed at $\alpha = 0.05$ level of significance to determine if significant differences existed among treatments means. The multiple comparisons were done for significant effects with the LSD test at $\alpha = 0.05$.

RESULTS AND DISCUSSION

LAI. Figure 1 shows the vertical distribution of LAI on May 2nd, 2007. Values corresponding to other days were not shown because they were similar to this result. When irrigated only 1 time during the growing season of winter wheat, the LAI at 0–20 and 60–80 cm above the ground surface were significantly (LSD, $P < 0.05$) decreased; however, there were no significant (LSD, $P < 0.05$) effects observed in the LAI at 20–40 and 40–60 cm above the ground surface. When irrigated 2 times during the growing season of winter wheat, the LAI at 0–20 cm above the ground surface increased significantly (LSD, $P < 0.05$) in case of T5 and T6; however, there were no significant effects (LSD, $P < 0.05$) observed in the LAI at 20–40, 40–60, and 60–80 cm above the ground surface. When irrigated at sowing, jointing, and heading stages, compared with T5 and T6, there were no significant effects (LSD, $P < 0.05$) observed in the LAI at 0–20, 20–40, 40–60, and 60–80 cm above the ground surface. In field crop studies, the interception by leaves of the incoming PAR is a major process of biomass production (Plénet et al. 2000). During the late growing season of winter wheat, the changes of LAI vertical distribution could affect the capture and utilization of PAR; therefore, the highly efficient photosynthetic colony could be achieved.

Plant height and aboveground dry matter. Table 2 indicates that plant height and aboveground dry matter were significantly (LSD, $P < 0.05$) affected by irrigation times under deficit irrigation in 2006–2007. Values corresponding to 2007–2008 are not shown because they were close to those

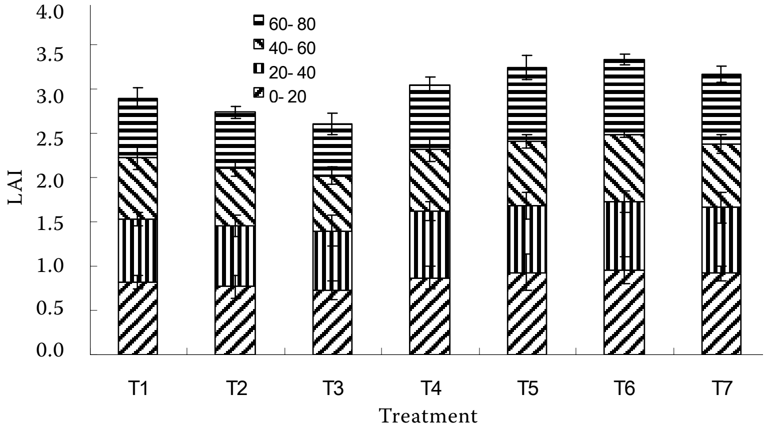

Figure 1. Vertical distribution of LAI in canopy after heading stage in different treatments (measurements on May 2nd, 2007); vertical bars are standard errors

of the 2006–2007 period. At jointing stage, plant height and aboveground dry matter were on similar levels in T1, T4, T5, and T7, they were all significantly (LSD, $P < 0.05$) higher than those in T2, T3, and T6. This could be explained by lower soil water content in T2, T3, and T6 resulting in the aboveground growth restriction. In maturity stage, the plant height for T2 reached 72.51 cm, which was slightly, but not significantly (LSD, $P < 0.05$) higher than T4 and T6 results. The lowest plant height was found in T3. These results indicated that jointing water was helpful to increase plant height. The aboveground dry matter for T4, T5, T6, and T7 were 1384.33, 1378.59, and 1408.87, 1306.12 g/m^2, respectively, which was not significantly (LSD, $P < 0.05$) different. However, the values of aboveground dry matter of T1, T2, and T3 were only 1209.23, 1216.06, and 1065.52 g/m^2, respectively, which were significantly (LSD, $P < 0.05$) lower than those of T4, T5, T6, and T7. These results indicate that irrigation two or three times in the growing season of winter wheat under deficit irrigation conditions could provide better environment for wheat growth and development, as irrigation water was used more efficiently.

PAR capture ratio. PAR reflection ratio, PAR penetration ratio and PAR capture ratio are summarized in Table 3. When only 1 irrigation was conducted in the growing season of winter wheat, both T1 and T2, not T3, were significantly (LSD, $P < 0.05$) lower than the other treatments. Irrespective of whether 2 or 3 irrigations were applied, the PAR penetration ratio gave no significant (LSD, $P < 0.05$) differences between treatments; the PAR capture ratio was significantly (LSD, $P < 0.05$) higher than in T2 and T3. The main reason of such results is that LAI at 0–20 cm above the ground surface increased significantly (LSD, $P < 0.05$) with repeated irrigation. In contrast, under the conditions of single irrigation, with irrigation

Table 2. Plant height and aboveground dry matter in different growth stages in 2006–2007

Treatment	Jointing		Maturity	
	plant height (cm)	aboveground dry matter (g/cm^2)	plant height (cm)	aboveground dry matter (g/m^2)
T1	37.03^{ab}	374.80^{a}	68.33^{cd}	1209.23^{b}
T2	33.49^{b}	357.15^{b}	72.51^{a}	1216.06^{b}
T3	32.14^{b}	356.80^{b}	60.16^{e}	1065.52^{c}
T4	41.37^{a}	377.85^{a}	72.20^{ab}	1384.33^{a}
T5	42.35^{a}	376.95^{a}	66.14^{d}	1379.59^{a}
T6	31.55^{b}	357.35^{b}	69.76^{abc}	1408.87^{a}
T7	39.03^{a}	373.45^{a}	68.95^{bcd}	1306.12^{ab}

Values followed by a different letter are significantly different at 5% probability level

Table 3. PAR capture ratio in winter wheat canopy

Treatment	Reflection ratio (%)	Penetration ratio (%)	Capture ratio (%)
T1	2.85^{cd}	4.89^{c}	92.25^{b}
T2	2.79^{d}	8.45^{b}	88.76^{c}
T3	3.05^{b}	15.35^{a}	81.60^{d}
T4	3.23^{a}	4.15^{cd}	92.63^{b}
T5	3.06^{b}	1.83^{d}	95.11^{a}
T6	3.00^{b}	3.65^{cd}	93.35^{ab}
T7	3.10^{ab}	4.19^{cd}	92.71^{ab}

The data was the average values on May 3rd and May 4th, 2007; values corresponding to the other days are not shown

stage later, the PAR penetration ratio as well as the PAR capture ratio significantly (LSD, $P < 0.05$) decreased; it can be also attributed to the LAI at 0–20 and 60–80 cm above the ground surface that significantly (LSD, $P < 0.05$) decreased with the irrigation stages later. Hence, under the conditions of deficit irrigation, irrigation 2 or 3 times as well as full irrigation once at sowing could help to increase the PAR capture ratio in the later growing season of winter wheat.

Grain yield and yield components. Table 4 indicates that the grain yield and yield components were significantly affected by different irrigation regime under deficit irrigation. T4 resulted in the highest spike numbers (665.36 spikes/m^2), followed by T6, T2, T1, T5, and T7, while the lowest spike numbers of 530.36 spikes/m^2 was observed in the case of T3. The kernel number of T6 was significantly (LSD, $P < 0.05$) higher than of the other treatments. Irrigation timing during the later part of the growing season of winter wheat could improve the thousand kernel weight, and the largest thousand kernel weight was observed in the case of T3, which was significantly (LSD, $P < 0.05$) higher than the other treatments. The highest grain yield (665.76 g/m^2) was recorded for T6; it can be attributed to increased kernel numbers and spike numbers, which compensated for the lower thousand kernel weight, followed by T5, T7, and T4, but not significantly different (LSD, $P < 0.05$). Compared with T5 and T6, the grain yield of T2 and T3 was significantly (LSD, $P < 0.05$) lower. The lowest grain yield in the case of T2 can be attributed to decreased thousand kernel weight; and the reduced grain yield in T3 can be attributed to decreased spike numbers, although the thousand kernel weight was significantly (LSD, $P < 0.05$) increased. Therefore, selecting suitable irrigation timing under deficit irrigation is of great importance to improve yield potential.

RUE. Figure 2 shows the RUE of winter wheat. Under the conditions of irrigation only 1 time during the growing season of winter wheat, T1 resulted in the highest RUE (0.47 g/mol), followed by T2, and the lowest RUE of 0.43 g/mol was observed in T3. It was apparent that in the growing season of winter wheat irrigated only once, the RUE decreased with irrigation timing later. Under the conditions of irrigation 2 or 3 times during the growing season of winter wheat, the highest RUE was found in T6 (0.56 g/mol), followed by T5 and T7, and the lowest RUE of 0.51 g/mol was observed in T4. Hence, as the time of irrigation differed the RUE was not consistent, i.e., if irrigated 2 times during the growing season, irrigation should be applied at jointing and heading; it contributed to

Table 4. The average grain yield and yield components of winter wheat in 2006–2007 and 2007–2008 growing season

Treatment	Spike numbers (spikes/m^2)	Kernel numbers (seed numbers/spike)	Thousand kernel weight (g)	Grain yield (g/m^2)
T1	574.64^{b}	29.39^{b}	36.04^{d}	559.10^{bc}
T2	592.86^{b}	30.80^{b}	28.94^{e}	546.35^{c}
T3	530.36^{c}	28.85^{b}	44.26^{a}	538.22^{c}
T4	665.36^{a}	29.89^{b}	30.50^{e}	603.28^{abc}
T5	561.79^{bc}	29.43^{b}	41.21^{b}	652.39^{a}
T6	598.21^{b}	34.34^{a}	38.19^{c}	665.76^{a}
T7	560.36^{bc}	30.60^{b}	37.33^{cd}	628.65^{ab}

Values followed by a different letter are significantly different at 5% probability level

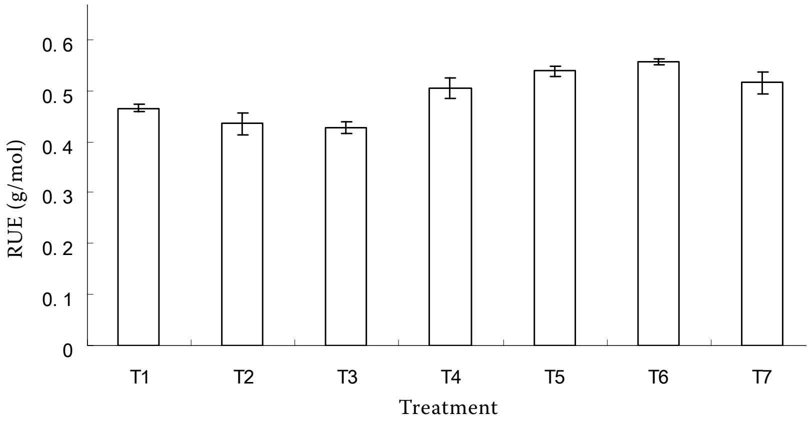

Figure 2. The average RUE of winter wheat in 2006–2007 and 2007–2008 growing seasons; vertical bars are standard errors

an increase in kernel number and spike number, and therefore, the grain yield and RUE were improved.

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