Radiation use efficiency and yield of winter wheat under deficit irrigation in North China

H. Han[1], Z. Li[1], T. Ning[1], X. Zhang[2], Y. Shan[3], M. Bai[1]

[1]*State Laboratory of Crop Biology, College of Agronomy, Shandong Agricultural University, Taian, P.R. China*
[2]*Yulin University, Yulin, P.R. China*
[3]*Henan University, Kaifeng, P.R. China*

ABSTRACT

Water stress is a frequent and critical limit to wheat (*Triticum aestivum* L.) production in North China. It has been shown that photosynthetic active radiation (PAR) is closely related to crop production. An experiment was conducted to investigate the effects of deficit irrigation and winter wheat varieties on the PAR capture ration, PAR utilization and grain yield. Field experiments involved Jimai 20 (J; high yield variety) and Lainong 0153 (L; dryland variety) with non-irrigation and irrigated at jointing stage. The results showed that whether irrigated at jointing stage or not, there was no significant difference between J and L with respect to the amount of PAR intercepted by the winter wheat canopies. However, significant differences were observed between the varieties with respect to the amount of PAR intercepted by plants that were 60–80 cm above the ground surface. This result was mainly caused by the changes in the vertical distributions of leaf area index (LAI). As a result, the effects of the varieties and deficit irrigation on the radiation use efficiency (RUE) and grain yield of winter wheat were due to the vertical distribution of PAR in the winter wheat canopies. During the late growing season of winter wheat, irrespective of the irrigation regime, the RUE and grain yield of J were significantly (LSD, $P < 0.05$) higher than those of L. These results suggest that a combination of deficit irrigation and a suitable winter wheat variety should be applied in North China.

Keywords: deficit irrigation; winter wheat; variety; radiation use efficiency; yield

The Huang-Huai-Hai plain in North China is one of the most important regions of agricultural production in China. The region covers the area of 1.445 million km^2, amounting to 15% of the national total (Zhang et al. 2007). A major crop in this region is winter wheat. Long-term average annual precipitation in the region ranges from 500 to 650 mm. The distribution of precipitation is uneven, with more than 70% of the annual precipitation falling from July to September. As a result, precipitation during the winter wheat growing season ranges from 100 to 180 mm, approximately 25–40% of crop water requirement over the growing season (Zhang et al. 1999), and supplemental irrigation is required for the winter wheat grain yield.

The Huang-Huai-Hai plain in North China, however, has only 7.2% of the total national water resources, and no sufficient surface water resources are available for irrigation. Consequently, groundwater has been used for irrigation. With the rapid development in winter wheat production, more groundwater was required for irrigation; this has resulted in a gradual decline in the groundwater table. Overexploitation of groundwater was deemed as unsustainable (Yang and Zehnder 2001), which led to excessive exploitation of water resources and a reduction in runoff (Chen and Xia 1999, Xia and Tan 2002). The excessive exploitation of groundwater resources for irrigation from shallow and deep aquifers in this region caused the water table to fall and created many environmental

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problems (Xia et al. 2005). The groundwater table keeps falling steadily at the rate of about 1 m/year and the main factors leading to this decrease are the expansion of wheat area to be irrigated with groundwater and the low water use efficiency (Zhang et al. 2006) Therefore, it is necessary to adopt water-saving agriculture countermeasures to achieve the largest possible increase in water use efficiency of winter wheat (Li et al. 2007); deficit irrigation is one of the most important aspects of water-saving in irrigated agriculture.

Some researchers studied the effects of deficit irrigation on the evapotranspiration (Eberbach and Pala 2005), water use efficiency (Lauenroth et al. 2000, Angus and Van Herwaarden 2001, Li et al. 2008b) and yield (Pan et al. 2003) of winter wheat; Zhang et al. (1999) discussed the relationship between evapotranspiration and yield. These studies, however, have not reported the integrated effects of the deficit irrigation on the radiation use efficiency (RUE) in North China.

Under field conditions, crop growth is dependent on the ability of canopy to intercept incoming radiation, which is a function of leaf area index (LAI) and canopy architecture, and convert it into new biomass (Gifford et al. 1984). The effects of deficit irrigation on the yield and water use efficiency may act by restricting one or both of these processes, or sometimes through a combination of both. The fraction of the incoming photosynthetic active radiation (PAR) that is absorbed by the canopy mainly depends on the LAI and crop geometry (Plénet et al. 2000). The conversion efficiency of the intercepted radiant energy into dry matter is called radiation use efficiency (Monteith 1977). Li et al. (2008a) showed that furrow planting pattern should be used in combination with deficit irrigation to increase the RUE and grain yield of winter wheat in North China. Miralles and Slafer (1997) indicated that post-anthesis RUE appeared to be closely and positively associated with the number of grains set per unit biomass at anthesis. Uhart and Andrade (1995) found that stresses reducing the leaf photosynthetic rate could result in lower RUE. These studies, however, focused only on one cultivar. At present, developing high water use efficiency wheat cultivars in North China is an important objective of water-saving agriculture. The aim of this study was to determine whether deficit irrigation affects the canopy characteristics responsible for the interception of incoming radiation and RUE during the late growing season of two wheat cultivars. In addition, radiation interception levels were measured after anthesis.

MATERIAL AND METHODS

Experimental site. This study was conducted at the experimental station of Shandong Agricultural University (36°10'19''N, 117°9'03''E) located in the Huang-Huai-Hai plain of North China. The mean annual precipitation is 697 mm, a majority of which comes in the period from July to later September. In 2005–2006, the precipitation in the winter wheat season was 126.8 mm (Table 1). Mean annual temperature is 12.9°C, and mean annual accumulated temperature greater than 0°C is 4731°C. The total yearly sunshine duration is 2627.1 h and the non-frost period lasts 195 days. The winter wheat Jimai 20 (J; normal cultivar) and Lainong 0153 (L; dryland cultivar) were planted on October 16 2005, and were harvested on June 7 2006. 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.

Experimental design. The experiments were conducted in triplicate using a randomized block design; for every cultivar, the following two amounts of irrigation were applied throughout the entire growth cycle of winter wheat: no supplemental irrigation (0), and irrigation only at the jointing stage (1). Irrigation application was 60 mm. Water was supplied from the outlet of a pump by using plastic pipes, and a flow meter was used to measure the amount of water applied. The area of the plots was 12.0 m^2. Between two irrigation plots, there was a 2-m-wide zone without irrigation to minimize the effects of two adjacent plots.

Measurements. The LAI and aboveground dry matter were measured from reviving up to harvest. During this period, approximately twice per month, the aboveground dry matter was measured by sampling triplicate 0.50 m × 0.50 m squares in each treatment/replicate. From each square sample, plant number, green leaf and dry weight were determined. The LAI was computed as the product of specific leaf area and the total leaf

Table 1. Precipitation in the growing season of winter wheat in 2005–2006

Month	10	11	12	01	02	03	04	05	06
Precipitation (mm)	4.6	5.4	3.8	4.7	7.8	0.0	23.5	77.0	0.0

mass divided by the sample area (320 cm^2), and the values of 0–20, 20–40, 40–60, and 60–80 cm above the ground surface were computed.

From anthesis to maturity, the radiation that was incident (PAR_{ci}), transmitted (PAR_{gi}), and reflected (PAR_{cr}) at the ground level was measured using a 1.5-m-long linear sensor (SunScan). To measure the transmitted radiation, the line sensor was placed parallel to the row direction and near the winter wheat roots of each plot in different positions (Li et al. 2008a, b). The average of these measurements was considered as the radiation transmitted by the canopy. The reflected PAR was measured with the SunScan covering the canopy of different treatments (Chen et al. 2003).

The PAR capture ratio was calculated as the ratio of the difference between the PAR_{ci} and PAR_{gi} 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 by a weather station (ET106) at a distance of 50 m from the experimental site. Every month, the data from the datalogger were electronically transferred to a cassette tape and then transferred from the cassette to a personal computer.

PAR penetration ratio is calculated as follows:

$$\text{PAR penetration ratio} = PAR_{gi}/PAR_{ci}$$

PAR reflection ratio is calculated as follows:

$$\text{PAR reflection ratio} = PAR_{cr}/PAR_{ci}$$

The RUE is calculated as follows (Plénet et al. 2000):

$$RUE = (W_n - W_{n-1})/(cPARa_n - cPARa_{n-1})$$

In this equation, W is the aboveground 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 in an area of 2.4 m^2 corresponding to the two central rows of each plot.

Statistical analyses. For the treatments, an analysis of variance (ANOVA) was used; it was performed at $\alpha = 0.05$ level of significance to determine whether 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

The irrigation and cultivars could alter the vertical distribution of LAI in the canopy after the heading stage (Figure 1). In the absence of irrigation, the LAI at 0–20 and 60–80 cm above the ground increased significantly (LSD, $P < 0.05$) in the case of J; however, there were no significant (LSD, $P < 0.05$) effects on the LAI at 20–40 and 40–60 cm above the ground surface. When irrigated at jointing, the LAI at 0–20 cm above the ground surface increased significantly (LSD, $P < 0.05$) in the case of J; however, there were no significant (LSD, $P < 0.05$) effects observed in the LAI at 20–40, 40–60, and 60–80 cm above the ground surface. During the late winter wheat growing season, the vertical distribution of LAI in the canopy could affect the capture and utilization of PAR.

PAR capture ratio

Table 2 shows the PAR capture ratio, PAR penetration ratio, and PAR reflection ratio in the late growing season of winter wheat. As for the cultivar, the PAR reflection ratio was not significantly different (LSD, $P < 0.05$) between treatments; however, both the PAR penetration ratio and PAR capture ratio were significantly different (LSD, $P < 0.05$) between treatments. With irrigation at jointing stage, the PAR penetration ratio significantly (LSD, $P < 0.05$) decreased in the case of both J and L; however, the PAR capture ratio had significantly (LSD, $P < 0.05$) increased. Whether irrigated at jointing stages or not, the PAR penetration ratio significantly decreased (LSD, $P < 0.05$) and the

Table 2. Effect of deficit irrigation and cultivars on PAR capture ratio in winter wheat canopy

Treatment	Capture ratio (%)	Penetration ratio (%)	Reflection ratio (%)
J0	87.86^{b}	7.70^{c}	4.44^{c}
L0	82.19^{d}	13.21^{a}	4.60^{a}
J1	90.16^{a}	5.48^{d}	$4.36^{c, d}$
L1	86.41^{c}	9.04^{b}	$4.55^{a, b}$

The data are the average values on 3 May, 6 May, 13 May, and 17 May 2006. Values followed by a different letter are significantly different at 5% probability level

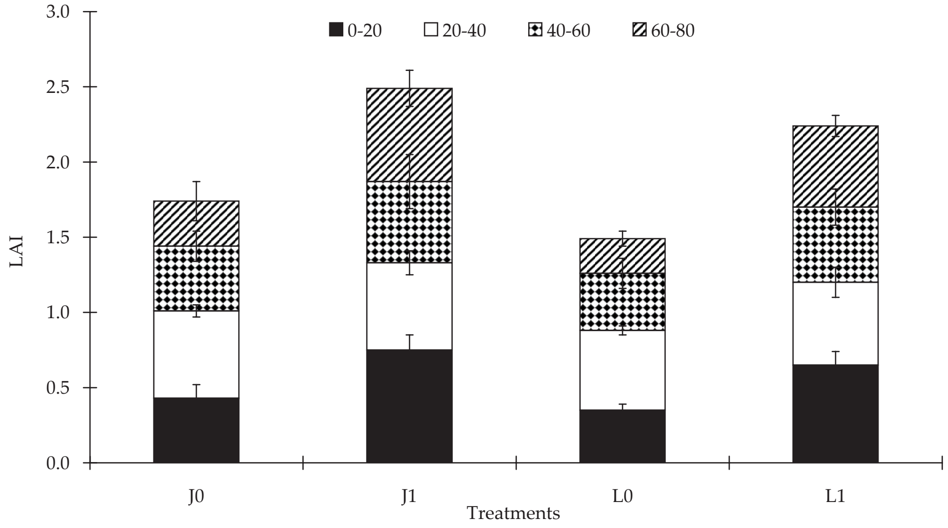

Figure 1. LAI above the ground surface 0–20, 20–40, 40–60, and 60–80 cm in winter wheat canopy after heading stage. Averaged measurements on 23 April and 14 May 2006. J0 and J1 stand for Jimai 20 with non-irrigation and irrigated at jointing stages; and L0 and L1 stand for Lainong 0153 with non-irrigation and irrigated at jointing stage. Vertical bars are standard errors

PAR capture ratio significantly increased (LSD, $P < 0.05$) in the case of J; this was mainly because the LAI of J at 0–20 or 60–80 cm above the ground surface significantly increased (LSD, $P < 0.05$). As for L, in both irrigation regimes, the PAR penetration ratio increased significantly (LSD, $P < 0.05$); consequently, the PAR capture ratio decreased significantly (LSD, $P < 0.05$). Hence, compared to L, J resulted in an increase in the PAR capture ratio in the late growing season, irrespective of irrigation.

Daily amount of PAR interception

Results of the daily PAR interception amounts were very similar between days; therefore, only data of 13 May 2006 are presented (Figure 2).

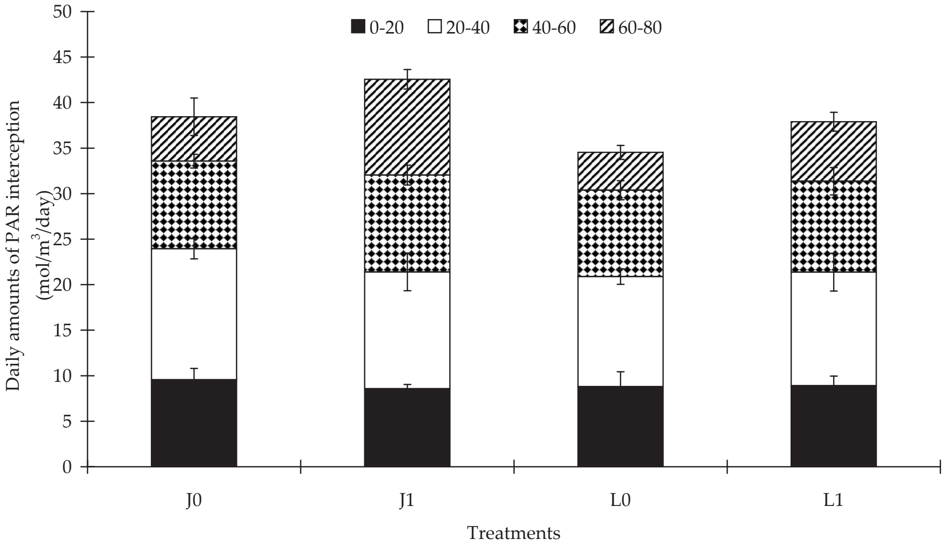

Figure 2. Daily amount of PAR interception in the wheat canopy with different cultivars and irrigation. The data was measured on 13 May 2006. The average incoming daily total of PAR was 920.74 μmol/m^2/s. J0 and J1 stand for Jimai 20 with non-irrigation and irrigated at jointing stages; and L0 and L1 stand for Lainong 0153 with non-irrigation and irrigated at jointing stage. Vertical bars are standard errors

The daily PAR interception amounts at 60–80 cm above the ground surface were contrary to those obtained at 0–20 cm above the ground surface. However, the daily PAR interception amounts at 0–20 cm above the ground surface were consistent with the PAR penetration ratio, i.e. the greater the PAR was captured at 0–20 cm above the ground surface, the higher were the PAR penetration values. In the absence of irrigation, the daily PAR interception amount was by 11.32% higher in J0 compared to L0; however, at 60–80 cm above the ground surface, the daily PAR interception amount was by 17.35% higher. Irrigation at jointing stage resulted in the daily PAR interception amount that was only by 12.33% higher in J1 compared to L1. However, at 60–80 cm above the ground surface, the daily PAR interception amount was by 61.10% higher. It is obvious that although winter wheat cultivars clearly altered the LAI and its distributions in the canopy, they had little effect on the PAR interception amount; nevertheless, they had a significant (LSD, $P < 0.05$) effect on the vertical distribution of PAR in the canopy. Irrespective of irrigation, J resulted in a significantly (LSD, $P < 0.05$) increased daily PAR interception amount at 60–80 cm above the ground surface; hence the flag leaves were mainly centralized at 60–80 cm above the ground surface. As a result, an increase in the PAR interception ratio in this part could definitely aid in the accumulation and transportation of photosynthetic products in the late growing season of winter wheat.

RUE and grain yield

Figure 3 shows the RUE and grain yield of winter wheat. In the absence of irrigation, the RUE and grain yield of J were by 0.05 g/mol and 216.92 kg/ha higher than those of L, respectively. It is apparent that in the absence of irrigation, J resulted in a significant increase in RUE and grain yield.

In the case of irrigation at jointing stage, J produced significantly (LSD, $P < 0.05$) higher RUE than L; it was higher by 0.10 g/mol. Furthermore, the yield of J was also significantly (LSD, $P < 0.05$) higher by 504.72 kg/ha than that of L. This suggests that irrespective of deficit irrigation, the RUE and grain yield of J always reached higher values in the experiment.

Many researchers, such as Whitfield and Smith (1989), Chen et al. (2003), and Li et al. (2008a) showed that crop yield was positively related to RUE; the values presented in this paper are in accordance with their results. However, the main reasons for the effects of deficit irrigation and winter wheat cultivars on the RUE and grain yield was not the change in the PAR capture amount in the canopy, but vertical distribution at 60–80 cm above the ground surface. As for winter wheat yield, more than 70% was the product of photosynthetic matter of green organ produced after heading in the late growing season; this was approximately 60% more than that produced by the flag leaves (Fang et al. 2006). PAR capture ratio in the upper layers of winter wheat canopy would contribute

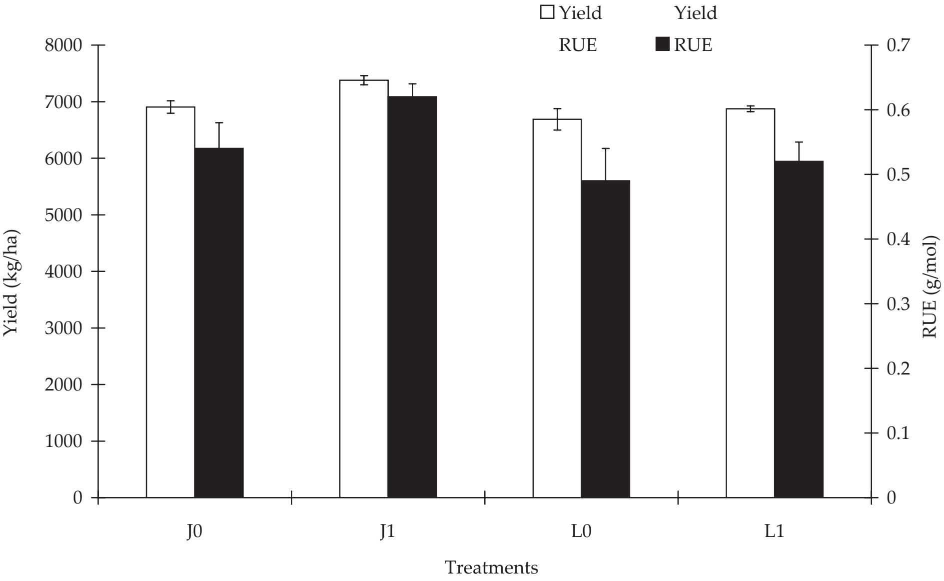

Figure 3. The average RUE and grain yield of winter wheat. J0 and J1 stand for Jimai 20 with non-irrigation and irrigated at jointing stages; and L0 and L1 stand for Lainong 0153 with non-irrigation and irrigated at jointing stage. Vertical bars are standard errors

to achieving higher grain yield. It is apparent that varieties could optimize the distributions of PAR in the winter wheat canopy; therefore, the highly efficient photosynthetic colony could be achieved as well as higher RUE and grain yield.

Non-irrigation resulted in a decrease in the RUE and grain yield in the case of J and L. Still, the RUE and grain yield in case of J were higher than those of L in both treatments. Only under the serious drought conditions, dryland varieties could have higher osmoregulation abilities, and photosynthetic rate decreased little (Ma et al. 1995). Based on the annual mean precipitation during the growing season of winter wheat in the Huang-Huai-Hai plain, North China, in most years, especially in the key stages of grain yield formation from April to May, the precipitation was frequent; winter wheat thus cannot confront serious drought conditions and deficit irrigation should be applied before this period. As for the cultivar selection, J resulted in a significant increase in RUE and grain yield, irrespective of irrigation. Hence, it can be assumed that a combination of deficit irrigation and J should be applied in the Huang-Huai-Hai plain, North China.

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Corresponding author:

Prof. Zengjia Li, Shandong Agricultural University, College of Agronomy, State Laboratory of Crop Biology,
Taian 271018, P.R. China
e-mail: hhf@sdau.edu.cn