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ROW SPACING AND IRRIGATION EFFECT ON RADIATION USE EFFICIENCY OF WINTER WHEAT

W. W. Zhong[1], J. Q. Liu[2], X. B. Zhou[1,*], Y. H. Chen[2] and J. J. Bi[2]

[1]Shandong Agricultural University, Agricultural College of Guangxi University, Nanning 530004, China
[2]State Key Laboratory of Crop Biology, Tai'an 271018, China
[*]Corresponding author email: whyzxb@gmail.com

ABSTRACT

Winter wheat is an important food crop in northern China. To achieving higher yields with less water has been the focus of researchers. Four planting patterns [row spacing (RS) × plant spacing], namely, 7 × 7 cm (RS7), 14 × 3.5 cm (RS14), 24.5 × 2 cm (RS24.5), and 49 × 1 cm (RS49), and four irrigation regimes, namely, 0, 60, 120, and 180 mm, were studied under field conditions during 2006–07 and 2007–08 at the Agronomy Experimental Station (36°09′N, 117°09′E) of Shandong Agricultural University in Tai′an, Shandong Province, China. This experiment aimed to study the effect of row spacing and irrigation on leaf area index (LAI), dry matter weight (DM), photosynthetically active radiation (PAR) capture ratio at different levels above the ground surface, grain yield and radiation use efficiency (RUE) of winter wheat. Results revealed higher average LAI and DM of RS14 than those of other treatments with all irrigation conditions. The canopy light interception of RS49 was significantly lower than those of other patterns. The PAR capture ratio of RS14 at 0–40 cm aboveground was lower than that at 40–80 cm aboveground, similar to those of RS7 and RS24.5 but not to that of RS49. Increased irrigation resulted in declines of PAR capture ratio at 0–40 cm aboveground but increased at 60–80 cm aboveground. Increasing amounts of irrigation resulted in increased yields of winter wheat, and the order RS14 ≈ RS7 > RS24.5 > RS49 was observed. Grain yields of RS7 and RS14 were significantly higher than those of RS24.5 and RS49 ($P < 0.01$). RS14 with irrigation at 120 mm may be the best option to increase yields and save water in northern China.

Key words: *Triticum aestivum* L.; planting pattern; leaf area index; photosynthesis active radiation; grain yield.

INTRODUCTION

Winter wheat (*Triticum aestivum* L.) is an important crop that is widely cultivated in northern China. The yield of winter wheat is low due limited water resources in Shandong Province. In this area, the average precipitation was 696.6 mm per year from 1971 to 2008 in Tai′an, which is located in Huanghuaihai Plain with a warm temperate semi-humid continental monsoon climate, and the most of precipitation was concentrated in July and August. This precipitation level does not meet the requirements of the winter wheat growth season (Sacks *et al.*, 2010) because high wheat yields mainly depend on water supplied by irrigation. However, China has a shortage of water, especially in the northern area.

Many researchers have investigated water-saving agricultural engineering techniques by subsurface drip irrigation and sprinkling irrigation (Payero *et al.*, 2008; Thompson *et al.*, 2009; Abd El-Wahed *et al.*, 2013), whereas other researchers have promoted the planting of drought-tolerant varieties (Kumar *et al.*, 2008). Some approaches, such as early sowing, high-density planting, straw mulching, and improved fertilization, have also been used to increase crop yield (Philip and Mustafa, 2005; Yau *et al.*, 2011; Zhang, *et al.*, 2014). Adopting a reasonable scheme for managing planting patterns and irrigation is essential to increase yield and save water because irrigation water is gradually becoming a scarce resource (Zhou *et al.*, 2011).

Different row spacings (RS) affect population distribution, canopy structure and various environmental factors in plants, such as light, fertilization, and water. Many studies have applied compromise methods to save water and produce high yields, which can reduce effects on the farmland environment (Roberts *et al.*, 2001; Mishra *et al.*, 2001; Heatherly *et al.*, 2002; Hussain *et al.*, 2003). Planting patterns can significantly affect the photosynthesis of leaves have been observed in many researches (Hussain *et al.*, 2012; Wang *et al.*, 2013). If plants are sowed sufficiently close to one another, the competition between plants increased. One plant can affect another and modify the soil and light interception, decreasing the plant growth rate (De Bruin and Pedersen, 2008).

Many researches have indicated that wide-precision planting can increase the light interception and water use efficiency, and row spacing of 7.5–15 cm can increase canopy coverage and reduce soil evaporation (Chen *et al.*, 2010). The present research focuses on the effects of planting patterns and irrigations on the leaf area index (LAI), dry matter weight (DM), photosynthetically active radiation (PAR) capture ratio at different levels above the ground surface. The combined responses of grain yield and radiation use efficiency (RUE) of winter wheat to identify the optimal allocation of RS and irrigation.

MATERIALS AND METHODS

This research experiment was conducted at the Agronomy Experimental Station of Shandong Agricultural University (36°10′N, 117°09′E), Taian, China, from 2006 to 2008. This site is representative of the main winter wheat growing region of Huanghuaihai Plain in China which is warm temperate semi-humid continental monsoon climate. The average long-term precipitation and temperature were 697 mm and 12.9 °C, respectively. The total precipitation levels were 765.5 and 627.5 mm in 2007 and 2008, respectively; the rainfall during 2007–2008 was 25% lesser than that during 2006–2007, and the temperature and sunshine hours were mentioned in Table 1. The soil of experimental site is silt loam (organic matter, 16.3 g/kg; N, 92.98 mg/kg; K, 95.45 mg/kg; P, 34.77 mg/kg; pH 6.9).

The present study was conducted from October to June in 2006–2007 and 2007–2008 and part of a continuous winter wheat–summer soybean [*Glycine max* (L.) Merr.] rotation experiment. Summer soybean plants were harvested by hand, and stubbles were removed. Then, field plots were ploughed by artificial. The fertilization with urea 140 kg/ha, potassium sulfate 126 kg/ha, diammonium phosphate 280 kg/ha were applied on the soil in the plot at the time of sowing. Winter wheat (cv. Shannong 919) was hand-planted at a density of 2.04×10^6 plant/ha on October 6, 2006 and October 10, 2007. Four planting patterns (RS × plant spacing), namely 7 × 7 cm (RS7), 14 × 3.5 cm (RS14), 24.5 × 2 cm (RS24.5), and 49 × 1 cm (RS49), and four irrigation conditions, including non-irrigation (0 mm, I0) and irrigation at 60 mm (I60), 120 mm (I120), and 180 mm (I180), were applied (Table 2). Each plot measured 3 m × 3 m. Treatments were replicated thrice, in a randomized block design. The amount of irrigation was maintained strictly from the outlet pump to the culture pools using plastic pipes. Dicot weeds in the winter wheat plots were controlled chemically by applying the herbicide 0.84 kg/ha 2-methyl-4-clorophenoxyacetic acid (MCPA) (Zhou *et al.*, 2015).

A total of 15 plants per plot were sampled every 10 days to determine the LAI, which was calculated using the following equation:

Leaf area = Leaf length × Leaf width × 0.83

All biomass fractions of fifteen plants were replaced in a drying oven at 105°C for 20 min, then dried at 80°C for 72h until reaching constant DM. The relative growth rate (RGR, g/g/d) was determined as:

RGR= (lnW2 - lnW1)/(t2 - t1)

where t2 is the harvesting time and t1 is the plant of GS37, W2 is the total DM at harvesting and W1 is DM at GS37.

The crop growth rate (CGR, g/m^2/d) was expressed as:

CGR= (W2 - W1)/A(t2 - t1); where A is the field area, other data is same as above.

Net assimilation rate (NAR, g/m^2/day) was calculated as:

NAR = (lnL2 - lnL1) × (W2 - W1)/(L2 - L1) × (t2 - t1)

where L2 is the final plant leaf area, L1 is the leaf area at GS37 (Portsmuth and Niinemets, 2006).

PAR was measured by SunScan (Delta T Devices Ltd., Cambridge, UK). A 1.5 m long linear sensor was placed parallel to the row direction. The crops were harvested by hand in a sample area of 1 m^2 on June 5, 2007 and June 13, 2008. RUE was calculated by equation:

E (%) = (h × M)/Q

where h is the rate of grain heat (17.8 kg/g), M is the grain yield, Q is the total solar radiation, and Q was 2.58×10^7 and 2.65×10^7 MJ/ha during the winter wheat growing seasons of 2006–2007 and 2007–2008, respectively.

All graphs were drawn using SigmaPlot 10.0 (SPSS Inc., Chicago, USA) and Origin 8.0 (OriginLab Corporation, Northampton, USA). All data were analyzed by ANOVA. The least significant difference test was used. Effects were considered significant in all statistical calculations at $P < 0.05$.

RESULTS

LAI: LAI is an important measure used to assess crop growth and material production capacity. LAI exhibited significant variance between different planting patterns and irrigations. During the winter wheat growth season, the change in LAI presented a '∩'-shaped curve trend, and maximum values were observed at GS50–GS65 (Figure 1).

In 2006–2007, under I0, the LAI averages of RS14 were 2.30%, 21.53%, and 53.74% higher than those of RS7, RS24.5, and RS49, respectively. The LAI averages of RS14 were 6.84% (I60), 5.52% (I120), and 5.34% (I180) higher than that of RS7; 17.05% (I60), 16.21% (I120), and 14.20% (I180) higher than that of RS24.5; and 34.00% (I60), 34.52% (I120), and 38.44% (I180) higher than that of RS49. In 2007–2008, under I0, the LAI averages of RS14 were 10.83%, 17.13%, and 16.60% higher than those of RS7, RS24.5, and RS49. The LAI averages of RS14 were 8.99% (I60), 10.71% (I120), and 10.73% (I180) higher than that of RS7; 17.46% (I60), 16.38% (I120), and 17.14% (I180) higher than that of RS24.5; and 44.50% (I60), 46.86% (I120), and 45.76% (I180) higher than that of RS49 ($P \leq 0.05$). These results indicate that the LAI exhibits no significant difference between RS14 and RS7, and RS14 and RS7 were higher than RS24.5 and RS49.

In 2006–2007, the LAI averages of I60, I120, and I180 were 11.62%, 26.30%, and 32.98% higher than that of I0 under RS7, 16.58%, 30.27%, 36.94% under RS14, 21.06%, 36.26%, 45.74% under RS24.5, and 33.75%, 48.89%, 52.08% under RS49, respectively. In 2007–2008, the LAI averages of I60, I120, and I180 were 26.06%, 35.53%, and 37.32% higher than that of I0 under RS7, 23.98%, 35.39%, 37.19% under RS14, 23.64%, 36.26%, 37.18% under RS24.5, and 17.18%, 25.91%, 28.55% under RS49, respectively. The results showed that LAI increased with an improvement in irrigation.

Dry matter weight: Figure 2 shows the accumulated DM of winter wheat at different growth stages exhibited an upward tendency. In 2006–2007, under the same amount of irrigation, the DM of RS14 was higher than that of RS7; the DM of RS24.5 and RS49 were significantly lower than that of RS14 ($P < 0.05$). In 2007–2008, under the same irrigation water, the average DM of RS14 was significantly higher than those of RS24.5 and RS49. Results have indicted that oversized RS results in decreasing accumulated DM and the results of both years were consistent. The RGR, CGR and NAR of four RSs were included in Figure 3. In 2006–2007, under the same irrigation water, RGR of RS14 was slightly higher than those of other RSs. There is no significant difference between RS7 and RS14 under I120 and I180 ($P > 0.05$). Under I0 and I60, NAR of RS14 was slightly higher than other treatments ($P < 0.05$). In 2007–2008, under the same irrigation water, RGR of RS14 was obviously higher than those of other RSs. Under I0 and I60 irrigation, NAR of RS14 was also slightly higher than those of RS24.5 and RS49 ($P < 0.05$), which was similar to RS7. The results indicated that RGR was minor changes in all treatments under RS and irrigation. NAR was related to leaf area size. The change trend of both years, DM, RGR, NAR, RGR increased with the increasing irrigation water.

PAR capture ratio: Figure 4 shows the diurnal change in PAR capture ratio at GS73 (May 17, 2007). The ratio exhibited a ‘V’-shaped curve trend from GS37 to GS73. Under the same amount of irrigation, the PAR capture ratio of RS14 was higher than those of RS7 and RS24.5; no significant difference was found between RS7, RS14, and RS24.5 ($P > 0.05$). The PAR capture ratio of RS49 was significantly lower than that of other RSs ($P < 0.05$). This ratio increased with increasing irrigation amount. Compared with that of I60, the PAR capture ratio of I120 increased. This result showed that irrigation could adjust the canopy architecture of winter wheat and increased the PAR capture. Among the different RSs, the order of PAR capture ratio was RS14 > RS7 > RS24.5 > RS49. This ratio can be achieved by reducing RS under uniform planting density conditions.

The ratio of the canopy was characterized by upper strong and lower weak (Figure 5). Planting patterns changed the PAR vertical distribution of winter wheat canopy. Under I0, the PAR capture ratio at 0–40 cm aboveground was significantly lower than at 40–80 cm ($P < 0.05$), and maximum values were reached at 60–80 cm (except RS49). The PAR capture ratio of RS49 at 0–40 cm aboveground was higher than that obtained at 60–80 cm aboveground. The greater the PAR captured at 0–20 cm aboveground, the lower the PAR capture ratio.

Increased irrigation resulted in enhanced amounts of PAR capture ratio at 60–80 cm aboveground. This finding is contrary to those obtained at 0–40 cm aboveground among all treatments. Thus, irrigation can increase the amount of upper canopy light captured.

Grain yield and RUE: RUE showed a crucial function in the growth and yield of winter wheat. During both years, under the same irrigation amount, the RUE of RS14 was highest and that of RS49 was the lowest in all planting patterns; the yield of RS14 was also significantly higher than those of RS7, RS24.5, and RS49 ($P < 0.0001$). In the absence of irrigation, RS14 resulted in the highest RUE and grain yield (Mg/ha), followed by RS7 and RS24.5. RS49 exhibited the lowest RUE and grain yield. The RUE and grain yield increased with increasing irrigation amount. Regardless of whether or not irrigation was applied, the RUE and yield of RS14 and RS49 were the highest and lowest, respectively, in all planting patterns. The RUE followed the order RS14 > RS7 > RS24.5 > RS49 (Table 3).

The yield variation was consistent during both years, which indicated that population distribution and increased irrigation could improve the RUE and yield. The yield of winter wheat during 2006–2007 was lower than that of 2007–2008. This result is mainly attributed to short periods of excessive rainfall, which causes winter wheat lodging during GS73 in 2007 and eventually decreases output.

Table 1. Monthly temperature, sunshine hours and precipitation for winter wheat growing seasons

Weather data	Seasons	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June
Temperature	2006/2007	17.34	8.84	0.41	-1.15	5.57	8.34	14.87	21.68	24.36
(°C)	2007/2008	14.29	6.41	1.83	-2.15	-0.27	9.25	14.69	20.87	23.78
Sunshine hours	2006/2007	200.4	161.2	141.8	174.3	160.4	175.2	224.8	247.2	183.4
(h)	2007/2008	135.7	172.5	104.8	101.4	193.6	232.2	192.3	241.9	187.5
Precipitation	2006/2007	5.3	14.2	9.5	0.0	2.1	46.7	15.2	118.8	0.7
(mm)	2007/2008	17.3	8.0	16.5	4.0	4.8	17.7	57.7	44.7	6.4

Table 2. Treatments with the timing and amount (mm) of irrigation for winter wheat in 2006–2008

Row spacing (RS)	Irrigation	GS37	GS50	GS73	Total
RS7	I0	0	0	0	0
	I60	60	0	0	60
	I120	60	60	0	120
	I180	60	60	60	180
RS14	I0	0	0	0	0
	I60	60	0	0	60
	I120	60	60	0	120
	I180	60	60	60	180
RS24.5	I0	0	0	0	0
	I60	60	0	0	60
	I120	60	60	0	120
	I180	60	60	60	180
RS49	I0	0	0	0	0
	I60	60	0	0	60
	I120	60	60	0	120
	I180	60	60	60	180

Table 3. Row spacing (RS) effects on grain yield (Mg/ha) and radiation use efficiency (RUE, %) of winter wheat in 2006/2007 and 2007/2008

Treatments		Grain yield		RUE	
		2006/2007	2007/2008	2006/2007	2007/2008
RS7	I0	7.0g*	7.7h	0.41g	0.44h
	I60	7.1fg	7.9f	0.42fg	0.45f
	I120	8.0bc	8.3d	0.47bc	0.48d
	I180	8.2b	8.6b	0.48b	0.49b
RS14	I0	7.1fg	7.8gh	0.41fg	0.44gh
	I60	7.7cde	7.9f	0.45cde	0.45f
	I120	8.1bc	8.3cd	0.48b	0.47cd
	I180	8.4a	8.7a	0.50a	0.49a
RS24.5	I0	6.8g	7.6i	0.40g	0.43i
	I60	7.4ef	7.8gh	0.43ef	0.44gh
	I120	7.9bcd	8.1e	0.46bcd	0.46e
	I180	8.0b	8.4c	0.47b	0.47c
RS49	I0	5.5i	7.3j	0.32i	0.41j
	I60	6.4h	7.6i	0.37h	0.43i
	I120	6.8g	7.8g	0.40g	0.44g
	I180	6.9g	8.1e	0.45b	0.46e

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

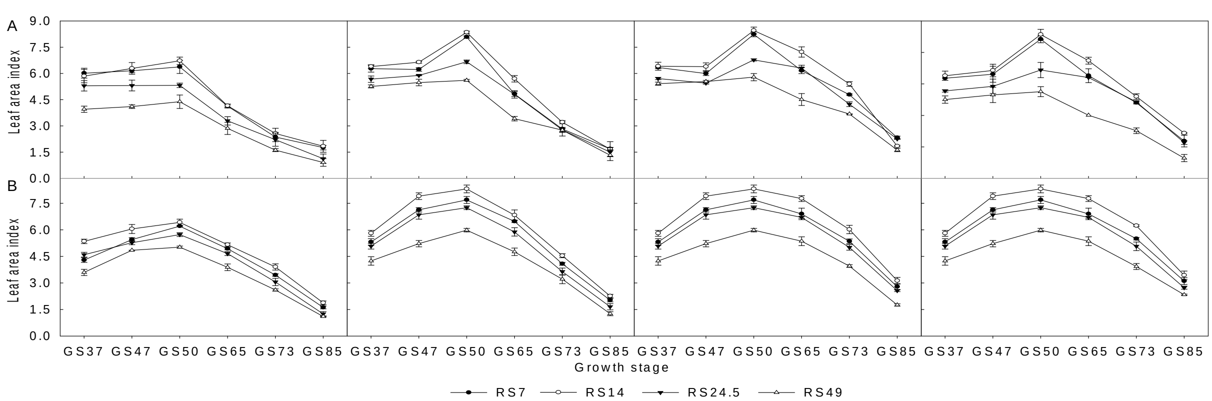

Fig. 1 Leaf area index of winter wheat at different growth stages in 2006/2007 (A) and 2007/2008 (B).

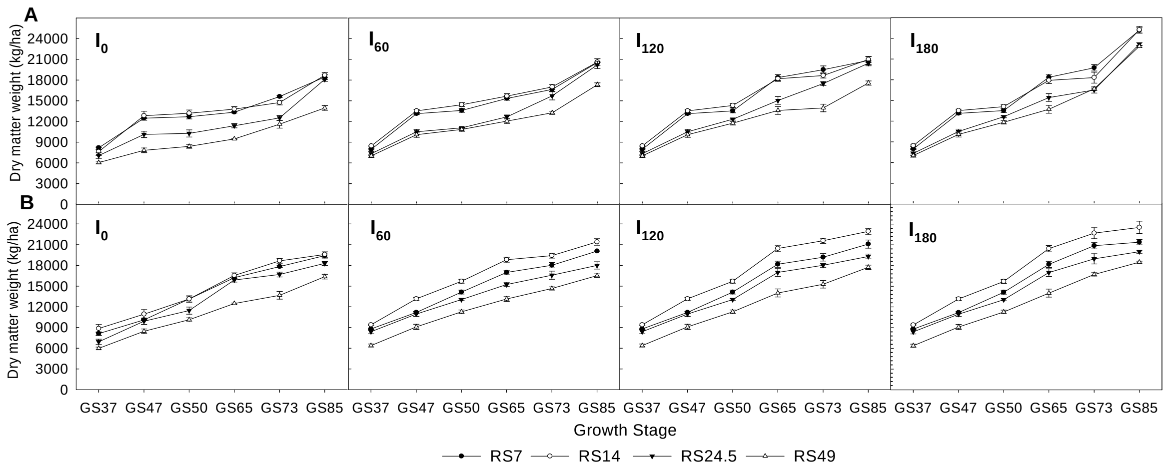

Fig. 2 Accumulated dry matter weight of winter wheat at different growth stages in 2006/2007 (A) and 2007/2008 (B).

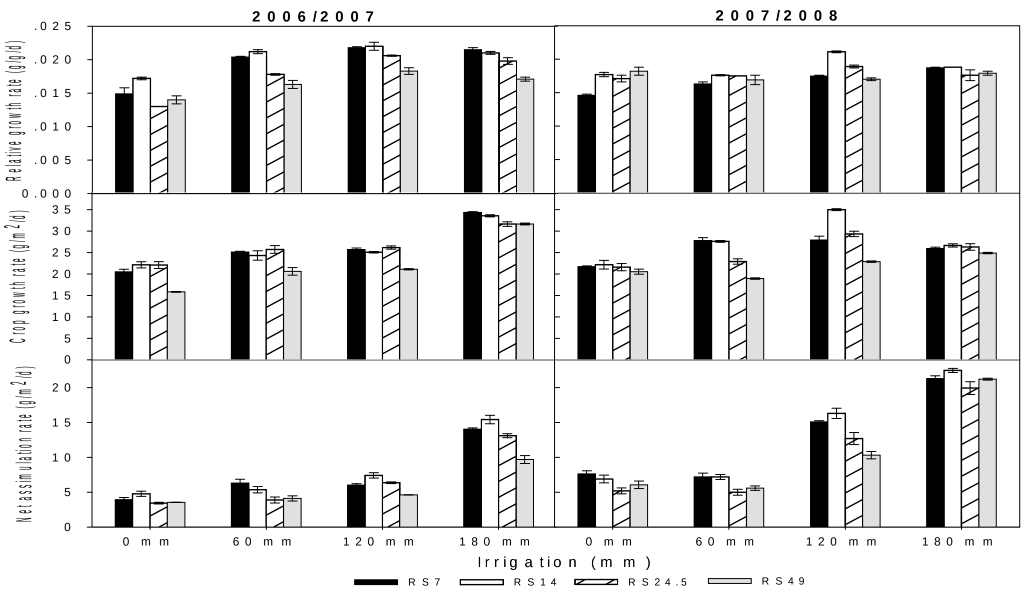

Fig. 3 The relative growth rate, crop growth rate and net assimilation rate of different row spacings in 2006/2007 and 2007/2008.

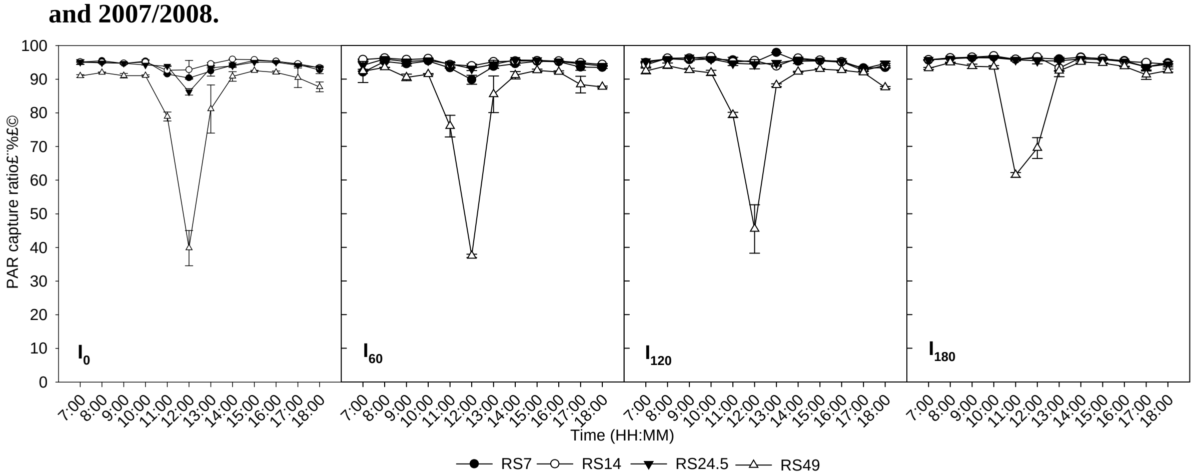

Fig. 4 The diurnal change of photosynthesis active radiations (PAR) capture ratio on May 17, 2007.

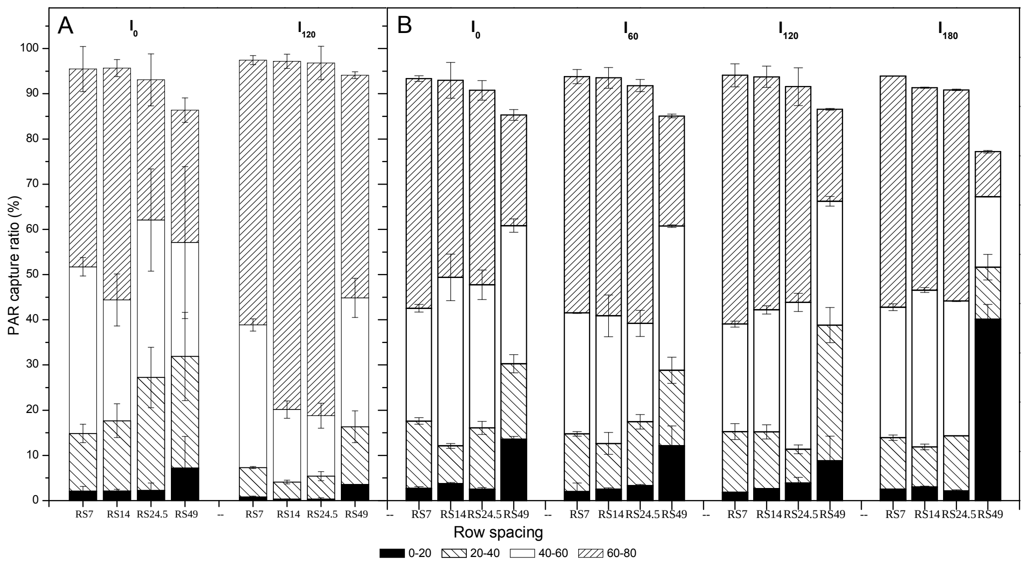

Fig. 5 Distribution of photosynthesis active radiations (PAR) capture ratio at different heights in 2006/2007 (A) and 2007/2008 (B). The data was measured on May 17, 2007 and May 18, 2008.

DISCUSSION

Leaves are the main photosynthetic organs of crops. LAI is an important factor that determines crop yield (Hamzei and Soltani, 2012). Among the RS7, RS14, RS24.5, and RS49 planting patterns, the LAI average of RS14 was higher than those of other planting patterns. RS49 was the lowest and significantly lower than that of RS14 ($P < 0.05$), which decreased by increasing RS. The narrow RS is feasible to achieve higher yield, thus, the farmers of North China should properly decrease RS. These results are in accordance with the study of Riahinia and Dehdashti (2008). Irrigation can increase the LAI of crops (Latiri-Souki *et al.*, 1998). Compared with that at I0, the LAI increased with increasing irrigation amount. The LAI of I180 was higher than those of other treatments, which is similar to I120, and the LAIs of I0 and I60 were significantly different from that of I180 ($P < 0.05$). This result indicated that RS and irrigation have an effect on LAI and contribute to prevent premature aging of leaves, which captured more light energy at GS85 to increase yield. Meanwhile, the DM of RS14 was higher than those of other RSs. Irrigation can increase the DM under the same RS. Results showed that oversized RS results in decreasing LAI and DM, RGR and NAR. The RS14 with I120 can obviously increase LAI and DM, may be the best performing for water saving and higher yield.

Under farming conditions, crop growth is dependent on the ability of the canopy to intercept incoming radiation, which is the function of LAI and canopy architecture (Andrade *et al.*, 2002). The total PAR capture ratio was not significantly different among different RSs, except RS49. The PAR capture ratio increased with increasing irrigation amount. The PAR at different levels exhibited noticeable differences. RS and irrigation determined the population structure of winter wheat plants. The increase in RS from 14 cm to 49 cm resulted in a decrease in PAR capture ratio. Radiation interception is a major determinant of growth (Mattera *et al.*, 2013). The distribution of the PAR capture ratio at different levels of a plant is another important factor that affects crop yield (Han *et al.*, 2014). Increasing amounts of irrigation resulted in increases in PAR at 40–80 cm aboveground, which was over 50% for every treatment. This result shows that PAR prevents premature aging and improves winter wheat yield. These results are consistent with the previous finding that the PAR capture ratio in the upper canopy of winter wheat should be over 50% to increase grain yield (Li *et al.*, 2008; Han *et al.*, 2014).

In 2006–2007 and 2007–2008, the grain yield and RUE of RS14 were significantly higher than the other treatments. Reasonable RS can coordinate the contradiction of population and individual development and promote the individual growth and uniform distribution of light energy to improve yield. The yield of I180 was the highest among all irrigation treatments, and no significant difference was found between I120 and I180. The LAI, NAR, the vertical distribution at 40–80 cm aboveground, and the amount of PAR capture ratio in the canopy contributed to the increases in RUE and yield.

The RS14 planting pattern can still be produced at a relatively high level without fully meet water requirement. In conclusion, an RS14 planting pattern under I120 is a reasonable cultivation approach that could promote the yield of winter wheat in northern China.

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