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Full Length Article

Row Spacing Pattern Effects on Plant Growth, Canopy Radiation Interception, and Grain Yield of Winter Wheat under the Water-Saving Conditions

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Abstract

Planting pattern affects the spatial distribution characteristic of individual plants in population and modifies the plant productivity of cereal crops. This study reported the effects of row spacing distance on growth traits, photosynthesis behaviors, and agronomic traits of winter wheat plants cultivated under water-saving conditions. Compared with control (row width of 15 cm), the narrowed row treatment (NRT, row width of 7.5 cm) led to improved plant growth traits, such as population tiller numbers, leaf area index (LAI), and biomass of the tested cultivars at various growth stages. The uptake capacity of plants for nitrogen (N), phosphorus (P), and potassium (K) was elevated under NRT with respect to control, which was in consistent with the positive effects of NRT in affecting chlorophyll contents (Chl) and photosynthetic rate (Pn). During late growth stage, the upper position of canopy under NRT intercepted more solar radiation (SR) than control, suggesting that NRT benefits the population for interception of SR that contributes to plant biomass production during the late growth phase. Compared with control, NRT increased population spike amounts while maintained comparable kernel numbers per spike and grain weights, resulting in increased yields and water use efficiency (WUE) for tested cultivars. Additionally, the cultivars showed drastic cultivar variation in row spacing pattern responses; the drought-sensitive cultivar Jimai 585 exhibited more promotive effects on growth and agronomic traits upon NRT with respect to Shimai 22, a drought-tolerant one. Together, narrowed row mode promotes the productivity of winter wheat cultivated under deficit irrigation, which associates with its modulation on plant growth, nutrient acquisition, photosynthesis, and canopy solar radiation interception during late stage. © 2020 Friends Science Publishers

Keywords: *Triticum aestivum*; Water-saving condition; Row spacing pattern; Growth and physiological trait; Yield and yield components

Introduction

Row spacing pattern determines the spatial distribution of plants in population and affects the interception of canopy for solar radiation during the middle and late growth stages, impacting largely on the agronomic traits of cereal crops (Park *et al.* 2003). A suite of investigations has confirmed the potential of suitable row width in improving the crop solar radiation interception rate (RIR), radiation use efficiency (RUE), and the yield formation capacity (Barbieri *et al.* 2000; Sharratt and McWilliams 2005; Adônis *et al.* 2015).

In past two decades, the row widths applied in cultivation of cereal crops, such as wheat, were gradually reduced due to application of the semi-dwarf cultivars that are suitable for the affluent water and inorganic nutrient conditions (Annicchiarico *et al.* 2005; Gentile *et al.* 2005). For example, the row widths for winter wheat cultivars in North China have been reduced to current 13–15 cm from previous 20 to 25 cm which was applied at end of the last century. Accompanied by the lowered row width, the traits associated with plant growth and development, yield formation capacity, and the water use efficiencies (WUE) of plants were drastically improved (Chen *et al.* 2010). These findings suggest the potential of narrowed row spacing in winter wheat cultivation.

High-yielding production for winter wheat followed by summer maize constitutes a major cropping system in North China. During the growth season of winter wheat (early of October to next mid-June), less rainfall amounts

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are provided for wheat plants due to the typical continental monsoon climate in this ecological zone. Thus, much more of the water resources used for plants is derived from the underground water storage (Sun *et al.* 2010). However, overdosed application of water resource during wheat cultivation has caused drastic reduction on underground water table, aside from the elevated production cost (Zhang *et al.* 2018). Therefore, improving the winter wheat productivity under water-saving cultivation condition has been an urgent issue for sustainable crop production in North China and other similar ecological regions.

Further understanding the physiological processes and yield formation capacities underlying row spacing pattern can benefit the winter wheat cultivation under water-saving conditions (Zhang *et al.* 2018). In this study, two wheat cultivars were used in contrasting water responses, Jimai 585, a cultivar acclimated to affluent water and Shimai 22, a cultivar to be drought-tolerant, to investigate effects of the narrowed row spacing pattern on physiological and agronomic traits upon water deprivation. The objectives of this study were concentrated on follow issues: (i) effects of narrowed row treatment (NRT, row width of 7.5 cm) on growth and nutrient acquisition of plants; (ii) roles of NRT in modifying photosynthesis and solar radiation interception of canopy during late stage; (iii) behaviors on yield, yield components, and WUE under NRT condition; (iv) cultivars variation on agronomic traits upon the modified row width patterns. This investigation provides insight into effective production for winter wheat under water-saving conditions by adopting NRT in North China as well as the similar ecological regions.

Materials and Methods

Experimental design

Field experiments were conducted at the Experimental Station of Hebei Agricultural University, Xinji city, China, during the 2016–2017 and 2017–2018 growth seasons. Average temperatures, precipitation amounts, sunshine duration, and solar radiation intensities during the growth seasons are given in Table 1. The top soil in experimental plots was loamy containing follow nutrients: organic matter 17.3 g/kg, available N 73.08 mg/kg, available P 20.56 mg/kg, and available K 125.46 mg/kg. The treatments were arranged in a spilt plot design with three replicates, in which, planting mode including row width of 15 cm, control and of 7.5 cm, narrow row treatment (NRT) and cultivar including Jimai 585, a cultivar acclimated to affluent water and Shimai 22, a cultivar of drought-tolerant were randomined in main- and sub-plots, respectively. Across the whole growth stage, deficit irrigation management generally adopted by local farmers, i.e., two irrigations performed prior to seed sowing with 82.5 mm of underground water and that at jointing stage with 75 mm of underground water was applified for all of the treatments. Before seed sowing, in total of 530 kg/ha of complex fertilizer (N-P_2O_5-K_2O for 15-15-15) was used as basal inorganic nutrients together with total N 120 kg/ha by topdressing mode at jointing stage. Seed rates sown were used to establish an approximately 3750 thousand seedling-population per hectare. In addition, before seed sowing, straws of the summer maize were mechanically broken followed by application of the basal complex fertilizer. Seed sowing was conducted on October 8 and 7 during the 2016–2017 and 2017–2018 seasons, respectively. Other practices such as chemical removal for weeds and control for disease and pest were similar to the conventional ones performed in Hebei plain, North China.

Measurements of plant growth traits

At jointing, booting, flowering, mid-filling, and maturity stages, population tiller numbers per square meter were counted in each plot. In addition, leaf areas in twenty representative plants sampled at each plot were assayed using a portable leaf area analyzer (LI3000, USA), by which leaf area index (LAI) following the conventional approach was calculated. Plant biomass was obtained from the oven-dried plant samples.

Assay of contents and accumulative amounts of nutrients in plants

The N, P, and K contents in plant samples after biomass assay were assessed following the previous methods. Of which, N contents were assessed using the semi-micro Kjeldahl method (Guo *et al.* 2011); P (P_2O_5) contents were measured using the vanadium molybdate blue colorimetric method (White *et al.* 1981); K (K_2O) contents were determined using the flame photometry method (Guo *et al.* 2011). The accumulative amounts of N, P, and K were determined by multiplying plant biomass and their contents, respectively.

Assay of photosynthetic parameters

At booting, flowering, mid-filling, and maturity stages, chlorophyll contents (Chl) and photosynthetic rates (Pn) of the flag leaves were assessed in the tested cultivars under each treatment. Of which, Chl was measured with SPAD reads detected by a chlorophyll analyzer (SPAD 502, Japan). Pn was determined by a portable photosynthesis system (CID, USA) assayed under following conditions: light intensities from 1000 to 1500 μmolE/m^2 s, CO_2 concentrations from 350 to 370 μl/L, and air temperature from 20 to 28°C.

Assay of RIR of canopy

Radiation interception rate (RIR) at different canopy positions was assessed under the row spacing treatments during late stage. For this, light intensities at upper layer

(20 cm below the top of canopy) and at middle layer (40 cm below the top of canopy) of the canopy in the tested cultivars were recorded using a light intensity analyzer (LX101, China). RIR at different canopy positions were calculated by dividing the solar radiation intensities at canopy positions assayed to those over the canopy.

Yields and yield components

At maturity, spikes in two square meters were counted in each plot to calculate the population spike number. Kernel numbers per spike were determined based on grain numbers counted from thirty representative spikes. Grain weights were obtained based on grain biomass after air drying. Grain yields were obtained based on air-dried grain weights in each plot harvested by a mini harvesting machine.

Measurement of WUE

Water consumption amounts (ET) under various treatments, including precipitation, amounts of irrigated water, and water storage in 2 m depth soil prior to seed sowing and at harvest, were determined across a growth circle (Zhang *et al*. 2018). Among these, the rainfall amounts were derived from the local climate station; irrigated water amounts are shown in Table 1; and the water storage in 2 m soil profile at two assayed times (*i.e.*, prior to seed sowing and at harvest) was determined by the water contents in soil samples with 40 cm depth layer interval. Plant WUEs were calculated using follow formula: WUE= Y/ET. In which, Y stands for grain yield whereas ET represents the consumed amount of total water during whole growth season (Zhang *et al.* 2008).

Statistical analysis

Averages and standard errors for all of the growth traits, nutrient contents, photosynthetic parameters, RIR, and agronomic traits were derived from the triplicate results across two growth seasons. Significant test analyses on above traits were performed using the SPSS 16.0 statistical software (SAS Institute, Cary, NC, 2004).

Results

Plant growth traits

Compared with control, the narrow row treatment led to increased population tiller numbers, LAI, and biomass at various growth stages (jointing, booting, flowering, mid-filling, and maturity stages) in cultivars Jimai 585 and Shimai 22. These results suggested the positive effects of NRT on the growth traits of plants treated by deficit irrigation. As to the two cultivars, Jimai 585 showed more improved growth traits above than Shimai 22 (Table 2). Therefore, narrowed row width can effectively improve winter wheat cultivation under the water-saving conditions, especially for cultivars acclimated to the affluent water supplies.

Accumulation of nutrient in plants

At growth stages, nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O) contents were assessed in the tested cultivars under control and NRT conditions. Compared with control, inorganic nutrients contents were increased in the cultivars under NRT at various growth stages, although the elevation effects were not significant at statistical level (Table 3). Likewise, the accumulative amounts of above nutrients in tested cultivars were significantly increased at each stage under NRT compared to control (Table 4). These results suggested the positive effects of NRT in promoting plant acquisition for inorganic nutrients, such as N, P, and K, possibly due to the improved root system that benefits nutrient uptake.

Photosynthetic functions

Chlorophyll contents (Chl) and photosynthetic rates (Pn) of upper leaves in the tested cultivars were investigated at booting, flowering, mid-filling, and maturity stages under control and NRT conditions. Results indicated that the Chl contents and Pn were elevated in both cultivars at various stages under NRT, compared to control (Fig. 1). Compared with Shimai 22, Jimai 585 displayed relatively enhanced NRT-elevation effects on photosynthetic parameters. Improved photosynthetic function under NRT is suggested to be associated with increased nutrient acquisition of the plants, which contributes to photosystem establishment and elevates enzyme activities involving Calvin cycle.

The RIR of canopy

At booting, flowering and mid-filling stages, the radiation interception rates (RIR) at different canopy layers were assayed. Compared with those under control, the RIR was increased at upper layer (20 cm below the top of canopy) while maintained comparable at middle layer (40 cm below the top of canopy) in tested cultivars under NRT condition (Fig. 2). These results suggested that NRT improves the solar radiation interception of population during late growth stage. The improved RIR of the wheat cultivars benefits the photosynthetic function and plant biomass production during late growth stage.

The yield and yield components

Compared with control, NRT significantly increased the population spike numbers, which was in consistent with significantly elevated population tiller numbers at various growth stages (Table 5). The kernel numbers per spike and grain weights were shown to be comparable between control and NRT in each cultivar. For the cultivars, Jimai 585 displayed higher NRT-elevation effect on population

Table 1: Meteorological factors during late grain stage at two growth seasons

Year	10 d	Average temperature (ºC)		Precipitation (mm)		Total sunshine (h)		Solar radiation (W/m^2)	
		May	June	May	June	May	June	May	June
2017	First	21.42	24.25	0.10	3.65	86.83	84.63	233.02	250.38
	Second	24.81	27.22	0.00	3.40	113.04	84.90	283.34	252.06
	Third	24.50	27.03	17.99	43.75	110.71	80.42	266.28	224.18
2018	First	20.32	26.53	5.56	31.88	87.88	86.13	242.03	232.33
	Second	22.13	26.60	23.83	21.75	45.73	82.83	250.16	239.41
	Third	23.63	30.13	43.00	0.43	111.42	85.82	274.42	231.00

Table 2: Plant growth traits of the tested cultivars under normal and NRT conditions

Growth season	Trait	Cultivar	Treatment	Growth stage				
				Jointing	Booting	Flowering	Mid-filling	Maturity
2016-2017	Population tiller (10^4 ha^{-1})	Jimai 585	Control	1177.25 c	1024.52 c	753.06 d	694.53 c	670.50 c
			NRT	1308.38 a	1099.54 b	978.18 b	754.56 b	730.52 b
		Shimai 22	Control	1218.46 b	1084.58 b	859.55 c	745.50 b	717.00 b
			NRT	1324.39 a	1149.18 a	1003.53 a	799.26 a	766.38 a
	LAI	Jimai 585	Control	2.28 c	5.65 c	4.65 b	3.23 c	0.45 c
			NRT	2.76 a	6.12 a	5.22 a	4.23 a	0.87 a
		Shimai 22	Control	2.56 b	5.86 b	4.81 b	3.53 b	0.66 b
			NRT	2.81 a	6.20 a	5.32 a	4.29 a	0.90 a
	Biomass (kg ha^{-1})	Jimai 585	Control	2.23 c	5.36 b	8.87 b	12.23 d	14.76 d
			NRT	2.54 ab	6.12 a	10.23 a	14.73 b	17.82 b
		Shimai 22	Control	2.43 b	5.56 b	10.02 a	13.87 c	16.76 c
			NRT	2.65 a	6.32 a	10.67 a	15.37 a	18.26 a
2017-2018	Population tiller (10^4 ha^{-1})	Jimai 585	Control	1187.50 c	1005.33 c	733.16 d	680.86 c	662.44 c
			NRT	1346.22 a	1043.90 b	970.50 b	743.42 ab	732.06 a
		Shimai 22	Control	1239.30 b	1030.22 b	928.38 c	722.15 b	706.85 b
			NRT	1370.05 a	1153.68 a	993.22 a	769.56 a	745.47 a
	LAI	Jimai 585	Control	2.35 c	5.44 c	4.48 c	3.20 c	0.48 c
			NRT	2.79 a	6.02 ab	5.37 a	4.17 a	0.82 a
		Shimai 22	Control	2.62 b	5.84 b	4.86 b	3.66 b	0.68 b
			NRT	2.85 a	6.23 a	5.43 a	4.31 a	0.85 a
	Biomass (kg ha^{-1})	Jimai 585	Control	2.32 c	5.36 c	8.91 d	11.99 d	14.80 d
			NRT	2.61 a	5.81 b	10.46 b	13.88 b	16.71 b
		Shimai 22	Control	2.47 b	5.65 b	9.75 c	12.89 c	16.24 c
			NRT	2.63 a	6.28 a	10.91 a	14.28 a	17.06 a

Data are shown by averages from triplicate results. Different lowercase letters on each trait at same season indicate to be statistical significance of the tested cultivars across the row spacing pattern treatments

spike numbers than Shimai 22, which is in agreement with behaviors of the cultivars on traits of plant growth, nutrient accumulation, and photosynthetic function upon modified spacing patterns. Thus, narrowed row width promotes the yield formation capacity in winter wheat when cultivated under limited water condition, due to positive elevation on tiller and spike formation of plants meanwhile sustainment of stable productivity per spike.

Plant WUEs

Plant WUE values of the tested cultivars under control and NRT were calculated based on the total water consumption amounts, water amounts irrigated, and grain yields (Table 5). Compared with control, NRT significantly increased the WUE of the two wheat cultivars examined (Table 5). For the cultivars, both Jimai 585 and Shimai 22 displayed increased WUE under NRT with respect to control. However, Jimai 585 showed higher WUE than Shimai 22 under NRT. These results indicated the efficient improvement of NRT on WUE for winter wheat plants when cultivated under the deficit irrigation conditions.

Discussion

Rowing spacing pattern acts as one of the critical cultivation practices, exerting drastic roles in regulating the productivity of cereal crops, due to its effects in modulating plant growth, development, and yield formation capacity (Maddonni *et al.* 2006). In this study, the effects of narrowed row pattern (NRT) in modifying growth traits of the plants at population level treated by deficit irrigation, using two types of cultivars displaying contrasting drought response (*i.e.*, Jimai 585, one acclimated to affluent water and Shimai 22, a cultivar being drought tolerant), was investigated. Compared with control, NRT exerted positive roles in regulating tiller formation, LAI, and plant biomass accumulation at population level at various growth stages. Previously, even pattern mode for individual plants in population was shown to positively impact on growth environment for single plant, elevating the acquisition capacity of plants for solar radiation, underground water, and inorganic nutrients *via* improved root system (Sharratt *et al.* 2005). The present study results confirmed the positive roles of NRT in improving population tiller formation and spike establishment at maturity, together

Table 3: Contents of nitrogen, phosphorus, and potassium of the tested cultivars under normal and NRT conditions

Growth season	Trait	Cultivar	Treatment	Growth stage				
				Jointing	Booting	Flowering	Mid-filling	Maturity
2016-2017	N content (%)	Jimai 585	Control	1.23 b	1.32 b	1.18 a	1.13 b	1.04 a
			NRT	1.25 ab	1.36 ab	1.21 a	1.14 ab	1.06 a
		Shimai 22	Control	1.25 ab	1.36 ab	1.20 a	1.14 ab	1.06 a
			NRT	1.26 a	1.38 a	1.23 a	1.16 a	1.08 a
	P_2O_5 content (%)	Jimai 585	Control	0.32 a	0.31 a	0.30 a	0.27 a	0.26 a
			NRT	0.34 a	0.32 a	0.31 a	0.29 a	0.27 a
		Shimai 22	Control	0.34 a	0.32 a	0.31 a	0.28 a	0.27 a
			NRT	0.35 a	0.33 a	0.32 a	0.29 a	0.28 a
	K_2O content (%)	Jimai 585	Control	1.32 a	1.28 a	1.53 a	1.12 b	0.98 b
			NRT	1.35 a	1.30 a	1.58 a	1.14 ab	1.00 ab
		Shimai 22	Control	1.33 a	1.29 a	1.55 a	1.13 b	1.01 ab
			NRT	1.35 a	1.30 a	1.58 a	1.15 a	1.02 a
2017-2018	N content (%)	Jimai 585	Control	1.32 b	1.38 a	1.21 a	1.16 a	1.02 b
			NRT	1.34 ab	1.39 a	1.24 a	1.18 a	1.04 ab
		Shimai 22	Control	1.33 ab	1.39 a	1.23 a	1.17 a	1.04 ab
			NRT	1.35 a	1.40 a	1.25 a	1.19 a	1.05 a
	P_2O_5 content (%)	Jimai 585	Control	0.34 b	0.32 a	0.31 a	0.26 b	0.24 b
			NRT	0.36 ab	0.34 a	0.33 a	0.28 ab	0.27 ab
		Shimai 22	Control	0.34 b	0.33 a	0.32 a	0.28 ab	0.26 ab
			NRT	0.37 a	0.35 a	0.34 a	0.29 a	0.28 a
	K_2O content (%)	Jimai 585	Control	1.35 a	1.31 a	1.56 b	1.17 a	0.96 b
			NRT	1.37 a	1.35 a	1.57 ab	1.19 a	1.02 a
		Shimai 22	Control	1.36 a	1.32 a	1.55 b	1.19 a	1.00 a
			NRT	1.37 a	1.35 a	1.58 a	1.20 a	1.03 a

Data are shown by averages from triplicate results. Different lowercase letters on each trait at same season indicate to be statistical significance of the tested cultivars across the row spacing pattern treatments

Table 4: Accumulative amounts of nitrogen, phosphorus, and potassium of the tested cultivars under normal and NRT conditions

Growth season	Trait	Cultivar	Treatment	Growth stage				
				Jointing	Booting	Flowering	Mid-filling	Maturity
2016-2017	N accumulative amount (kg ha^{-1})	Jimai 585	Control	27.43 c	70.75 c	104.67 c	138.20 d	153.50 d
			NRT	31.75 b	83.23 a	123.78 b	167.92 b	188.89 b
		Shimai 22	Control	30.38 b	75.62 b	120.24 b	158.12 c	177.66 c
			NRT	33.39 a	87.22 a	131.24 a	178.29 a	197.21 a
	P_2O_5 accumulative amount (kg ha^{-1})	Jimai 585	Control	7.14 d	16.62 c	26.43 c	33.02 c	37.64 c
			NRT	8.64 b	19.58 b	31.71 b	42.72 a	48.11 a
		Shimai 22	Control	8.26 c	17.90 c	30.86 b	38.70 b	44.92 b
			NRT	9.28 a	21.11 a	34.36 a	44.88 a	50.76 a
	K_2O accumulative amount (kg ha^{-1})	Jimai 585	Control	29.44 c	68.61 b	135.71 c	136.98 c	144.65 d
			NRT	34.29 a	79.56 a	161.63 a	167.92 a	178.20 a
		Shimai 22	Control	32.32 b	71.72 b	155.31 b	156.73 b	169.28 c
			NRT	35.78 a	82.16 a	168.59 a	176.76 a	186.25 a
2017-2018	N accumulative amount (kg ha^{-1})	Jimai 585	Control	30.63 c	73.98 d	107.85 d	139.03 c	150.96 c
			NRT	35.02 a	80.76 bc	129.70 b	163.77 a	173.78 ab
		Shimai 22	Control	32.88 b	78.50 c	119.87 c	150.82 b	168.85 b
			NRT	35.53 a	87.94 a	136.42 a	169.95 a	179.10 a
	P_2O_5 accumulative amount (kg ha^{-1})	Jimai 585	Control	7.89 c	17.16 c	27.63 c	31.16 c	35.52 c
			NRT	9.41 a	19.76 b	34.52 ab	38.86 ab	45.12 ab
		Shimai 22	Control	8.41 b	18.64 b	31.19 b	36.09 b	42.21 b
			NRT	9.74 a	21.99 a	37.11 a	41.42 a	47.76 a
	K_2O accumulative amount (kg ha^{-1})	Jimai 585	Control	31.33 b	70.23 c	139.05 c	140.23 c	142.08 c
			NRT	35.80 a	78.44 ab	164.22 a	165.16 a	170.44 a
		Shimai 22	Control	33.62 b	74.55 b	151.06 b	153.40 b	162.36 b
			NRT	36.06 a	84.80 a	172.44 a	171.38 a	175.69 a

Data are shown by averages from triplicate results. Different lowercase letters on each trait at same season indicate to be statistical significance of the tested cultivars across the row spacing pattern treatments

with enhanced plant biomass production, if wheat cultivars are cultivated under deficit irrigation conditions.

Inorganic nutrient acquisition of plants impacts drastically on the plant growth and development (Werf *et al.* 1995; Adônis *et al*. 2015). In this study, analyses on N, P, and K contents in plants at various stages indicated the positive effects of NRT in regulating plant nutrient acquisition in two tested cultivars. The nutrient contents were elevated in the cultivars examined under NRT together with significantly increased plant biomass at various stages. The NRT treatment drastically elevated the accumulative amounts of above nutrients, which suggest that narrowed row width exerted positive effects in regulating plant nutrition taken up under the water-limited conditions.

Table 5: Agronomic traits, water consumption amounts, and WUE of the tested cultivars under control and NRT conditions

Growth season	Cultivar	Treatment	Spike number (10^4 ha^{-1})	Kernel numbers	Grain weight (mg)	Yield (kg ha^{-1})	Water consumption (m^3 ha^{-1})	WUE (kg m^{-3})
2016-2017	Jimai 585	Control	670.50 c	31.11 b	40.58 a	7194.16 d	4041.66 a	1.78 d
		NRT	730.52 b	31.02 b	41.75 a	8042.24 c	3793.51 b	2.12 b
	Shimai 22	Control	717.00 b	32.83 a	40.56 a	8115.7 b	4078.24 a	1.99 c
		NRT	766.38 a	32.49 a	39.10 a	8276.25 a	3779.11 b	2.19 a
2017-2018	Jimai 585	Control	662.44 c	32.28 a	38.27 b	6956.05 d	3661.08 b	1.90 c
		NRT	732.06 a	32.22 a	39.89 ab	7997.84 b	3618.93 b	2.21 a
	Shimai 22	Control	706.85 b	32.04 a	40.18 a	7734.88 c	3926.34 a	1.97 b
		NRT	745.47 a	31.99 a	40.52 a	8213.17 a	3602.27 b	2.28 a

Data are shown by averages from triplicate results. Different lowercase letters on each trait at same season indicate to be statistical significance of the tested cultivars across the row spacing pattern treatments

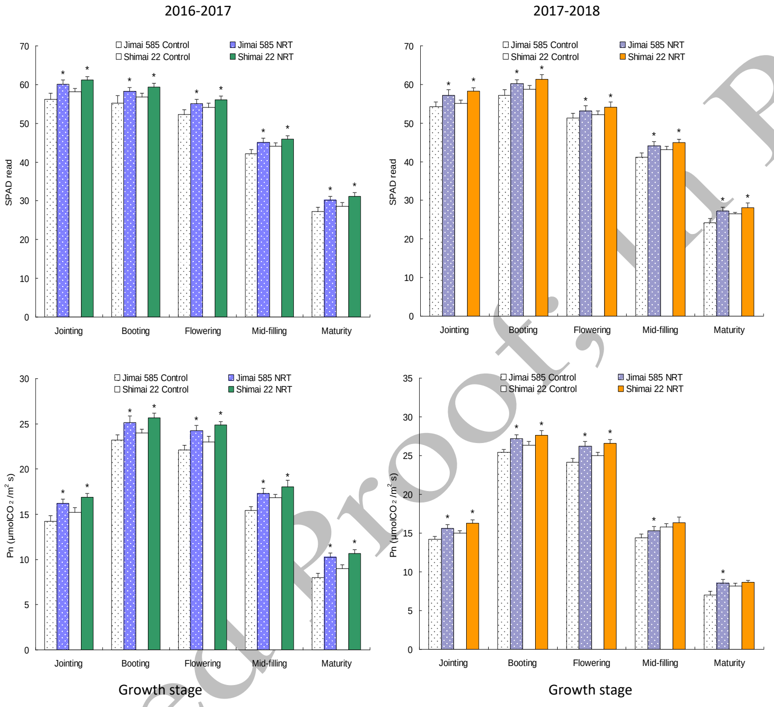

Fig. 1: Leaf chlorophyll contents (Chl) and photosynthetic rates (Pn) of the tested cultivars at various stages under control and NRT conditions

Data are shown by averages from triplicates together with standard errors. Symbol * indicates to be statistical significance of two tested cultivars under NRT relative to control at each assay time

Increased nutrient uptake of plants thus further contributes to the improved growth traits of the wheat cultivars. The mechanisms underlying root architecture system (RAS) establishment and inorganic nutrient uptake mediated by NRT are needed to be further characterized.

Photosystem (PSI and PSII) assembly and photosynthetic organ function are regulated by a suite of environmental factors, including solar radiation intensity, soil moisture, and the acquisition capacity of plants for nutrients stored in soils, such as N, P, and K (Arora *et al.* 2001; Yao and Liu, 2009). In this study, behaviors on Chl and Pn of the upper leaves were measured during late growth stage (from booting stage to maturity stage) in wheat cultivars under control and NRT conditions. Compared with control, NRT significantly elevated the Chl contents and Pn of the flag leaves at various stages. These results are in consistent with the previous findings which indicated the positive effects of narrowed row width on photosynthetic function (Stewart *et al.* 2003). Thus, the improvement on Chl biosynthesis and Pn behavior under NRT was associated with the increased nutrient acquirement, which positively impacts on the function of the photosynthetic apparatus upon deficit irrigation management.

Row spacing pattern alters spatial distribution of the plants at population level, by which to impact on the solar radiation interception of canopy during late growth stage in various crop species (Steiner, 1986; Ruíz and Bertero, 2008). In this study, a drastic variation on solar radiation interception rate (RIR) during late stage between two row spacing treatments was observed. Compared with control, NRT drastically enhanced canopy RR at upper

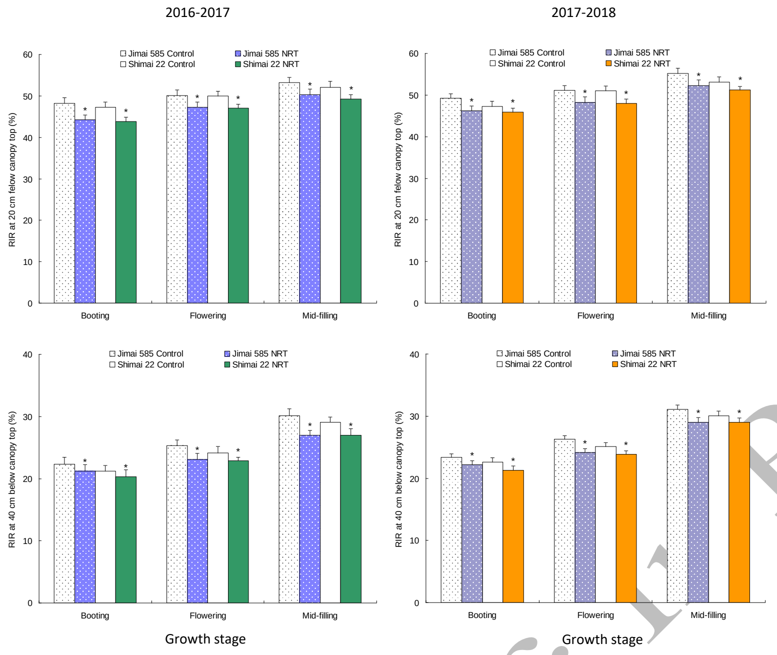

Fig. 2: Solar radiation interception rates of canopy in the tested cultivars under control and NRT conditions

Data are shown by averages from triplicates together with standard errors. Symbol * indicates to be statistical significance of two tested cultivars under NRT relative to control at each assay time

layers (20 cm below the top of canopy) and sustained comparable canopy RIR at middle layers (40 below the top of canopy), at booting, flowering, and mid-filling stages. It has been reported that enhanced RIR during late stage contributes to plant biomass production at the population level (Wang *et al.* 2004). Therefore, the improved canopy RIR during late growth stage promotes the plant biomass and kernel dry mass accumulation in winter wheat plants cultivated by deficit irrigation condition.

The yield components of cereal crops, namely, population spike numbers, kernel numbers per spike, and grain weights, are generally inhibited each other among them (Rahman, 2010). For example, increase of the population spike numbers by increasing amounts of seed rate led to limited plant growth and development, which reduced the individual productivity at maturity (Huang and Jing 2011). In this study, compared with control, NRT significantly improved grain yields in tested wheat cultivars, suggesting its positive effects on winter wheat plants treated by deficit irrigation. Analysis on yield components revealed that the population tiller numbers and the population spike numbers were significantly increased at maturity in two tested cultivars under NRT with respect to control. Although increased population spike amounts, compared with control, NRT sustained comparable kernel numbers per spike and grain weights in the cultivars examined. Thus, NRT improves the yield formation capacity of winter wheat by enhancing population spike formation meanwhile sustainment of stable productivity per spike.

Improving plant WUE is critical for crop cultivation in a limited water supply cropping system (Oweis *et al.* 2000; Zhang *et al.* 2005). In this study, investigations on plant WUE under two different row patterns indicated that NRT promoted the WUE of wheat plants treated by limited water resource. The plants under NRT displayed similar water consumption amounts and increased grain yields, which led to improved WUE of the wheat cultivars. Inhibition of soil evaporation rate lowers consumption rate for soil water storage and improves plant WUE behaviors Liu *et al.* 2006). Thus, the positive WUE under NRT is associated with the inhibition of evaporation due to more even coverage of plants on soil surface. The mechanisms as to water transport pathways across soil, plants, and atmosphere in winter wheat cropping system under NRT are needed to be further investigated.

Wheat cultivars displayed drastic variation on drought stress response (Adrien *et al.* 2009; Wang *et al.* 2015). Drought-tolerant cultivars possess relatively strong capacity on grain biomass production under water-saving conditions with respect to those acclimated to affluent water supplies (Rizza *et al.* 2012). In this study, analysis on grain yields and plant WUE at maturity in wheat cultivars obtained similar results, namely, the drought tolerant cultivar Shimai 22 was shown to be more improvement on above traits than the drought-sensitive cultivar Jimai 585. However, variations on grain yields, plant WUE as well as other growth traits, nutrient accumulative amounts, photosynthetic traits, and canopy RR during late stage between control and NRT were shown to be enlarged in Jimai 585; this cultivar showed elevated above traits under

NRT with respect to Shimai 22. These results suggested the genotype variation in response to NRT across winter wheat cultivars. The drought-sensitive cultivar Jimai 585 is prone to be planted under narrowed row distance to be possibly related to the much more of coverage of soil surface that inhibit evaporation. Therefore, narrowed row spacing is more suitable for adoption to the deficit irrigation-sensitive cultivars treated by deficit irrigation management.

Conclusion

Row spacing width exerts drastic roles in modulating plant growth traits, photosynthetic function and agronomic traits for winter wheat cultivars cultivated under water-saving conditions. Narrowed row treatment (NRT) positively affected population tiller numbers, LAI, and biomass together with increased uptake of N, P, and K of plants. These traits are in consistent with the effects of NRT on regulating chlorophyll contents (Chl) and photosynthetic rate (Pn). During late growth stage, the upper canopy position under NRT intercepted elevated solar radiation (SR) in tested cultivars relative to control and increased population spike formation capacity, while maintained comparable kernel numbers per spike and grain weights, which leads to enhanced grain yields and water use efficiency (WUE) of the wheat cultivars. The drought-sensitive cultivar Jimai 585 displayed more variation on plant growth and agronomic traits upon NRT than drought-tolerant cultivar Shimai 22, suggesting the potential of the drought-sensitive cultivars for cultivation under NRT upon the water deprivation management.

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