INTERNATIONAL JOURNAL OF AGRICULTURE & BIOLOGY
ISSN Print: 1560–8530; ISSN Online: 1814–9596
19–0142/201x/00–0–000–000
DOI: 10.17957/IJAB/15.1058
http://www.fspublishers.org

Full Length Article

Effect of Population Horizontal Structure and Water Condition on Physiological Characteristic and Evapotranspiration of Winter Wheat

X.B. Zhou[1], L. Yang[1], L.B. Shi[2] and Y.Y. Yong[1*]
[1]*Agricultural College of Guangxi University, Nanning 530004, China*
[2]*MAP Division (Shandong) of Sinochem Agriculture Holdings, Jinan 250100, China*
[*]For correspondence: xunbozhou@gmail.com

Abstract

The population horizontal structure of crop and soil water conditions affects the moisture physiological characteristics of leaves and yield of winter wheat. In a three-year study from 2011 to 2014, the osmotic potential, water potential, relative water content and abscisic acid (ABA) content of leaf, and regression of evapotranspiration versus the grain yield of wheat were determined. Field experiments were conducted in two-factor split-plot design with three replicates. We established three moisture levels (main plot), as follows: 0, 90 and 180 mm irrigation amounts; and three population horizontal structures (split plot), as follows: single, single-twin and twin rows. Results showed that irrigation improved the water physiological traits of winter wheat leaves. The order of leaf osmotic potential, water potential, and relative water content were 180 mm > 90 mm > 0 mm and the order of ABA content was in the reverse order. However, we observed no significant differences between 90 and 180 mm irrigation amounts in most cases. Under same irrigation amounts, the leaf osmotic potential, water potential, and relative water content of the twin row were 6.0, 1.4 and 1.6% higher, respectively, than those of single row; however, ABA content and leaf turgor potential were 16.7 and 50% lower than that of single row. The 180 mm irrigation level obviously increased leaf turgor potential. Moreover, a positive correlation was observed between evapotranspiration and yield. Considering the optimum allocation of water resources and water requirements of winter wheat, we recommend a twin row combined with 90 mm irrigation under precision sowing as a good agronomic option in North China. © 2019 Friends Science Publishers

Keywords: *Triticum aestivum*; Leaf water traits; Leaf ABA content; Evapotranspiration; Grain yield

Introduction

Winter wheat (*Triticum aestivum* L.) is major cultivated crop in Northern China. However, water shortage is a crucial problem in this area. Tai'an, a semi-humid continental monsoon climate city, has a precipitation of only 170–180 mm during the wheat growing season. This precipitation is low and limits the yield of wheat; thus irrigation is an indispensable agronomic practice (Zhang *et al*., 2016). Moreover, freshwater resource shortage in wheat-producing regions is a global problem (Ramírez-Rodrigues *et al*., 2016). Agricultural production is faced with the challenge of global food security. Increased human food demands increasing crop yields and this requirement is made difficult by environmental problems (Foley *et al*., 2011; Konzmann *et al*., 2013). On the other hand, groundwater resources are overexploited and the crop yields are not further increased (Wada *et al*., 2014). Increasing the wheat grain yield is expected to be difficult due to different biotic and abiotic stresses (Manickavelu *et al*., 2012). Moreover, over 70% of the water consumption in China goes to agricultural irrigation (Thomas, 2008). Irrigation plays a vital role in the alleviation of poverty and food security in China and the world (Lobell *et al*., 2008; Zhang *et al*., 2019). Therefore, valid water-saving practices must be applied in agricultural production. Limited irrigation, deficit irrigation, supplemental irrigation, sub-surface drip irrigation and sprinkler irrigation have been found to be effective irrigation patterns (Abd El-Wahed and Ali, 2013; Ali *et al*., 2019).

Population horizontal structure mainly involves row spacing, in which narrow-spaced rows and width-narrow rows affect the moisture physiological characteristics of plants, evapotranspiration and yield (Hussain *et al*., 2014; Kadam *et al*., 2017). Moreover, ridge, furrow planting, no-tillage and straw mulching significantly affect field environment and increase yields as well (Maqsood *et al*., 2013; Yan *et al*., 2017). Appropriate population structure can improve the microclimate of winter wheat farmlands (Zhao *et al*., 2018). Suitable plant density is an important optimization strategy for reducing water use (Ren *et al*., 2016). Water, light, relative humidity and soil temperature are environmental factors that can affect crop growth and development (Mao *et al*., 2017). The turgor potential is an important parameter determining the survival of plants under

To cite this paper: Zhou, X.B., L. Yang, L.B. Shi and Y.Y. Yong, 201x. Effect of population horizontal structure and water condition on physiological characteristic and evapotranspiration of winter wheat. *Intl. J. Agric. Biol*. 00: 000–000

stress conditions (Wahid, 2004). Improving agricultural management strategies will support farmers, as they will be equipped with tools that can influence crop production (Phelan *et al*., 2018). A good population horizontal structure can improve the microclimate of a winter wheat farmland.

The purpose of this study was to improve population horizontal structure by changing planting pattern and optimizing the water status of winter wheat, thereby benefitting crop growth and increasing yields under deficit irrigation and precision sowing in Northern China. This three-year field experiment aimed to determine the effects of population horizontal structure, in combination with water conditions on (i) physiological moisture indicators of winter wheat, including leaf osmotic potential, water potential, turgor potential, relative water content and abscisic acid content and (ii) regression of evapotranspiration versus winter wheat grain yield in Northern China.

Materials and Methods

The experiment was conducted at the Agronomy Experimental Station of Shandong Agricultural University, Tai'an, China (36°09′ N, 117°09′ E) during 2011–2014. The precipitations in the experimental field in 2011/2012, 2012/2013 and 2013/2014 growing seasons were 205.8, 195.8 and 158.4 mm, respectively and the long-term (1971–2011) precipitation average was 174.2 mm in the growing season (Table 1).

A split-plot experimental design was used, and water condition was the main plot with three irrigation amounts: 0, 90 and 180 mm. One-third (0, 30 and 60 mm) of the total irrigation amounts was supplied to the plots at GS34, GS48 and GS70. Population horizontal structure was a split plot with three planting patterns: single, single-twin and twin rows (Fig. 1). Each plot was 3 m × 3 m in size and each experiment was performed with three replications.

The planting density of winter wheat (*Triticum aestivum* L. var. Jimai 22) was 200×10^4/ha on October 9, 2011, October 10, 2012 and October 9, 2013. The wheat was harvested on June 9, 2012, June 8, 2013 and June 5, 2014. Fertilizers were applied as base, diammonium phosphate 261 kg/ha and potassium sulfate 210 kg/ha before sowing. Half of the total nitrogen (urea 383.7 kg/ha) as base fertilizer and topdressing during growth stage (GS) 30 (Zadoks *et al*., 1974) were applied. All side concrete slabs were 15 cm wide and each plot was 200 cm deep.

Four flag leaves undergoing each treatment were measured for the following physiological traits. The leaf osmotic potential and water potential were sampled at GS35, GS45, GS49, GS71 and GS80 and measured by using a 5520 Vapor Pressure Osmometer and Psypro Water Potential System (Wescor, Inc., Logan, USA), respectively. Before the test, the measured leaves were wiped cleaned and dried. Samples were obtained by using a 0.6 cm diameter round puncher and placed into the sample room, after waiting for approximately 20 min and reading. The relative water content of leaves was measured at GS32, GS35, GS44, GS49 and GS70. The values were computed using the following equations:

$$\text{Turgor potential} = \text{water potential} - \text{osmotic potential} \quad (1)$$

$$\text{Leaf relative water content} = (FW - DW) / (SFW - DW) \times 100\% \quad (2)$$

Where FW is the fresh weight (g), DW is dry weight (g) and SFW is the saturated fresh weight (g).

The leaf abscisic acid (ABA) was measured at GS32, GS35, GS40, GS45, GS47, GS50, GS68, GS73 and GS79. The leaf sample (1 g) was collected, cleaned and quickly frozen in liquid nitrogen canister for 10 min and stored at -80°C super cold refrigerator. Test plant tissue sample extracted in accordance with the method described by Guerfel *et al*. (2009). ABA contents (ng/g) were determined by using enzyme-linked immunosorbent assay (ELISA).

The evapotranspiration values of GS01-24, GS24-35, GS35-49, GS49-71 and GS71-91 were computed using the following equation:

$$\text{Evapotranspiration (mm)} = \Delta W + I + P \quad (3)$$

Where ΔW is the soil water storage change (mm, Mao *et al*., 2017), I is the irrigation amounts (mm) and P is the rainfall (mm). Based on observations, the surface run-off was negligible.

The test data were analyzed by using SAS9.2. SigmaPlot12.5 (SPSS Inc., Chicago, IL) was used for drawing. Data were analyzed with an ANOVA to determine whether significant differences existed among the different treatments.

Results

Leaf Osmotic Potential

The results of two growth seasons experiments are shown in Fig. 2. The leaf osmotic potential increased with increasing irrigation amounts; the values of 0, 90 and 180 mm treatments were caused leaf osmotic potentials to reach -1.73, -1.58 and -1.52 MPa, respectively. Rainfed treatment was lower than those of irrigation treatments. Under 0 mm (rainfed), the leaf osmotic potential of the single row was significantly lower than those of single-twin and twin row at GS71 and GS80. Under 90 mm, there was no significant difference among the treatments ($P > 0.05$) while at 180 mm, the single row was significantly lower than those of single-twin and twin rows at GS80 ($P < 0.05$). Under different irrigation levels, the average leaf osmotic potentials of the single, single-twin, and twin rows was -1.65, -1.60 and -1.58 MPa, respectively.

Leaf Water Potential

The results of the three growth season experiments are shown in Fig. 3. The change trend of leaf water potential was similar to that of leaf osmotic potential, and increased with increasing number of irrigations. Irrigation with 0, 90

Table 1: The monthly rainfall (mm) of winter wheat growth seasons during 2011–2014 and 1971–2011

Growth seasons	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Total
2011/2012	13.4	99.2	14.7	1.8	0.1	25.9	43.7	7.0	205.8
2012/2013	15.7	18.4	19.0	5.1	13.2	13.6	12.8	98.0	195.8
2013/2014	3.7	26.5	0.0	0.0	17.1	0.3	32.7	78.1	158.4
1971–2011	36.0	17.4	8.2	5.6.	9.8	16.4	29.0	51.9	174.2

and 180 mm treatments caused leaf water potential to reach -1.60, -1.45 and -1.37 MPa, respectively. The leaf water potential at 0 mm level (rainfed condition) had a trend of decreasing during the whole growth stage and irrigation treatments had no change. Moreover, 180 mm irrigation increased the leaf water potential at GS80. Under different irrigation levels, the average leaf water potentials of single, single-twin and twin rows reached -1.45, -1.49 and -1.47 MPa, respectively. No significant difference was seen among the treatments ($P > 0.05$).

Leaf Turgor Potential

Irrigation with 0, 90 and 180 mm treatments were caused leaf turgor potentials to reach 0.138, 0.132 and 0.151 MPa, respectively. The 180 mm irrigation level increased leaf turgor potential. The average leaf turgor potential of GS35, GS45, GS49, GS71 and GS80 were 0.095, 0.051, 0.027, 0.087 and 0.441 MPa, respectively, there was a trend of increase at the later growth stages. There were differences among population horizontal structures. Under 0 mm (rainfed) and 180 mm, the leaf turgor potential of the single row was significantly higher than those of single-twin and twin row at GS71 and GS80 ($P < 0.05$). Under different irrigation levels, the average leaf turgor potential of the single, single-twin, and twin rows was 0.206, 0.103 and 0.112 MPa, respectively (Fig. 4).

Leaf Relative Water Content

The effects of the three growth season experiments on leaf relative water content are shown in Fig. 5. The change trend of leaf relative water content was similar to that leaf osmotic potential, and increased with increasing of irrigation amounts: irrigation amounts of 0, 90 and 180 mm treatments caused leaf relative water content to reach 79.1, 80.6 and 81.3%, respectively. The leaf relative water content of the twin row was significantly higher than that of the single row at GS70 (0 mm), GS32 (90 mm) and GS44 (180 mm) ($P < 0.05$). The leaf relative water content of different treatments showed a decreasing trend with growth stage development. Under same irrigation amounts, the leaf relative water contents of the single, single-twin, and twin rows were 79.9, 79.9 and 81.2%, respectively.

Leaf ABA Content

The results of the two growth season experiments showed that ABA content decreased with increasing irrigation amounts: irrigation amounts of 0, 90 and 180 mm treatments caused leaf ABA content to decrease to 25.12, 24.24 and 23.17 ng/g, respectively. Moreover, ABA content in 0 mm treatment (rainfed condition) was significantly higher than that of irrigation treatments ($P < 0.05$). During growth seasons, the leaf ABA content was significantly different between population horizontal structures under 90 mm irrigation amounts ($P < 0.05$) and the order was single row (27.31 ng/g) > single-twin row (24.51 ng/g) > twin row (20.90 ng/g). Under different irrigation levels, the leaf ABA content of single, single-twin, and twin rows were 26.15, 23.98 and 22.40 ng/g, respectively. ABA content in the single row was significantly ($P < 0.05$) higher than those of the single-twin and twin rows (Fig. 6). A positive correlation was seen between ABA content (y: ng/g) to growth stage (x), as calculate by the linear equation $y = 0.7112x + 20.655$, $R^2 = 0.4186$ ($P = 0.0037$).

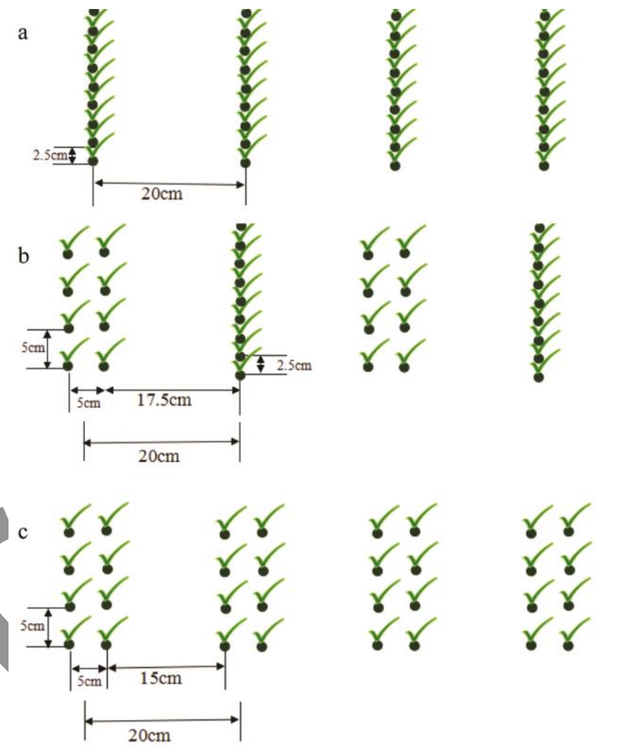

Fig. 1: Population horizontal structure schematic diagram. a, single row; b, single–twin row; c, twin row

Regression of Evapotranspiration versus Grain Yield

The results showed that irrigation increased the evapotranspiration in different treatments (Table 2). The

Table 2: The evapotranspiration (mm) of winter wheat in different growth stages and regression of total evapotranspiration versus grain yield (2011–2014)

Growth seasons	Treatments	GS01–24	GS24–35	GS35–49	GS49–71	GS71–91	Regression equation
2011/2012							
Irrigation mounts	0 mm	128.6a	131.1b	95.1b	38.5c	20.5c	$y = -0.0011x^2 + 2.0912x$
	90 mm	128.6a	142.1a	107.1a	52.8b	51.0b	$R^2 = 0.6271$
	180 mm	128.6a	141.3a	106.1a	66.8a	67.0a	$P < 0.0001$
Horizontal structure	Single	133.1a	137.6a	103.8a	49.7b	45.5b	y: yield (g/m^2)
	Single–twin	122.5b	138.6a	101.1a	55.8a	44.7b	x: evapotranspiration (mm)
	Twin	130.3a	138.3a	103.4a	52.6ab	48.4a	
2012/2013							
Irrigation mounts	0 mm	69.3a	80.2c	43.9c	37.4c	22.5c	$y = -0.0023x^2 + 2.9411x$
	90 mm	69.3a	94.3a	77.1b	60.8b	44.8b	$R^2 = 0.8905$
	180 mm	69.3a	88.5b	121.0a	87.8a	60.1a	$P < 0.0001$
Horizontal structure	Single	66.7a	75.7c	78.4b	59.6b	43.7a	y: yield (g/m^2)
	Single–twin	68.6a	95.9a	75.4c	61.2b	43.2a	x: evapotranspiration (mm)
	Twin	72.4a	91.3b	88.3a	65.1a	40.5a	
2013/2014							
Irrigation mounts	0 mm	64.7a	80.9c	26.4c	25.8c	74.5c	$y = -0.0026x^2 + 3.2227x$
	90 mm	64.7a	90.2b	47.6b	62.5b	96.5b	$R^2 = 0.7725$
	180 mm	64.7a	100.9a	72.8a	91.3a	126.2a	$P < 0.0001$
Horizontal structure	Single	70.3a	92.7a	54.7a	63.1a	103.0a	y: yield (g/m^2)
	Single–twin	64.5b	92.4a	47.2b	59.0b	100.2b	x: evapotranspiration (mm)
	Twin	58.8c	87.0b	45.0b	57.1c	94.0c	

Values followed by the same letter in a column are not significantly different according to $LSD_{0.05}$

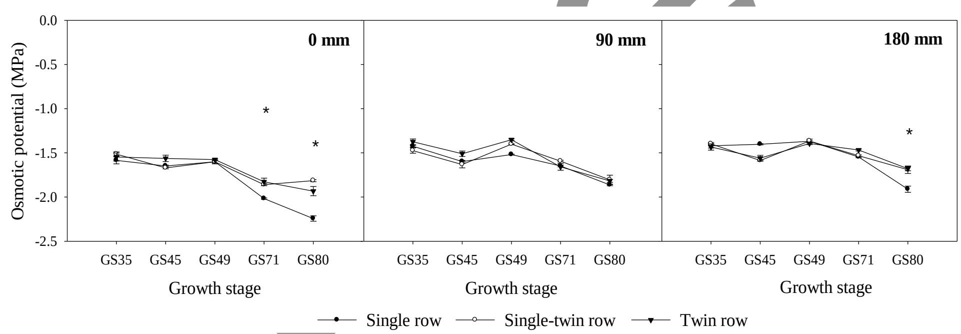

Fig. 2: Effects of population horizontal structure and water condition on the leaf osmotic potential. Mean of two growth seasons (2011/2012 and 2013/2014); 0 mm, 90 mm and 180 mm were irrigation amounts; the bars are the SE; asterisk was significantly difference at 0.05 level

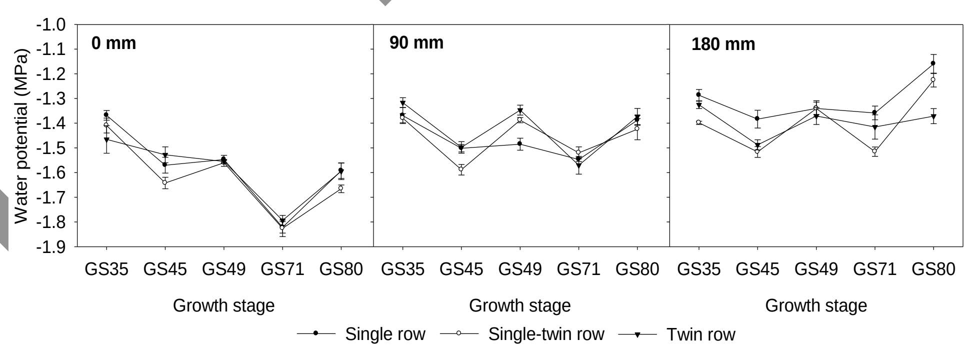

Fig. 3: Effects of population horizontal structure and water condition on the leaf water potential. Mean of three growth seasons (2011/2012, 2012/2013 and 2013/2014); 0 mm, 90 mm and 180 mm were irrigation amounts; the bars are the SE

evapotranspiration showed an increased trend as irrigation amount increased at different growth seasons. For population horizontal structure, the evapotranspiration of single row was relatively low at GS01-24; as a whole, single-twin row was average at GS35-49, GS49-71 and GS71-91. Regression equation of total evapotranspiration (x: mm) versus grain yield (y: g/m^2) was $y = -0.0134x^2 + 13.392x - 2575.4$ ($R^2 = 0.6794$, $P < 0.0001$) in 2011/12, $y = -0.0056x^2 + 5.1754x - 367.37$($R^2 = 0.9051$, $P < 0.0001$) in 2012/13 and $y = 0.0049x^2 - 2.2177x + 946.05$ ($R^2 = 0.8651$, $P < 0.0001$) in 2013/14.

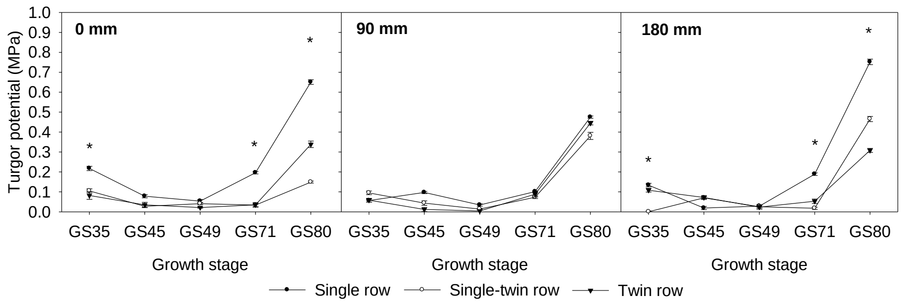

Fig. 4: Effects of population horizontal structure and water condition on the turgor potential. Mean of three growth seasons (2011/2012, 2012/2013 and 2013/2014); 0 mm, 90 mm, and 180 mm were irrigation amounts; the bars are the SE; asterisk was significantly difference at 0.05 level

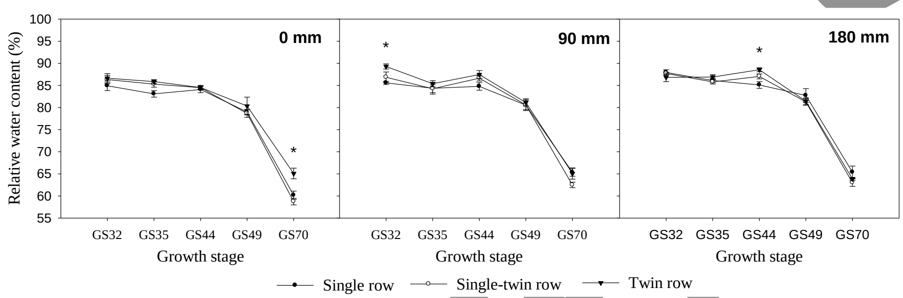

Fig. 5: Effects of population horizontal structure and water condition on the leaf relative water content. Mean of three growth seasons (2011/2012, 2012/2013 and 2013/2014); 0 mm, 90 mm and 180 mm were irrigation amounts; the bars are the SE; asterisk was significantly difference at 0.05 level

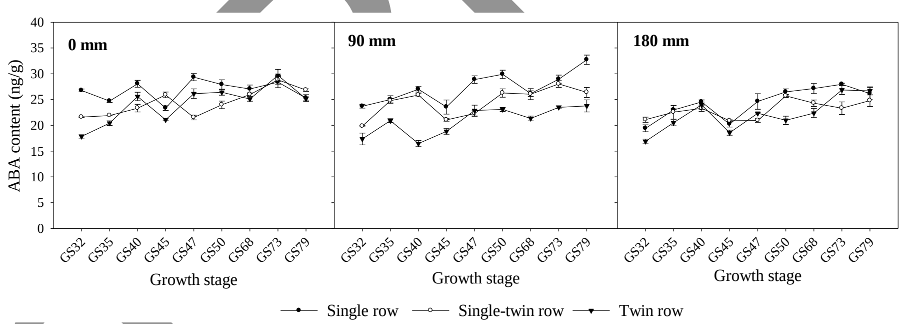

Fig. 6: Effects of population horizontal structure and water condition on the leaf abscisic acid (ABA) content. Mean of two growth seasons (2012/2013 and 2013/2014); 0 mm, 90 mm and 180 mm were irrigation amounts; the bars are the SE

These results showed that evapotranspiration increased as grain yield increased. The total evapotranspiration and yield were 387 mm and 724 g/m^2 (single row), 389 mm and 767 g/m^2 (single-twin row) and 393 mm and 781 g/m^2 (twin row) in 2011–2014, respectively.

Discussion

The leaf-water relationship and physiological traits changed as the plants responded to the environment. The experiment results showed that the population horizontal structure and water condition affected the moisture physiological characteristic of the plants. The irrigation treatments increased the leaf osmotic potential, water potential, and relative water content, and the order of water treatments was 180 mm > 90 mm > 0 mm. Moreover, the irrigation alleviated the drought stress in winter wheat (Alghory and Yazar, 2019). Under different irrigation levels, the order of average water potential was single row < single-twin row ≈ twin row; the order of average leaf turgor potential was single row > single-twin row ≈ twin row; however, the order of average leaf relative water content was single row = single-twin row < twin row. This result showed enhanced plant potential for sustaining high nitrogen-metabolizing enzyme activities to supplement osmotic adjustments under soil drought conditions (Zahoor *et al*., 2017). Higher irrigation could improve soil water condition and increased leaf turgor potential, as a result, affected the stomatal opening, biochemical activities and promoted crop growth (Huilian *et al*., 2004). In single row there was relative higher leaf turgor potential, which may be due to a reduced stem elongation after GS35 (Zhang *et al*., 2016). Low leaf water led to stomatal closure and reduced photosynthesis, and these changes could limit plant growth and yield formation (Puri and Swamy, 2001). Chaves and Oliveira (2004) reported that water stress negatively affects agricultural productivity. Therefore, improved water physiological traits would benefit and increase yield.

The ABA content has been linked to drought tolerance (Duque and Setter, 2013). Moreover, the accumulation of ABA in leaf reduces stomatal opening and induces leaf abscission (Adjebeng-Danquah *et al*., 2016). The experimental results showed that leaf ABA content decreased after irrigation, and the order of different population horizontal structures was single row > single-twin row > twin row under same irrigation amounts. Additionally, the ABA content was higher under stress conditions than in irrigation, and was negatively correlated with above-ground biomass (Adjebeng-Danquah *et al*., 2016). The results showed that there were linear relationships between leaf turgor potential and leaf water potential, osmotic potential, relative water content, ABA during GS35-GS80 and correlation coefficients (r) were 0.2894, -0.8577, -0.9687, 0.3848, respectively. The leaf turgor potential had a positive correlation with the leaf water potential and ABA, but had negative correlation with the leaf osmotic potential and relative water content. These results are similar with some of earlier studies for maize (Naeem *et al*., 2018). Concurrently, the water traits of plant showed a deteriorating trend with growth stage development. The results showed that the total evapotranspiration of the single, single-twin and twin rows were similar. Moreover, yield of single row was the lowest and that of the twin row was the highest during 2011–2014. This result showed that optimum population horizontal structure is crucial for higher gain yield.

Conclusion

This three-year study demonstrated that population horizontal structure and water conditions can highly affect osmotic potential, water potential, turgor potential, relative water content and ABA content of leaf and evapotranspiration; optimize agricultural measures could increase the yield of winter wheat. Considering the optimal allocation of water resources and water requirements of winter wheat in North China, the twin row combined with 90 mm irrigation amounts is a good agronomic option to improve winter wheat performance in semi-arid regions.

Acknowledgements

The research was sponsored by the National Natural Science Foundation of China (31760354), Guangxi Natural Science Foundation (2017GXNSFAA198036).

Reference

Abd El-Wahed, M.H. and E.A. Ali, 2013. Effect of irrigation systems, amounts of irrigation water and mulching on corn yield, water use efficiency and net profit. *Agric. Water Manage.*, 120: 64–71

Adjebeng-Danquah, J., J. Manu-Aduening, V.E. Gracen, S.K. Offei and I.K. Asante, 2016. Genotypic variation in abscisic acid content, carbon isotope ratio and their relationship with cassava growth and yield under moisture stress and irrigation. *J. Crop Sci. Biotechnol.*, 19: 263–273

Alghory, A. and A. Yazar, 2019. Evaluation of crop water stress index and leaf water potential for deficit irrigation management of sprinkler-irrigated wheat. *Irrig. Sci.*, 37: 61–77

Ali, S., Y. Xu, I. Ahmad, Q. Jia, X. Ma, A. Sohail, Manzoor, M. Arif, X. Ren, T. Cai, J. Zhang and Z. Jia, 2019. The ridge-furrow system combined with supplemental irrigation strategies to improves radiation use efficiency and winter wheat productivity in semiarid regions of China. *Agric. Water Manage.*, 213: 76–86

Chaves, M.M. and M.M. Oliveira, 2004. Mechanisms underlying plant resilience to water deficits: prospects for water-saving agriculture. *J. Exp. Bot.*, 55: 2365–2384

Duque, L.O. and T.L. Setter, 2013. Cassava response to water deficit in deep pots: root and shoot growth, ABA, and carbohydrate reserves in stems, leaves and storage roots. *Trop. Plant Biol.*, 6: 199–209

Foley, J.A., N. Ramankutty, K.A. Brauman, E.S. Cassidy, J.S. Gerber, M. Johnston, N.D. Mueller, C.O'Connell, D.K. Ray, P.C. West, C. Balzer, E.M. Bennett, S.R. Carpenter, J. Hill, C. Monfreda, S. Polasky, J. Rockström, J. Sheehan, S. Siebert, D. Tilman and D.P.M. Zaks, 2011. Solutions for a cultivated planet. *Nature*, 478: 337–342

Guerfel, M., A. Beis, T. Zotos, D. Boujnah, M. Zarrouk and A. Patakas, 2009. Differences in abscisic acid concentration in roots and leaves of two young Olive (*Olea europaea* L.) cultivars in response to water deficit. *Acta Physiol. Plant.*, 31: 825–831

Huilian, X., W. Xiaoju, W. Jihua, X. Rongyan and Z. Aihua, 2004. Leaf turgor potential, plant growth and photosynthesis in organically fertilized sweet corn. *Pedosphere*, 14: 165–170

Hussain, I., R. Rasheed and A. Wahid, 2014. Seasonal variations in some water relations and biochemical attributes of two genetically diverse maize cultivars. *Braz. J. Bot.*, 37: 417–428

Kadam, S.A., S.D. Gorantiwar, S.N. Das and A.K. Joshi, 2017. Crop evapotranspiration estimation for wheat (*Triticum aestivum* L.) using remote sensing data in semi-arid region of Maharashtra. *J. Ind. Soc. Remote Sens.*, 45: 297–305

Konzmann, M., D. Gerten and J. Heinke, 2013. Climate impacts on global irrigation requirements under 19 GCMs, simulated with a vegetation and hydrology model. *Hydrol. Sci. J.*, 58: 88–105

Lobell, D.B., M.B. Burke, C. Tebaldi, M.D. Mastrandrea, W.P. Falcon and R.L. Naylor, 2008. Prioritizing climate change adaptation needs for food security in 2030. *Science*, 319: 607–610

Manickavelu, A., K. Kawaura, K. Oishi, T. Shin-I, Y. Kohara, N. Yahiaoui, B. Keller, R. Abe, A. Suzuki, T. Nagayama, K. Yano and Y. Ogihara, 2012. Comprehensive functional analyses of expressed sequence tags in common wheat (*Triticum aestivum*). *DNA Res.*, 19: 165–177

Mao, X.M., W.W. Zhong, X.Y. Wang and X.B. Zhou, 2017. Effects of precision planting patterns and irrigation on winter wheat yields and water productivity. *J. Agric. Sci.*, 155: 1394–1406

Maqsood, M., M.A. Shehzad, A. Wahid and A.A. Butt, 2013. Improving drought tolerance in maize (*Zea mays*) with potassium application in furrow irrigation systems. *Intl. J. Agric. Biol.*, 15: 1193–1198

Naeem, M., M.S. Naeem, R. Ahmad, M.Y. Ashraf, M.Z. Ihsan, F. Nawaz, H.R. Athar, H.T. Abbas and M. Abdullah, 2018. Improving drought tolerance in maize by foliar application of boron: water status, antioxidative defense and photosynthetic capacity. *Arch. Agron. Soil Sci.*, 64: 626–639

Phelan, D.C., M.T. Harrison, G. McLean, H. Cox, K.G. Pembleton, G.J. Dean, D. Parsons, M.E.A. Richter, G. Pengilley, S.J. Hinton and C.L. Mohammed, 2018. Advancing a farmer decision support tool for agronomic decisions on rainfed and irrigated wheat cropping in Tasmania. *Agric. Syst.*, 167: 113–124

Puri, S. and S.L. Swamy, 2001. Growth and biomass production in *Azadirachta indica* seedling in response to nutrients (N and P) and moisture stress. *Agrofor. Syst.*, 51: 57–68

Ramírez-Rodrigues, M.A., P.D. Alderman, L. Stefanova, C.M. Cossani, D. Flores and S. Asseng, 2016. The value of seasonal forecasts for irrigated, supplementary irrigated and rainfed wheat cropping systems in northwest Mexico. *Agric. Syst.*, 147: 76–86

Ren, X., D. Sun and Q. Wang, 2016. Modeling the effects of plant density on maize productivity and water balance in the Loess Plateau of China. *Agric. Water Manage.*, 171: 40–48

Thomas, A., 2008. Agricultural irrigation demand under present and future climate scenarios in China. *Glob. Planet. Chang.*, 60: 306–326

Wada, Y., D. Wisser and M.F.P. Bierkens, 2014. Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources. *Earth Syst. Dyn.*, 5: 15–40

Wahid, A., 2004. Analysis of toxic and osmotic effects of sodium chloride on leaf growth and economic yield of sugarcane. *Bot. Bull. Acad. Sin.*, 45: 133–141

Yan, Z.X., C. Gao, Y.J. Ren, R. Zong, Y.Z. Ma and Q.Q. Li, 2017. Effects of pre-sowing irrigation and straw mulching on the grain yield and water use efficiency of summer maize in the North China Plain. *Agric. Water Manage.*, 186: 21–28

Zadoks, J.C., T.T. Chang and C.F. Konzak, 1974. A decimal code for the growth stages of cereals. *Weed Res.*, 14: 415–421

Zahoor, R., W. Zhao, M. Abid, H. Dong and Z. Zhou, 2017. Potassium application regulates nitrogen metabolism and osmotic adjustment in cotton (*Gossypium hirsutum* L.) functional leaf under drought stress. *J. Plant Physiol.*, 215: 30–38

Zhang, Y., Y. Wang and H. Niu, 2019. Effects of temperature, precipitation and carbon dioxide concentrations on the requirements for crop irrigation water in China under future climate scenarios. *Sci. Total Environ.*, 656: 373–387

Zhang, Z., X.B. Zhou and Y.H. Chen, 2016. Effects of irrigation and precision planting patterns on photosynthetic product of wheat. *Agron. J.*, 108: 2322–2328

Zhao, Y.X., X.M. Mao and X.B. Zhou, 2018. Effect of previous crop nitrogen application on yield of following maize under different planting patterns. *J. Anim. Plant Sci.*, 28: 1441–1446

(Received 23 January 2019; Accepted 27 February 2019)