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Full Length Article

Effects of Shading and Waterlogging on the Photosynthesis and Yield Performance of Winter Wheat in Jiangsu Province, China

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Abstract

Jiangsu Province is one of major wheat-producing areas in China. In this region, winter wheat is often vulnerable to waterlogging stress in spring because of the cloudy and rainy weather. Moreover, the growth of winter wheat can be threatened simultaneously by inadequate sunlight. Waterlogging and inadequate sunlight have been thought to be common agricultural meteorological disasters in Jiangsu Province. However, little is known about the impact of the combined waterlogging and shading stress on the growth of winter wheat and the underlying mechanisms. Therefore, the aim of this work was to investigate the impacts of shading, waterlogging and combined stress on the photosynthetic ability and yield performance of winter wheat at the booting, flowering and grain-filling stages. The results showed that the photosynthetic ability of winter wheat was significantly influenced after treatment with shading, waterlogging and combined stress, and the impacts became more severe with the prolonged treatment. In terms of yield components, shading and waterlogging had the greatest impact on grain yield, followed by 1000-grain weight and grain number per spike. In conclusion, waterlogging and combined stress had more severe impact on the 1000-grain weight of winter wheat. The flowering and grain-filling stages were the sensitive stages at which winter wheat responded to shading and waterlogging. This study will be of great significance to enhance our understanding of the impact of shading and waterlogging on the growth of winter wheat and find ways to improve stress tolerance of winter wheat to adverse weather condition to further increase grain yield. © 2019 Friends Science Publishers

Keywords: Shading; Waterlogging; Winter wheat; Growth; Grain yield

Introduction

Waterlogging is a common agro-meteorological disaster in cloudy and rainy weather. Heavy rainfall leads to excessive soil water in the root zone that creates anaerobic conditions by overly wet soil for a prolonged period, subsequently affecting the growth of crops and ultimately leading to the yield loss (Ahmed *et al.*, 2013; Wu *et al.*, 2018). The potential damage of waterlogging to winter wheat has been studied by many researchers around the world, including the mechanisms of waterlogging-induced damage, impacts, adaptive responses/ tolerance, zoning, risk-based early warning, simulation of the water distribution in soil, and so on (Li *et al*., 2011; Haque *et al*., 2012; Yavas *et al*., 2012; Yu and Chen, 2013; Wu *et al*., 2014a; Yu *et al*., 2014). Among these, a great deal of attention is still given to determining mechanisms of waterlogging-induced damage in the field. Many studies have shown that waterlogging could induce various morphological and physiological changes in winter wheat (Irfan *et al*., 2010; Hossain *et al*., 2011; Hayashi *et al*., 2013).

Though most of previous studies investigate the damage of waterlogging as sole stress to crop growth, more and more researchers start paying attention to potential synergistic effects of waterlogging with other factors, such as salt stress, high temperature stress, and so on (Zheng *et al*., 2009; Sharma *et al*., 2010). Except these factors, inadequate sunshine duration also potentially affects the growth of winter wheat given that the sunlight is the most important environmental factor affecting the photosynthesis in plants. Shading has been found to affect the grain number of spike (Sabine and Jeuffroy, 2001), the transportation of assimilation materials to grains (Liu *et al*., 2015), the dry matter weight of grains (Sabine and Jeuffroy, 2004), consequently affecting the final biomass and harvest index (Li, 2011). These studies highlight the need to comprehensively investigate possible synergistic impact of the combined waterlogging and shading stress on crops.

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Jiangsu Province is one of major wheat-producing areas in China where a rice-wheat rotation is practiced. Winter wheat is conventionally planted in spring which is usually cloudy and rainy. Spring is a key season for winter wheat to obtain high yield. However, the soil is often over-wetted due to excessive rainfall, which is characterized by high soil moisture, low soil permeability and poor soil drainage. The over-wetted soil easily results in waterlogging stress for winter wheat. If the wheat suffers waterlogging stress in spring, the grain-filling stage might be shortened, consequently leading to low grain-filling rate, reduction in both fresh and dry grain weights, and finally loss of grain yield. It is reported that waterlogging is a common agricultural meteorological disaster in Jiangsu province (Jiang *et al*., 2008). Moreover, a cloudy and rainy weather reduces sunshine duration that also restricts the growth of winter wheat. However, there are few reports on the impact of inadequate sunshine duration on the growth of winter wheat in Jiangsu province. Jin and Shi (2006) found that waterlogging coupled with the sharp decline in sunshine hours had more severe impact on crop growth. With the global warming and an increasing number of extreme climatic events, the inadequate sunshine duration and waterlogging stress due to continuous heavy rainfall in this region have become critical metrological factors restricting grain yield and quality of winter wheat (Jiang *et al*., 2008; Wu *et al*., 2014a).

The common experimental method to simulate waterlogging stress is conducted only by artificially controlling soil moisture, without consideration of the influence of inadequate sunshine duration that can be mimicked by use of the shading screen to cover the crops. However, the separate treatment of either waterlogging or shading stress fails to reflect the real weather condition under which winter wheat grows. Therefore, the aim of the work was to study the impact of combined waterlogging and shading stress on the growth of winter wheat by observing the photosynthetic performance and yield components of winter wheat at three important growth stages (*i.e*., booting, flowering and grain-filling stages). The winter wheat cultivar, Yangmai 13, commonly planted in Jiangsu province was selected in this study. During these three stages, waterlogging and shading stress frequently occurs. This study will enhance our understanding of the impact of the combined shading and waterlogging stress on the growth of winter wheat and provide technical strategy to improve winter wheat tolerance with adverse weather condition in order to increase grain yield of winter wheat and ensure food safety.

Materials and Methods

Experimental Design

The impact of combined waterlogging and shading stress on the growth of winter wheat was studied in a pot experiment conducted at the experimental station of Nanjing University of Information Science and Technology, Nanjing (32°30′N, 118°42′E), Jiangsu, China. The winter wheat cultivar, Yangmai 13, was grown in the fine-texture yellow brown soil with medium fertility.

The plants were grown in plastic pots (18 cm in height and 28 cm in diameter) filled with 3.8 kg of soil with supplementation of 40 g compound fertilizer providing about 38% of total nitrogen (N), phosphorus (P) and potassium (K). The soil and fertilizer were mixed before sowing the seeds. Seeds were sown on November 20, 2015, and at the 3-leaf stage, seedlings were thinned to seven uniform and health plants in each pot. The plants were treated by waterlogging, shading and combined stress at booting, flowering and grain-filling stages, respectively, nine pots per treatment. The treatments were lasted for 9 days and includes: CK (control), S1 (shading stress at the booting stage), W1 (waterlogging stress at the booting stage), SW1 (combined shading and waterlogging stress at the booting stage), S2 (shading stress at the flowering stage), W2 (waterlogging stress at the flowering stage), SW2 (combined shading and waterlogging stress at the flowering stage), S3 (shading stress at the grain-filling stage), W3 (waterlogging stress at the grain-filling stage), SW3 (combined shading and waterlogging stress at the grain-filling stage). The experiment was a completely randomized block design, with three replicates per treatment.

The control groups were maintained under normal conditions without waterlogging and shading stress. For waterlogging treatment, 1–2 cm water layer was maintained above the soil surface. For shading treatment, 2 layers of the shading screens were placed on the top of the plants to shade 65% of the intensity of sunlight, which was measured by a LI-6400 portable photosynthesis system. The shading screens were placed 170 cm above the ground. The treatments were lasted for 9 days. After treatments, the shading screens were removed and the excessive water was drained. All plants were then grown under normal conditions.

Measurement of Photosynthetic Performance

Photosynthetic performance was measured in the flag leaves 2 days, 6 days and 9 days after the initiation of treatment, respectively, using a LI-6400 portable photosynthesis system (LiCor Inc., Lincoln, NE, USA) with the use of the Li-6400-02B Red/Blue LED light source at a photosynthetic active radiation (PAR) of 1100 $\mu mol \cdot m^{-2} \cdot s^{-1}$. The measurements were taken between 9:00 a.m. and 11:00 a.m. Photosynthetic performance indices, including net photosynthetic rate (Pn), transpiration rate (Tr), stomatal conductance (Gs) and intercellular CO_2 concentration (Ci) of flag leaves were measured. For comparison, the photosynthetic performance indices of control groups were referred as CK1, CK2 and CK3 at the booting, flowering and grain-filling stages, respectively.

Grain Yield and Yield Components

At maturity, spikes in each pot were recorded, and three spikes were randomly sampled in each pot to count the grain number per spike. The harvested grains were initially heated for 15 min at 105℃, and then dried at 80℃. Dried grains were weighed to determine grain yield in winter wheat.

Statistical Analysis

All data were statistically analyzed using the SPSS software (SPSS Inc., Chicago, IL, USA). Differences among treatments were assessed by one-way ANOVA with followed by Dunnett's post hoc tests. The difference in $P < 0.05$ was considered statistically significant.

Results

Effects on Net Photosynthetic Rate (Pn)

At booting and flowering stages, the net photosynthetic rate (Pn) of flag leaves of winter wheat under shading (S1, S2), waterlogging (W1, W2), and combined stress (SW1, SW2) decreased significantly compared to control (Fig. 1A and B). The net photosynthetic rates (Pn) showed a decreasing trend with the prolonged treatment (Fig. 1A and B) in particular with 9 d shading (S1, S2), waterlogging (W1, W2) and combined stress (SW1, SW2) decreased significantly than with the short-term (2 d) and mid-term (6 d) stress (Fig. 1A and B).

At the grain-filling stage, the short-term (2 d) and mid-term (6 d) shading (S3) stress had no impact on the net photosynthetic rates (Pn) in winter wheat. However, waterlogging (W3) and combined stress (SW3) significantly decreased the net photosynthetic rates (Pn) (Fig. 1C). The long-term (9 d) shading (S3), waterlogging (W3) and combined stress (SW3) could decrease the net photosynthetic rates (Pn) in winter wheat.

Nonetheless, at flowering and grain-filling stages, shading and waterlogging stress showed a greater impact on the net photosynthetic rates (Pn) in winter wheat.

Effects on Stomatal Conductance (Gs)

Compared to the controls, stomatal conductance (Gs) in winter wheat under shading (S1, S2, S3), waterlogging (W1, W2, W3) and combined stress (SW1, SW2, SW3) decreased significantly at booting, flowering and grain-filling stages (Fig. 2A, B and C). At the booting stage, the stomatal conductance (Gs) increased initially and then decreased in the end of the treatments (S1, W1, SW1) (Fig. 2A). At the flowering stage, the stomatal conductance (Gs) showed a decreasing trend with the prolonger treatments (S2, W2, SW2) (Fig. 2B). Interestingly, at the grain-filling stage, the stomatal conductance (Gs) increased initially and decreased in the end under shading (S3) and combined stress (SW3). On the other hand, the stomatal conductance (Gs) (W3) showed a constantly increasing trend under waterlogging (Fig. 2C). Overall, shading and waterlogging had greater impacts on the stomatal conductance (Gs) in winter wheat at flowering and grain-filling stages.

Effects on Intercellular CO_2 Concentration (Ci)

The intercellular CO_2 concentrations (Ci) in winter wheat under shading (S1, S2, S3), waterlogging (W1, W2, W3) and combined stress (SW1, SW2, SW3) decreased significantly compared to control at booting, flowering and grain-filling stages (Fig. 3A, B and C). There was no difference of the intercellular CO_2 concentrations (Ci) among treatments with shading (S1, S3), waterlogging (W1, W3) and combined stress (SW1, SW3) at booting and grain-filling stages (Fig. 3A and C), however, significant difference was found among treatments with shading (S2), waterlogging (W2) and combined stress (SW2) at the flowering stage (Fig. 3B), indicating its more sensitive to shading and waterlogging at the flowering stage.

Effects on Transpiration Rate (Tr)

The transpiration rate (Tr) in winter wheat under shading (S1, S2, S3), waterlogging (W1, W2, W3) and combined stress (SW1, SW2, SW3) decreased significantly compared to control at booting, flowering and grain-filling stages (Fig. 4A, B and C). At the booting stage, with the prolonged treatment, the transpiration rate (Tr) increased initially and then decreased in the end of the treatments (S1, W1, SW1) (Fig. 4A). At flowering and grain-filling stages, the transpiration rate (Tr) showed a continuously decreasing trend with the prolonger treatments (S2, S3, W2, W3, SW2, SW3) (Fig. 4B and C).

Effects on Yield Components

Though shading (S1) and waterlogging (W1) imposed at the booting stage did not affect the grain number per spike in winter wheat compared to control, combined stress (SW1) significantly reduced the grain number per spike (Table 1). All stresses (S2, W2, SW2, S3, W3, SW3) imposed at flowering and booting stages significantly reduced the grain number per spike compared to the controls (Table 1). No difference in the grain per spike was found among stresses (S2, W2, SW2) at the flowering stage. Waterlogging (W3) imposed at the grain-filling stage reduced the grain number per spike most significantly relative to shading (S3) and combined stress (SW3).

The shading and waterlogging did not affect 1000-grain weight of winter wheat at the booting stage compared to the controls. Except shading stress (S2) imposed at the

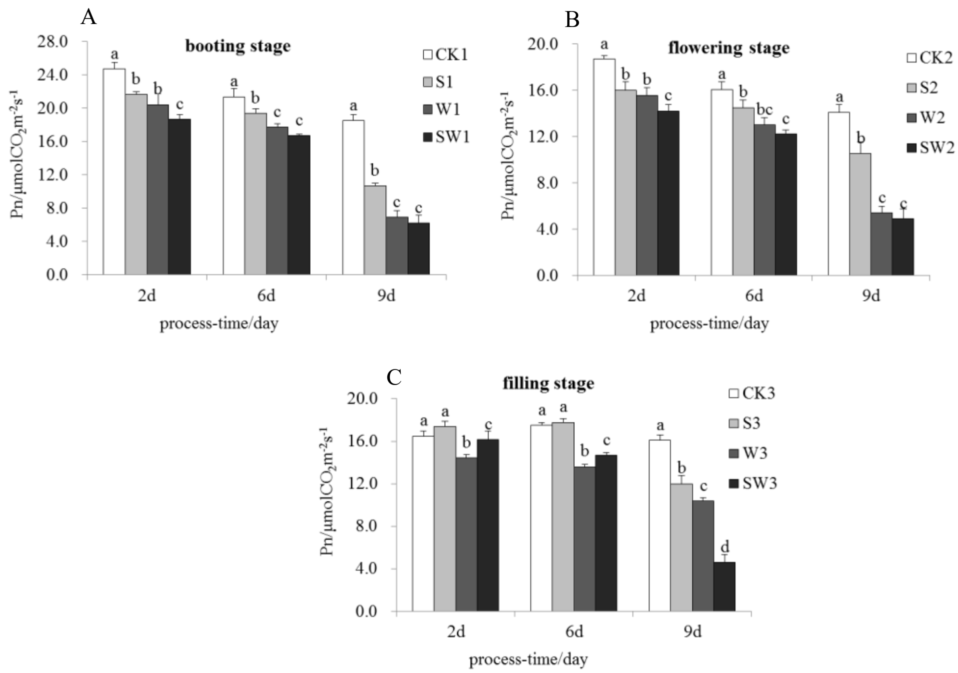

Fig. 1: Effects of shading and waterlogging stress on net photosynthetic rate (Pn) in winter wheat at different stages. CK, control; S, shading stress; W, waterlogging stress; SW, combined shading and waterlogging stress. Data are presented as mean ± SD (n=3). Different lowercase letters indicate significant difference at $P < 0.05$

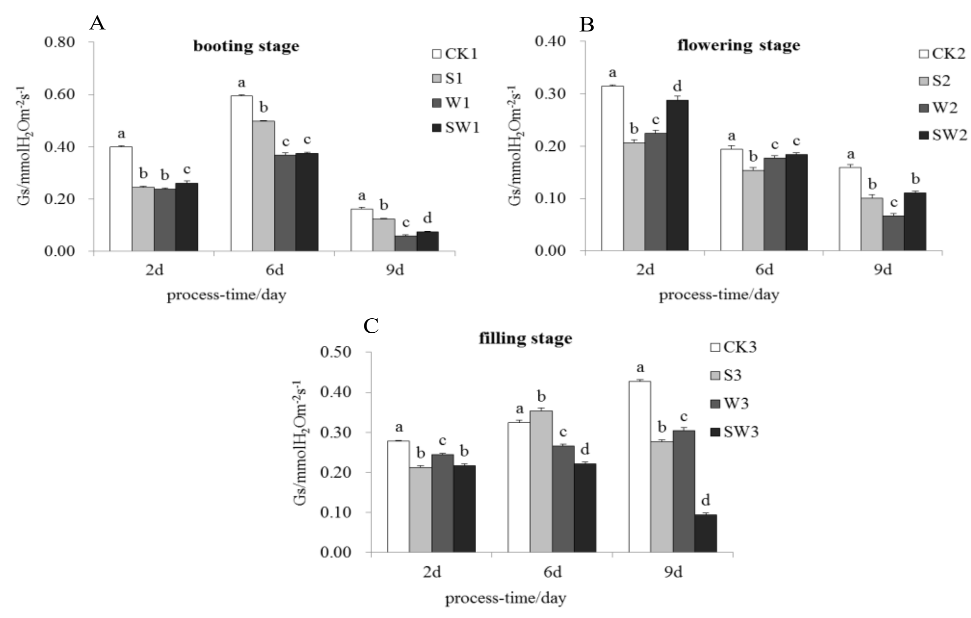

Fig. 2: Effects of shading and waterlogging stress on stomatal conductance (Gs) in winter wheat at different stages. CK, control; S, shading stress; W, waterlogging stress; SW, combined shading and waterlogging stress. Data are presented as mean ± SD (n=3). Different lowercase letters indicate significant difference at $P < 0.05$

flowering stage, other treatments (W2, SW2, S3, W3, SW3) imposed at flowering and grain-filling stages significantly reduced the 1000-grain weight compared to the controls (Table 1). Waterlogging (W2) imposed at the flowering stage had most severe impact on the 1000-grain weight of winter wheat.

As for grain yield, all treatments including shading, waterlogging and combined stress significantly decreased grain yield compared to controls (Table 1). At the booting stage, there was no difference in the grain yield among

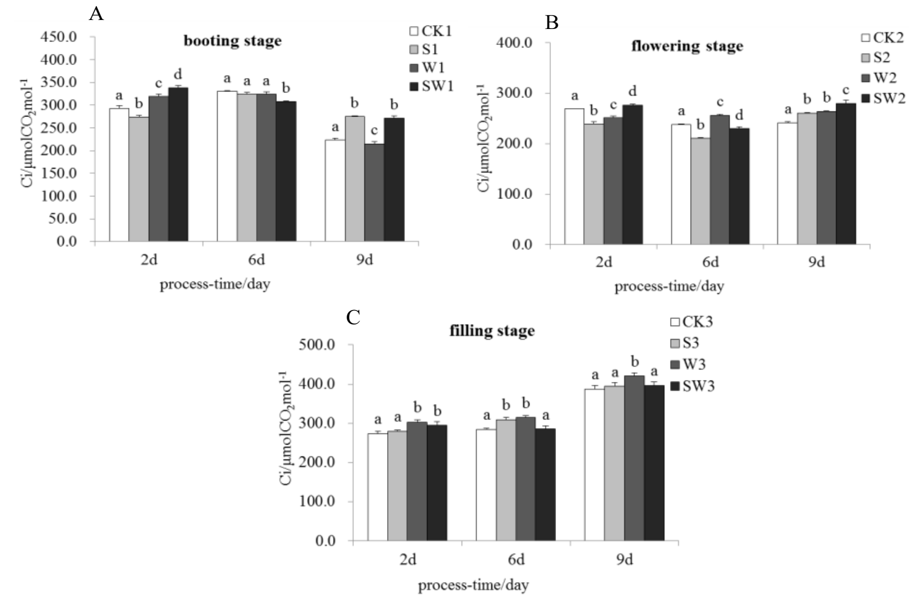

Fig. 3: Effects of shading and waterlogging stress on intercellular CO_2 concentration (Ci) in winter wheat at different stages. CK, control; S, shading stress; W, waterlogging stress; SW, combined shading and waterlogging stress. Data are presented as mean ± SD (n=3). Different lowercase letters indicate significant difference at $P < 0.05$

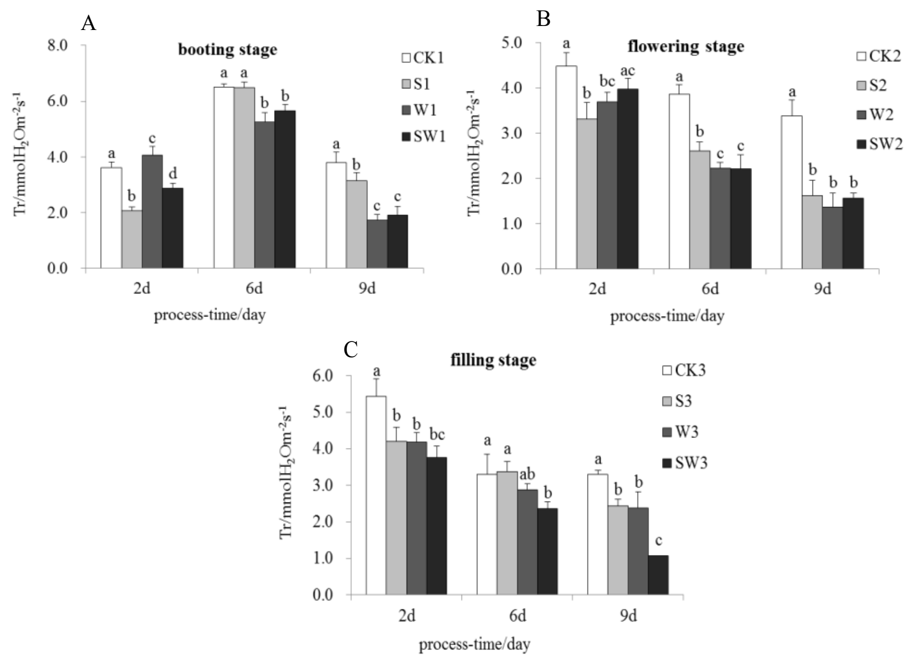

Fig. 4: Effects of shading and waterlogging on transpiration rate (Tr) in winter wheat at different stages. CK, control; S, shading stress; W, waterlogging stress; SW, combined shading and waterlogging stress. Data are presented as mean ± SD (n=3). Different lowercase letters indicate significant difference at $P < 0.05$

treatments (S1, W1 and SW1). At the flowering stage, waterlogging (W2) caused the most significant reduction in grain yield relative to shading (S2) and combined stress (SW2). At the grain-filling stage, the combined stress (SW3) caused the most significant reduction in grain yield relative to shading (S3) and waterlogging stress (W3).

Discussion

Waterlogging and insufficient sunshine duration during the crop-growing season are the most common agro-meteorological disasters in China and elsewhere in the world. Exposure of winter wheat to shading and

Table 1: Effects of shading and waterlogging stress on grain yield and yield components in winter wheat at different stages

Stages	Treatment	Grain number per spike	1000-grain weight (g)	Grain yield (g)
	CK	51.0 ± 1.00a	44.2 ± 0.70a	49.9 ± 0.81a
Booting	S1	50.0 ± 1.00a	43.1 ± 0.30a	44.4 ± 0.95b
	W1	51.3 ± 0.58a	43.1 ± 0.52a	44.5 ± 0.96b
	SW1	49.0 ± 1.00b	43.0 ± 0.95a	44.2 ± 0.77b
Flowering	S2	45.7 ± 0.58c	42.5 ± 1.12ab	43.0 ± 0.35bc
	W2	45.3 ± 1.15c	31.8 ± 1.20f	35.4 ± 0.96f
	SW2	45.0 ± 1.00c	41.2 ± 0.86bc	41.8 ± 0.30cd
Grain-filling	S3	46.0 ± 1.00c	38.6 ± 1.34d	40.6 ± 1.25d
	W3	43.3 ± 0.58d	40.6 ± 0.44c	41.1 ± 1.20d
	SW3	46.3 ± 0.58c	35.7 ± 1.20e	38.3 ± 1.15e

CK, control; S, shading stress; W, waterlogging stress; SW, combined shading and waterlogging stress; the numbers of 1, 2 and 3 represent the booting, flowering and grain-filling stage, respectively. Data are presented as mean ± SD (n=3). Different lowercase letters in each column indicate significant difference at $P < 0.05$

waterlogging significantly reduces its photosynthetic ability (Dickin and Wright, 2008; Zheng *et al*., 2009; Wang *et al*., 2013). The impact of these stresses on crops can be measured by various photosynthesis-related indicators, such as the photosynthetic rates (Pn), the stomatal conductance (Gs), the intercellular CO_2 concentration (Ci), the transpiration rate (Tr), and so on. In general, winter wheat would initiate some corresponding adaptive mechanisms in response to shading and waterlogging. In this study, winter wheat was exposed with 9-day shading and waterlogging at booting, flowering and grain-filling stages, respectively. It was found that, after the short-term (2 d) and mid-term (6 d) exposure to treatments, the stomatal conductance (Gs) and intercellular CO_2 concentration (Ci) were increased to improve the photosynthetic rates (Pn) and adjusted the transpiration rate (Tr) in order to enhance water use efficiency. With the prolonged exposure to treatments (9 d), the impacts of shading, waterlogging and combined stress on winter wheat became more severe, the stomatal conductance (Gs), intercellular CO_2 concentration (Ci) and the transpiration rate (Tr) showed the decreasing trend. It was also found that the changes of these indicators changed with the prolonged treatment. Similarly, Wu *et al.* (2012) reported that waterlogging reduced the photosynthetic performance of wheat flag leaves, and intercellular CO_2 concentration (Ci) and stomatal conductance (Gs) showed increasing trend.

On the other hand, the adaptive action seems to have limited ability for crops to tolerate waterlogging or other meteorological disasters over the prolonged treatment. Wang *et al.* (2012) reported that shading and waterlogging still decreased the photosynthetic rates (Pn) of winter wheat at booting, flowering and grain-filling stages although adaptive mechanisms was initiated to tolerate these stresses by maintaining photosynthesis in the early period of treatment. In present study, shading and waterlogging continuously decreased the photosynthetic rates (Pn) of winter wheat with the prolonged treatment.

Shading and waterlogging had the most severe impact on grain yield, followed by 1000-grain weight and grain number per spike. The grain yield is the comprehensive indictor of the grain number per spike and 1000-grain weight. Shading and waterlogging imposed at the booting stage had no impact on the grain number per spike and 1000-grain weight, however, these stresses reduced grain yield of winter wheat compared to the controls, suggesting that reduced grain yield by shading and waterlogging is a synergistic effect of grain number per spike and 1000-grain yield (Li *et al*., 2001; Sabine and Jeuffroy, 2004; Mu *et al*., 2010; Wu *et al*., 2014b).

Taken together, the results suggest that the impact of shading, waterlogging and combined stress highly depends on the growth stage. Winter wheat shows more sensitivity to waterlogging at the flowering stage, while more sensitivity to combined stress at the grain-filling stage. Some studies found that waterlogging at the vegetative stage had a greater impact on the growth of crops than at the productive stage (Setter and Waters, 2003; de San Celedonio *et al*., 2014). In contrast, other studies found that the impact of 35-day waterlogging at tillering and jointing stages on grain yield in winter wheat was greater than at booting and grain-filling stages, and waterlogging at the grain filling stage had least effect on wheat yield (Wu *et al*., 2015). Given that the duration of waterlogging is an important factor affecting the growth of winter wheat, the difference among the studies might be related to the varying duration of waterlogging.

Conclusion

In conclusion, shading had the least impact on the growth of winter wheat, waterlogging and combined stress had much greater impact on winter wheat with no difference between two of them. Moreover, under the same stress, winter wheat at the flowering and grain-filling stages were influenced most severely, especially the final grain yield. Therefore, the flowering and grain-filling stages were considered to be the most sensitive growth stages to shading and waterlogging.

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