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Abstract. Waterlogging and shading result from continuous rain are the main meteorological disasters for wheat (*Triticum aestivum* L.) production. In order to evaluate the effects of waterlogging and shading on yield components of winter wheat (both independent and combined), pot experiments were conducted using two representative cultivars in local, Ningmai 13 and Yangmai 13. In total, 4 treatments, including CK (control), WA (waterlogging alone), SA (shading alone) and WS (both waterlogging and shading) were established with three duration (5, 10 and 15 d, respectively) at jointing and grain-filling stages. Results showed that, in the case of non-stressed environment, Yangmai 13 got a better production compared with Ningmai 13 (grain yield per plant was 14.25 g and 15.97 g for Ningmai 13 and Yangmai 13, respectively). However, compared with Yangmai 13, Ningmai 13 got a better yield under stresses at jointing stage, while a similar yield was observed when stresses are at grain-filling stage. By comparing wheat yield and its components, the negative effects of the stresses showed a tendency that WA> WS> SA at jointing stage, whereas WS> WA> SA at grain-filling stage. The result demonstrated that shading had a compensative effect on waterlogging at jointing stage while an addictive effect at grain-filling stage. Reduction of wheat production caused by continuous rain depended on the growth stages. Effect of growth stage on grain yield should be considered when waterlogging and shading packages of wheat growth model were established.

Keywords: winter wheat, waterlogging, shading, yield components

1 Introduction

The winter wheat production in Jiangsu Province covers an area of 2.13 M ha, accounting for approximate 9% of the overall winter wheat area of China in 2012 [1]. However, most winter wheat in Jiangsu is planted in paddy fields in a rice–wheat rotation [2], which results in poor drainage conditions. Furthermore, continuous rain is frequent during the growth season of winter wheat due to the subtropical monsoon climate [3, 4]. The total rainfall is 500–800 mm during the wheat growth season, which far exceeds requirements for winter wheat production [5]. In addition, frequency of extreme weather events is increasing globally and regionally [4]. Therefore, soils are easily waterlogged in Jiangsu and waterlogging has become a prime limitation for wheat production locally.

Previous experimental results on plants have shown that waterlogging stress restricts root growth, decreases root hydraulic conductance [6], results in leaf senescence [7], shortens the grain filling time [8] and reduces final wheat yield [9, 10]. The influence of waterlogging on yield components of wheat has been studied by many researchers. Grain yield under waterlogging treatments was 10–15% lower than that under non-waterlogging treatments [6]. Plot experiment showed that waterlogging from anthesis to maturity would accelerate the senescence of flag leaves, leading to a reduction of grain-filling rate and grain weight [11]. Results of a pot experiment indicated that waterlogging reduced the accumulation of starch in the grains, and the allocation of carbon assimilates to grain yield [7]. However, damage from waterlogging depends on the growth stage, waterlogging duration and wheat cultivar [12, 13]. Thus, different growth stages should be considered when establishing experiment.

Shading always accompanies waterlogging during continuous rain events. Similarly to waterlogging, shading could also reduce dry matter accumulation and grain yield [14, 15] by reducing radiation, impairing net photosynthesis in leaves [16] and reducing the LAI (leaf area index) [17]. However, diffuse light increase under shading can compensate for the reduced radiation [18]. The decrease of LAI is compensated by increases of the bottom leaf area, and the reduction in photosynthetic rate (Pn) of flag leaf is compensated by the increase in Pn of the third leaf [17]. Furthermore, shading increases transport of dry matter from organs to grain [19]. Thus, the shading effect depends on the cultivar and the shading level applied [19].

Although the physiology of wheat under waterlogging and shading stress has been studied independently, research on the combined stress is still scant, especially in consideration of different stress durations and different growth stages. Hence, the objective of the present study was to study the independent effects of waterlogging, shading as well as their combined effect on the yield components of winter wheat at jointing and grain-filling stages. The results will advance our understanding of winter wheat yield under continuous rain events and could be used to improve wheat yield evaluation models by calibrating the combined effect of waterlogging and shading.

2 Experiments and Methods

2.1 Experimental design

The experiment was established during the winter wheat growing season of 2013–2014 at the Experimental Station of Jiangsu Academy of Agricultural Sciences, Nanjing (32°2′N, 118°52′28″E), China. Two representative local wheat cultivars, Ningmai 13 and Yangmai 13, were grown in plastic pots with height at 20 cm and diameter at 25 cm. Each pot was filled with 12 kg of air-dried soil, and seven small holes (1 cm in diameter) were drilled to drain excess water. The soil contained 13.7 g/kg organic carbon, 54.95 mg/kg available nitrogen, 24.25 mg/kg Olsen-phosphorus and 105.03 mg/kg available potassium. Soils of each pot was pre-mixed with 0.7 g of N, 0.3 g of P_2O_5 and 0.7 g of K_2O, and another 0.4 g of N was applied at jointing stage to each pot. 12 seeds were sown to each pot on 5 November 2013, and then limited to four plants at the 3-leaf stage.

Four treatments were established: CK (control, non-stressed plants), WA (waterlogging alone), SA (shading alone) and WS (combined waterlogging and shading). The WA treatment was achieved by reserving a 1 cm water layer above soil surface (pots were placed in an artificial pool and the depth of water layer adjusted manually). For the SA treatment, a black polyethylene screen was fitted about 180 cm above the ground to block about 80% of the total radiation. The WS treatment was achieved by combining both waterlogging and shading treatments. All treatments started when jointing and grain-filling stage was reached (5 March and 18 April 2014, respectively), and there were three durations (5, 10 and 15 d respectively) for each treatment. At the end of each treatment, excess water was drained and the black polyethylene screen removed.

Two pots of each treatment and duration for both cultivars were retained until maturity (20 May 2014) for measurement of yield components. Generally, spike number per plant (SN), grain number per spike (GN), 1000-kernel weight (TKW) and grain yield per plant (GY) were recorded.

2.2 Statistics Analysis

Significant differences between the treatments was determined by one-way analysis of variance. $P<0.05$ was used as the standard for significance by least significant difference (LSD). Statistical analysis was performed using the SPSS 16.0.

3 Results

3.1 Effects of waterlogging and shading on wheat grain yield at jointing stage

All three treatments had a limited effect on SN at jointing stage. Significant difference was seldom shown between treatments, cultivars and treatment durations (Fig. 1).

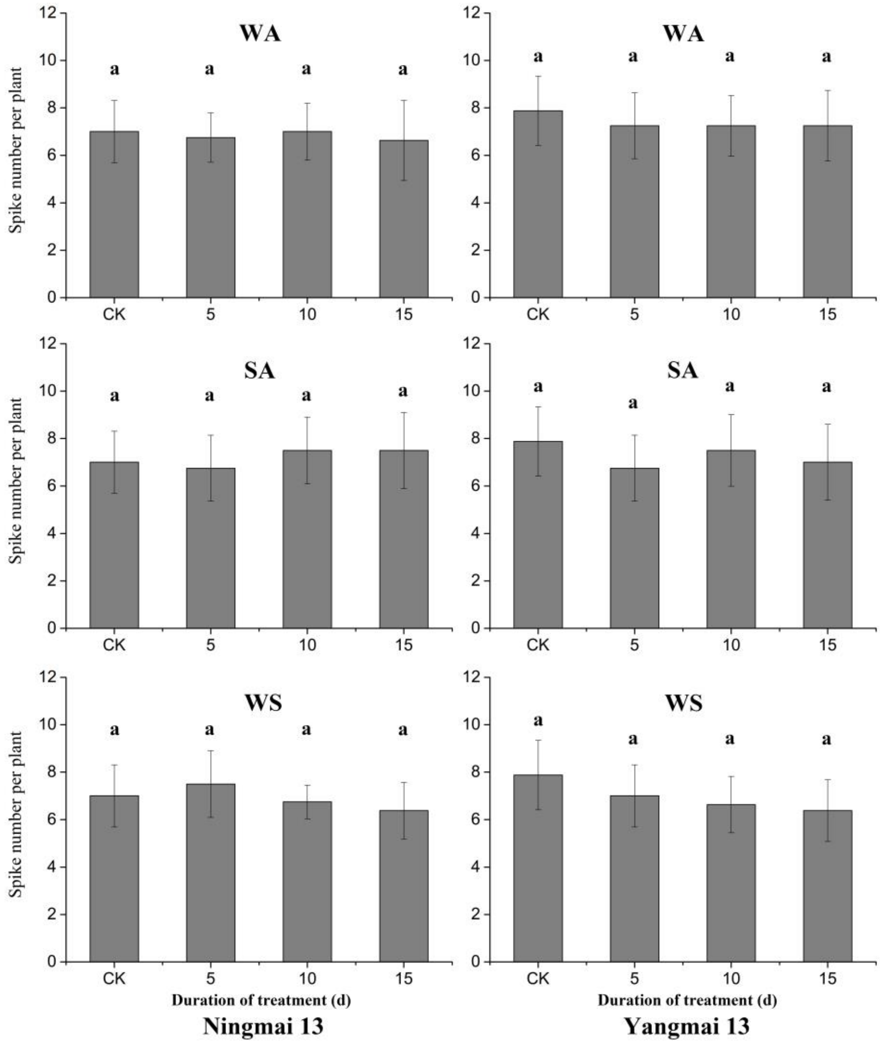

Fig. 1. Effects of different treatments (CK, WA, SA and WS) on spike number per plant at jointing stage

Different letters represent Significant differences at $P<0.05$. Error bars represent the standard deviation.

GN and TKW showed no significant differences for both cultivars under SA (Fig. 2, Fig. 3). There was a significant reduction of GN for both cultivars under WA (Fig. 2).

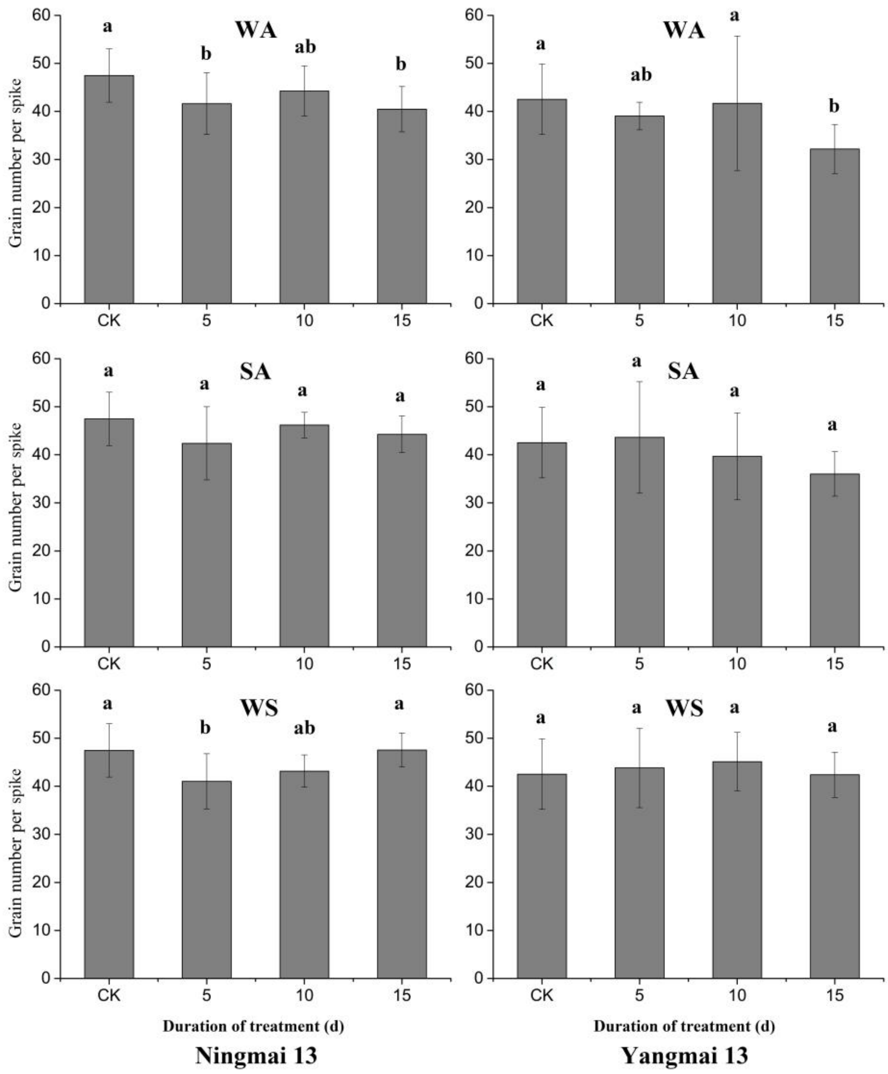

Fig. 2. Effects of different treatments (CK, WA, SA and WS) on grain number per spike at jointing stage

Different letters represent significant differences at $P<0.05$. Error bars represent the standard deviation.

Ningmai 13 showed good tolerance to WA and WS with no significant decreases of TKW. However, TKW of Yangmai 13 significantly decreased under both WA and WS (Fig. 3).

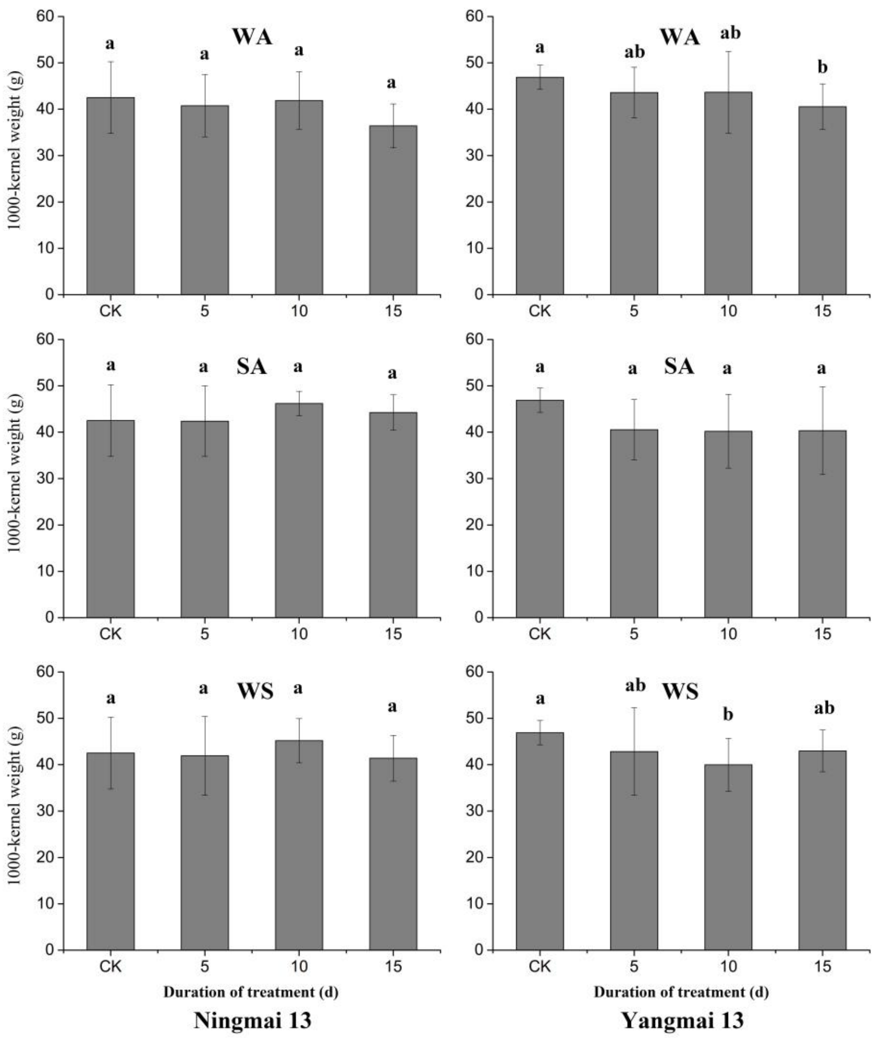

Fig. 3. Effects of different treatments (CK, WA, SA and WS) on 1000-kernel weight at jointing stage

Different letters represent significant differences at $P<0.05$. Error bars represent the standard deviation.

With increased duration of WA treatment, GY of both cultivars decreased (Fig. 4). After 15 d of waterlogging, GY significantly decreased (14.25 to 9.57 g and 15.97 to 9.40 g for Ningmai 13 and Yangmai 13, respectively; $P<0.05$). The effects of SA and WS on GY depended on the cultivar. GY of Ningmai 13 under SA and WS decreased non-significantly compared with CK. However, there were greater decreases in GY for Yangmai 13 under SA and WS, and decreases were significant when duration reached 10 d. Under all stresses, GY was significantly reduced for Yangmai 13 and was lower than for Ningmai 13 (Fig. 4). Thus, Ningmai 13 had better tolerance to stresses than Yangmai 13 at jointing stage.

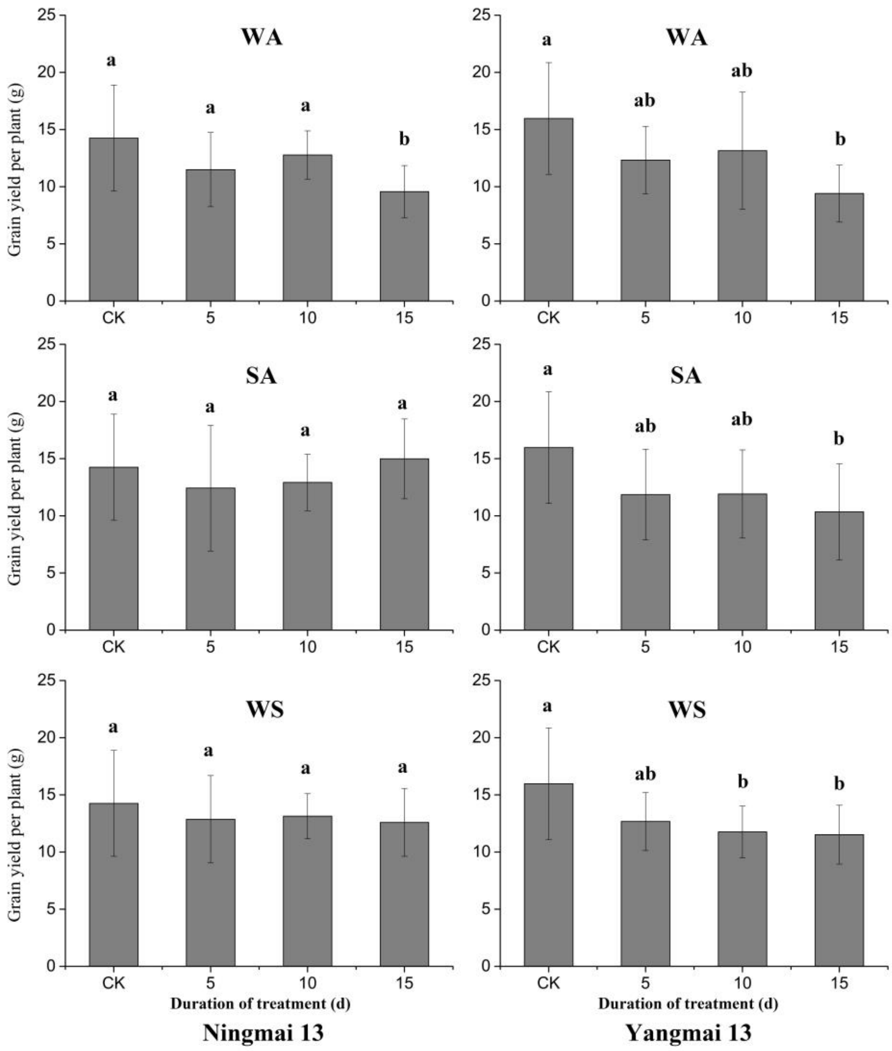

Fig. 4. Effects of different treatments (CK, WA, SA and WS) on grain yield per plant at jointing stage

Different letters represent significant differences at $P<0.05$. Error bars represent the standard deviation.

Wheat yields under different treatments showed an order of CK > SA > WS > WA at jointing stage. Ningmai 13 had a significant yield reduction only under WA, mainly due to the reduction of GN. Yangmai 13 had significant yield reductions under all three treatments but for different reasons: yield reduction was caused by decrease of GN and TKW under WA; by decrease in GN under SA; and by decrease in TKW under WS.

2.2 Effects of waterlogging and shading on wheat grain yield at grain-filling stage

All three treatments at grain-filling stage showed non-significant effects on SN (Fig. 5), which is similar to that at jointing stage (Fig. 1). The reason is mainly due to that SN had been determined before jointing and grain-filling stages. Therefore, waterlogging and shading have a limited effect on SN.

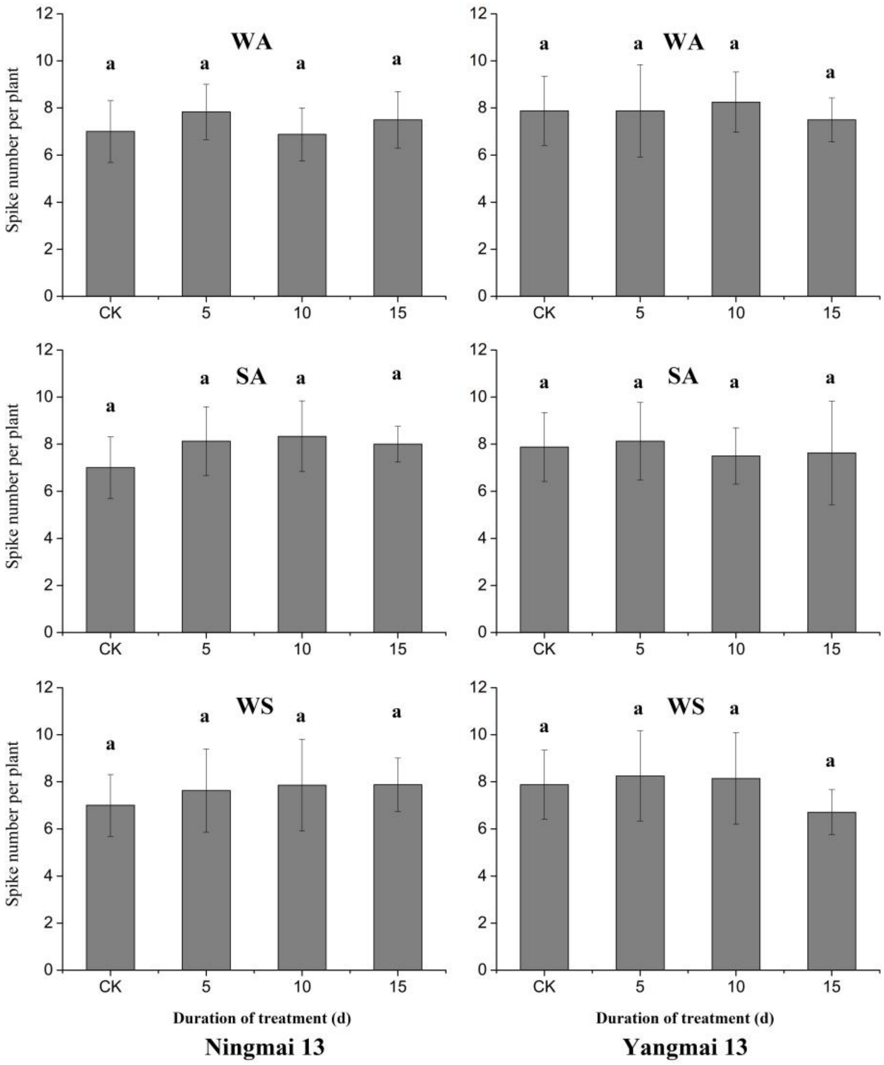

Fig. 5. Effects of different treatments (CK, WA, SA and WS) on spike number per plant at grain-filling stage

Different letters represent significant differences at $P<0.05$. Error bars represent the standard deviation.

Waterlogging and shading showed a weak effect on GN at grain-filling stage. Significant but limited reductions of GN were observed only for Ningmai 13 under WA and SA (Fig. 6).

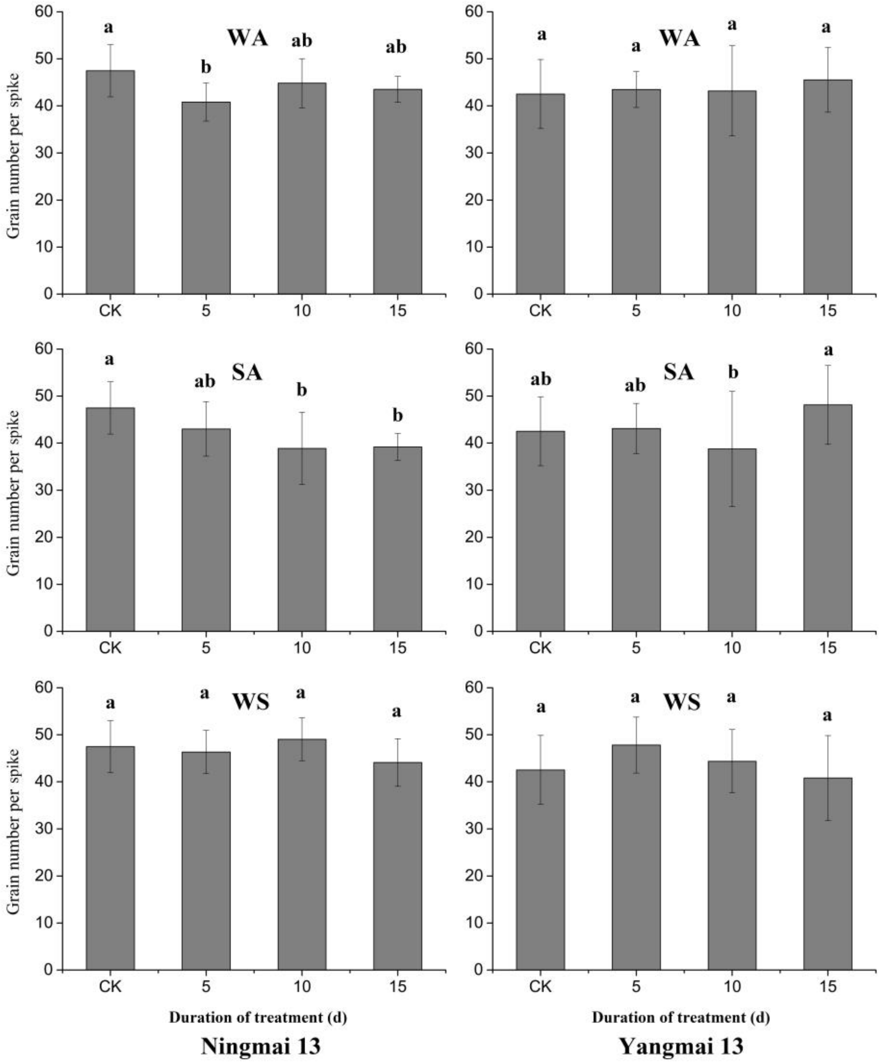

Fig. 6. Effects of different treatments (CK, WA, SA and WS) on grain number per spike at grain-filing stage

Different letters represent significant differences at $P<0.05$. Error bars represent the standard deviation.

All three treatments caused reduction on TKW compared with CK at grain-filling stage. And significant reduction was shown after 15 d of stresses (Fig. 7). Moreover, TKW under different treatments showed an order of SA> WA > WS. The results indicated that WA caused a more severe damage to grain-filling compared with SA, while shading caused an addictive damage when accompanied with waterlogging at grain-filling stage.

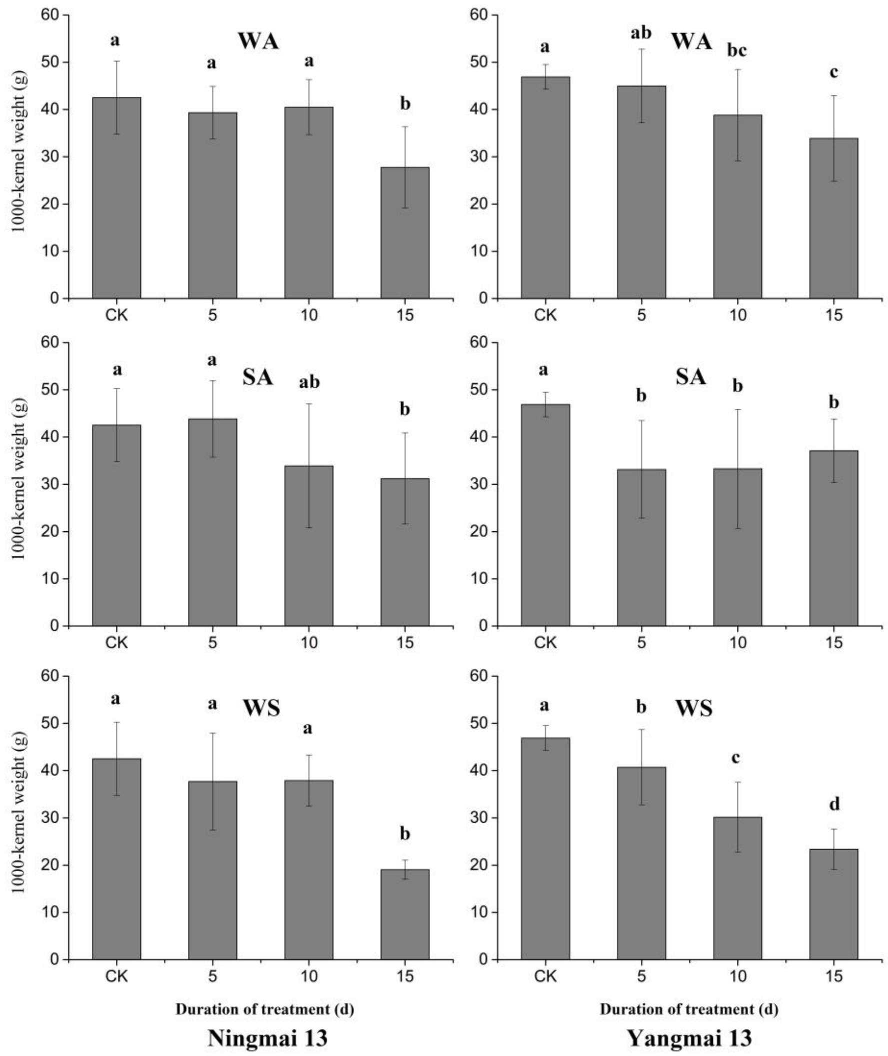

Fig. 7. Effects of different treatments (CK, WA, SA and WS) on 1000-kernel weight at grain-filing stage

Different letters represent significant differences at $P<0.05$. Error bars represent the standard deviation.

GY of both cultivars showed a reduction when suffering waterlogging at grain-filling stage. After 15 d of WA, GY significantly decreased compared with CK (14.25 to 9.2 g and 15.97 to 11.48 g for Ningmai 13 and Yangmai 13, respectively; $P<0.05$). WS showed a similar reduction of GY compared with WA when the stress duration is shorter than 10 d, but a larger reduction when duration reached 15 d (Fig. 8).

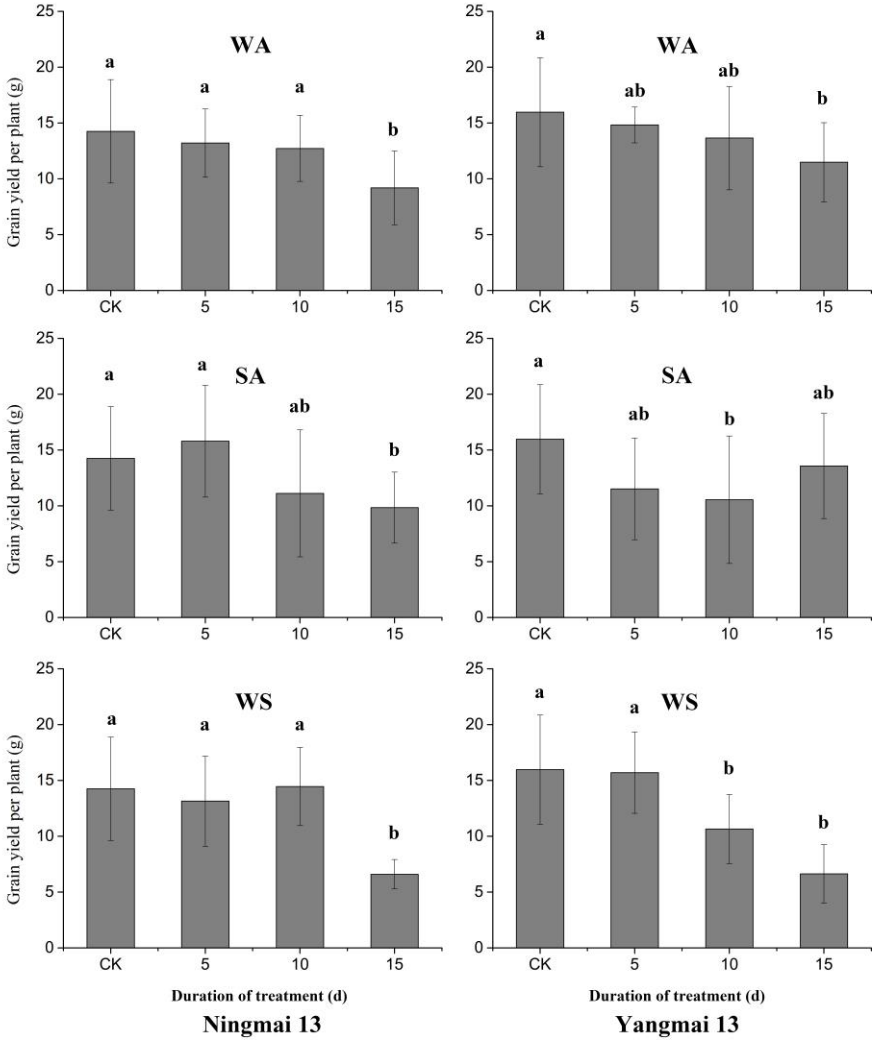

Fig. 8. Effects of different treatments (CK, WA, SA and WS) on grain yield per plant at grain-filing stage

Different letters represent significant differences at $P<0.05$. Error bars represent the standard deviation.

Wheat yields under different treatments showed an order of CK > SA > WA > WS at grain-filling stage, which was different from the order at jointing stage. Three treatments all caused significant yield reduction for both cultivars when durations were over 10 d. The yield reduction was mainly due to the reduction of TKW.

4 Discussion

Waterlogging caused severe yield reduction at both jointing and grain-filling stages and the reduction amplified with increased duration. After 15 d waterlogging treatment, yield of Ningmai 13 and Yangmai 13 was significantly reduced by 28-41% compared to CK at two growth stages ($P<0.05$), which is similar to former studies [20]. However, the yield reduction was due to different reasons at both stages. Waterlogging caused yield reduction mainly results from the reduction of GN at jointing stage, indicating that waterlogging at jointing stage would influence the booting stage. At grain-filling stage, SN and GN have been determined. Thus, yield reduction was mainly results from the reduction of TKW. After 15 d WA treatment at grain-filling stage, TKW of Ningmai 13 and Yangmai 13 were 27.76 and 33.88 g respectively, which is lower than CK (42.51 and 46.89 g) and the same treatment at jointing stage (36.39 and 40.57 g). The result indicated that grain-filling process was severely impaired when suffering waterlogging stress at grain-filling stage.

Due to the increases in aerosols and air pollutants, the reduction rate of solar radiation is approximate 2.6% per 10 years [17]. Shading becomes a constraint of winter wheat production in the

Yangtze River Basin [21]. Results of the present study also showed that shading would cause yield reduction of winter wheat. Shading at grain-filling stage induced a greater reduction than at jointing stage. The difference is mainly due to the duration of recovery. After removal of stresses at jointing stage, there was a recovery for more than 60 d until harvest. But at grain-filling stage, the recovery duration was less than 30 d. The shorter recovery duration resulted in the significant reduction of TKW under SA treatment at grain-filling stage, thus the yield reduction was greater than that at jointing stage.

Compared with independent waterlogging and shading stresses, the combined stress (WS) is a more realistic situation in a continuous rain event. Results of combined stress treatment showed that WS at different growth stages induced different effects on wheat yield. WS had a less negative effect compared with WA at jointing stage, whereas a greater negative effect at grain-filling stage. The result indicated a compensative effect of shading on waterlogging at jointing stage, but an additive effect at grain-filling stage. The difference was mainly due to the process of recovery. Recent studies indicate that mechanisms of plant resistance to waterlogging and subsequent recovery are highly different [22]. The compensative effect from shading might be for both morphological and biochemical reasons [17]. Therefore, shading at jointing stage showed a limited effect on wheat yield and had a compensative effect under WS. However, compensative effect of shading was impeded due to natural leaf senescence at grain-filling stage. Thus a different effect from shading was shown at different stages.

5 Conclusions

Independent and combined stresses of waterlogging and shading all caused the yield reduction of winter wheat, and stresses at different stages have different impacts. WS caused a less severe reduction than WA at jointing stage whereas a more severe reduction at grain-filling stage. The results indicated that shading had a compensative effect on waterlogging at jointing stage, but an addictive effect at grain-filling stage. The different effect is mainly due to recovery process of winter wheat after removal of stresses. However, most present wheat growth models are based on the experiment of waterlogging alone, without considering the effect of shading during continuous rain events. Thus, the present study advances the understanding on the physiology of winter wheat under combined stress of waterlogging and shading. Winter wheat growth models could be improved to avoid overestimating or underestimating production losses due to continuous rain.

Acknowledgment

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