Effects of Heat Stress on Grain Filling Rate in Different Wheat Varieties (Postprint)

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Abstract

To provide a basis for breeding new wheat varieties with high and stable yield and heat tolerance, a study was conducted on the yield, thousand-grain weight, and grain-filling process of 12 commercial wheat varieties from the Northern Winter Wheat Region and the Huang-Huai Winter Wheat Region under normal and heat stress conditions. The experiment was carried out during the 2014–2015 growing season at the Xinji Malan Farm in Hebei Province, using greenhouse warming as the heat stress treatment. Grain-filling rates of different varieties under normal and heat stress treatments were measured during the wheat grain-filling period, and after harvest, yield and thousand-grain weight were determined, and heat susceptibility index was calculated. The results showed that 'Zhongmai 175' , 'Heng 4399' , 'Heng 4444' , 'CA0816' , and 'Zhongmai 875' exhibited high yields under both natural growth and heat stress conditions. Heat stress occurring during the rapid grain-filling stage and slow grain-filling stage in the middle-to-late grain-filling period significantly affected wheat thousand-grain weight and yield by influencing the grain-filling rate. Based on the thousand-grain weight heat susceptibility index, the heat tolerance of different wheat varieties was evaluated, and it was found that 'Jingdong 8' , 'CA0816' , 'CA1062' , 'Zhongmai 875' , 'Zhongmai 895' , and 'Heng 4444' had a thousand-grain weight heat susceptibility index < 1, indicating they were heat-tolerant varieties; other varieties had a thousand-grain weight heat susceptibility index ≥ 1, classifying them as heat-sensitive varieties. Analysis of grain-filling rates under normal and heat stress conditions for different varieties revealed that the onset time of heat stress effects on grain-filling rate differed among varieties with different heat tolerance levels: grain-filling rates of heat-tolerant varieties were only affected by heat stress during the late grain-filling stage, whereas heat-sensitive varieties were affected by heat stress during the middle grain-filling stage. In summary, 'CA0816' , 'Zhongmai 875' , and 'Heng 4444' were varieties with both good yield performance and

heat tolerance; 'Heng 4399' and 'Zhongmai 175' had moderate thousand-grain weight heat susceptibility indices but exhibited high yields under both natural growth and heat stress conditions; 'Jingdong 8' showed good heat tolerance but slightly lower yield performance. All the above varieties can be utilized as excellent heat-tolerant resources in breeding programs, and in breeding practice, it is necessary to jointly use yield data and thousand-grain weight heat susceptibility index to evaluate a variety' s value in heat tolerance breeding.

Full Text

Preamble

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Effects of Heat Stress on Grain-Filling Rate of Different Wheat Varieties

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Abstract

To provide a basis for achieving high and stable wheat yields and breeding heat-tolerant varieties, we investigated the yield, 1000-kernel weight, and grain-filling processes of 12 commercial wheat varieties from the North China Winter Wheat Belt and Huanghuai Winter Wheat Region under both normal and heat-stressed conditions. The experiment was conducted during the 2014–2015 growing season at Malan Farm in Xinji, Hebei Province. Greenhouse heating was used as the heat stress treatment during the grain-filling period. Grain-filling rates were measured for different varieties under normal and heated conditions, while yield and 1000-kernel weight were determined after harvest to calculate thermal sensitivity indices. The results showed that 'Zhongmai 175' , 'Heng 4399' , 'Heng 4444' , 'CA0816' , and 'Zhongmai 875' maintained relatively high yields under both natural and heat-stressed conditions. Heat stress occurring during the rapid and slow grain-filling stages (mid-to-late grain filling) significantly affected 1000-kernel weight and yield by reducing grain-filling rate. Evaluation of heat tolerance using the 1000-kernel weight thermal sensitivity index revealed that 'Jingdong 8' , 'CA0816' , 'CA1062' , 'Zhongmai 875' , 'Zhongmai 895' , and 'Heng 4444' had indices less than 1, indicating good heat tolerance, while other varieties with indices $ $1 were heat-sensitive. Analysis of grain-filling rates under normal and heat-stressed conditions showed that the timing of heat stress impact differed among varieties: heat-tolerant varieties were affected only during late grain filling, whereas heat-sensitive varieties showed effects during mid-grain filling. In conclusion, 'CA0816' , 'Zhongmai 875' , and 'Heng 4444' exhibited both high productivity and heat tolerance; 'Heng 4399' and 'Zhongmai 175' showed moderate thermal sensitivity indices but high yields under both conditions; and 'Jingdong 8' demonstrated excellent heat tolerance though slightly lower productivity. These varieties can serve as valuable heat-tolerant resources in breeding programs, where both yield data and 1000-kernel weight thermal sensitivity indices should be used jointly to evaluate breeding value.

Keywords: wheat; heat stress; grain-filling rate; thermal sensitivity index; heat tolerance; high and stable yield
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Results and Analysis

2.1 Temperature Conditions Under Different Heat Stress Treatments

The heading dates of the different varieties fell on April 23 and 24, 2015. On April 24, we tagged 150 main stems per variety that had reached uniform anthesis. Subsequently, 20 spikes per variety were sampled every 6 days until maturity, after which plot yield and 1000-kernel weight were measured. Grain dry weight was determined by threshing and weighing kernels, with grain-filling rate calculated as kernel weight divided by filling days.

Previous studies indicated that applying greenhouse heat stress too early could affect spikelet flowering and seed set. Therefore, heating treatment was initiated 15 days after anthesis. [Figure 1: see original paper] shows daily maximum temperatures and daily duration of temperatures >30°C under both natural and heat-stressed conditions. During 15–30 days post-anthesis, temperature differences between treatments were mostly within 5°C, with heat stress maintaining temperatures above 30°C for less than 5 hours daily and peak temperatures reaching 32–33°C. This period coincided with the rapid grain-filling stage, where heat stress pressure was moderate. After 30 days post-anthesis, as grain-filling rates slowed, temperature differences between treatments increased to over 5°C, sometimes exceeding 10°C, with heat stress maintaining temperatures above 30°C for up to 9 hours daily, creating substantial stress. Generally, wheat grain filling ceases when ambient temperature exceeds 30°C, and high temperatures combined with hot dry winds or moisture stress cause premature ripening. Thus, the mid-to-late grain-filling stage is particularly vulnerable to heat damage.

2.2 Effects of Heat Stress on Yield, 1000-Kernel Weight, and Thermal Sensitivity Index

Yield, 1000-kernel weight, and their thermal sensitivity indices were compared across 12 winter wheat varieties (Table 1). Under normal conditions, 'Zhongmai 175' , 'Heng S29' , 'Heng 4399' , 'Heng 4444' , 'CA0816' , and 'Zhongmai 875' showed high yields. Under heat stress, 'Zhongmai 175' , 'CA0816' , 'Heng 4399' , 'Heng 4444' , 'Zhongmai 875' , and 'Jingdong 8' maintained high yields. The varieties with consistently high yields under both conditions were 'Zhongmai 175' , 'CA0816' , 'Heng 4399' , 'Heng 4444' , and 'Zhongmai 875' .

Varieties 'Jingdong 8' , 'CA1062' , 'CA0816' , 'Zhongmai 875' , 'Zhongmai 895' , and 'Heng 4444' had yield thermal sensitivity indices less than 1, classifying them as heat-tolerant. 'Heng S29' and 'Shi 4366' showed high thermal sensitivity indices, indicating poor heat tolerance. For 1000-kernel weight, 'Jingdong 8' , 'Zhongmai 895' , and 'Zhongmai 875' maintained high values (45–50 g) under both conditions. 'Jingdong 8' , 'CA0816' , 'CA1062' , 'Zhongmai 875' , 'Zhongmai 895' , and 'Heng 4444' had 1000-kernel weight thermal sensitivity indices below 1 (heat-tolerant), while 'Hengguan 35' , 'Shiyou 17' , 'Heng S29' , and 'Shi 4366' showed high indices (heat-sensitive).

Significance analysis of yield and 1000-kernel weight differences between treatments (Table 1) revealed that heat stress significantly reduced yield and kernel weight for all varieties except 'Jingdong 8' , whose 1000-kernel weight was not significantly affected. 'Jingdong 8' showed the smallest yield and 1000-kernel weight thermal sensitivity indices, demonstrating the best heat tolerance. Analysis of yield and 1000-kernel weight thermal sensitivity indices showed consistent trends, with a significant correlation coefficient of 0.93, indicating that the 1000-kernel weight thermal sensitivity index can serve as an indicator of heat tolerance.

2.3 Grain-Filling Rates of Different Wheat Varieties Under Natural and Heat-Stressed Conditions

Climate differences across wheat regions and variation in anthesis/grain-filling periods can cause differences in the inflection points of the S-shaped kernel weight accumulation curve. Analysis of 1000-kernel weight accumulation curves under local natural conditions showed that the slope represents grain-filling rate. As shown in [Figure 2: see original paper], kernel weight increased gradually from anthesis to 12 days post-anthesis (gradual increase stage), rapidly from 12–30 days (rapid increase stage), and slowed again from 30–42 days (slow increase stage).

Grain-filling rates at different stages under natural and heat-stressed conditions are presented in Table 2 . During early grain filling (0–12 days, gradual increase stage), before greenhouse heating began, filling rates were 0.6–0.8 $g \cdot 1000\ kernels^{-1} \cdot d^{-1}$ with no significant differences among varieties. From 12 days post-anthesis, filling rates accelerated, reaching 1.6–2.1 g • 1000 kernels^{-1} • d^{-1} during the rapid increase stage (12–30 days). 'Zhongmai 875' showed the fastest rate at 2.1 g • 1000 kernels^{-1} • d^{-1}. After 30 days, filling rates declined, with greater variation among varieties (0.2–0.7 g • 1000 kernels^{-1} • d^{-1}).

Heat stress treatment began during the rapid increase stage, and varieties showed distinct responses. 'Shi 4366' , 'Heng S29' , 'Shiyou 17' , 'Hengguan 35' , and 'Zhongmai 175' showed significantly affected filling rates, while other varieties showed no significant differences from natural conditions.

Comparative analysis of 1000-kernel weight accumulation curves under natural and heat-stressed conditions (Fig. 2), arranged by ascending thermal sensitivity index (Table 1), revealed that 'Jingdong 8' (most heat-tolerant) showed nearly identical curves under both conditions. As heat tolerance decreased, differences appeared earlier: 'CA0816' and 'CA1062' (index 0.6, good tolerance) showed divergence at 36 days; 'Zhongmai 875' , 'Zhongmai 895' , 'Heng 4444' , and 'Heng 4399' (index 0.6–1.0, moderate-high tolerance) diverged at 30 days; 'Heng 4399'(index =1.0, moderate tolerance) showed essentially no kernel weight increase after 30 days under heat stress. Heat-tolerant and moderately tolerant varieties showed differences only during the slow increase stage. In contrast, heat-sensitive varieties (index 1.3–1.7) including 'Zhongmai 175' , 'Heng 4399' , 'Shiyou 17' , 'Heng S29' , and 'Shi 4366' showed divergence during the rapid increase stage, resulting in greater impacts on kernel weight.

Discussion and Conclusion

Analysis of climate characteristics in the Huanghuai Wheat Region revealed that daily maximum temperatures rarely exceed 30°C during early grain filling, providing optimal conditions. However, temperatures above 30°C frequently occur during late grain filling in late May and early June. Our temperature records (Fig. 1) showed that during the late rapid increase stage (20–30 days post-anthesis), temperatures already exceeded 30°C at noon, surpassing the optimal range for grain filling. During the slow increase stage (30 days post-anthesis to maturity), heat stress temperatures were higher and lasted longer, making wheat highly vulnerable to heat stress that slows or terminates grain filling, causing premature ripening. Hu et al. [17] used artificial climate chambers to simulate heat stress at different grain-filling stages and concluded that early and mid-grain filling heat stress had the greatest impact on yield, with later stages being less critical. Our study, based on natural climate patterns, identified mid-to-late grain filling as the high-incidence period for heat stress with significant production impacts.

This study investigated effects of mid-to-late grain filling heat stress on grain-filling rate, 1000-kernel weight, and yield. Heat stress generally reduced grain-filling rate, kernel weight, and yield, consistent with previous findings [7,17–18]. However, earlier studies did not deeply analyze differences in heat tolerance among varieties or the patterns of grain-filling differences among heat-tolerance types. Our analysis of yield and kernel weight differences and thermal sensitivity indices under natural and heat-stressed conditions revealed that 'Zhongmai 175' and 'Heng 4399' were highly productive varieties with moderate thermal sensitivity indices but high yields under both conditions. 'CA0816', 'Zhongmai 875', and 'Heng 4444' showed both high productivity and heat tolerance. 'Jingdong 8' demonstrated the most outstanding heat tolerance. These six varieties can serve as parental lines in heat-tolerance breeding programs to develop high-yielding, heat-tolerant cultivars. 'Heng S29' showed high yield potential but poor heat tolerance, with severe reductions in kernel weight and yield under heat stress, suggesting its productivity could be utilized if heat tolerance is improved.

Analysis of grain-filling characteristics under natural and heat-stressed conditions revealed that varieties differed in heat sensitivity and the degree of filling rate impact. The primary effect of heat stress was altering the onset time of reduced grain-filling rates. Heat-tolerant varieties (1000-kernel weight thermal sensitivity index <1.0) showed impacts mainly after 30 days post-anthesis, with reduced filling rates but essentially unchanged filling duration. Moderately tolerant varieties (index 1.0) ceased grain filling after 30 days under heat stress (e.g., 'Heng 4399'), shortening filling duration but leaving early-to-mid filling largely unaffected. Heat-sensitive varieties (index >1.0) experienced earlier impacts, with reduced filling rates during the rapid increase stage, making the magnitude of rapid-stage filling rate more critical for kernel weight.

In breeding practice, both yield data and 1000-kernel weight thermal sensitivity index should be used jointly to evaluate a variety's value in heat-tolerance breeding. 'CA0816', 'Zhongmai 875', 'Heng 4444', 'Heng 4399', 'Zhongmai 175', and 'Jingdong 8' can all be utilized as excellent genetic resources in heat-tolerance breeding programs.

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Note: Figure translations are in progress. See original paper for figures.