Field Crops Research 222 (2018) 143–152

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Prominent winter wheat varieties response to post-flowering heat stress under controlled chambers and field based heat tents

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ARTICLE INFO

Keywords:
Grain filling
Grain yield
Heat stress
Spike temperature
Winter wheat

ABSTRACT

Post-flowering heat stress shortens grain filling duration and limits resource allocation to grains leading to lower productivity in wheat. Wheat grown in Kansas and US Great Plains, often experiences temperatures of 30 °C during grain filling, leading to lower productivity. Thus, characterizing Kansas prominent and newly released varieties for post-flowering heat stress will define the gap in heat tolerance that will need to be addressed through breeding. In the present study, seven Kansas varieties were phenotyped for heat tolerance under a controlled chamber study and two field experiments. To impose heat stress in the controlled chambers, plants grown at 25 °C were transferred to high day temperature (35 °C) chambers, 10 days after first sign of anthesis. Under field conditions, custom built “heat tents” were placed over the plots ten days after 50% flowering and remained until maturity. Plants grown under heat stress exhibited early senescence indicating a shorter grain filling period compared to control. Early maturing varieties recorded higher percent reduction in grain yield under heat stress. Post-flowering heat stress induced significant reduction in thousand kernel weight, grain number, harvest index and grain yield over control. Percent reduction in yield ranged from 6 to 51% under severe heat stress exposure in controlled environments and 2–27% with heat stress exposure using field based tents. Among the varieties tested SY Monument and Larry performed well under both conditions suggesting that they are relatively better suited for locations that face consistent heat stress exposure during the post-flowering stage. Our findings highlight the need to explore wider genetic diversity including wild wheat to infuse greater heat stress resilience into ongoing wheat breeding programs.

1. Introduction

Negative impacts of global warming on crop production is a growing concern. Warming could be either due to increased occurrence of short term heat spikes or due to a gradual long-term increase in mean temperature (Sadras and Dreccer, 2015). With a predicted increase in global mean surface temperature varying between 0.3 and 4.8 °C by the end of 21st century, crop production will be challenged by heat stress, leading to significant economic damage (IPCC, 2014; Lyman et al., 2013; Tack et al., 2015, 2017). Using a multi-model ensemble approach, Asseng et al. (2015) concluded that for every °C increase in mean temperature, the global wheat (*Triticum aestivum* L.) production would reduce by about 6%. Wheat one of the important staple cereal and a major source of calories for humans (FAO, 2015) is highly sensitive to heat stress during reproductive and grain filling phase (Wollenweber et al., 2003; Farooq et al., 2011). Optimum temperature for normal growth and development in wheat ranges between 12 and 24 °C and temperatures > 30 °C are shown to induce significant yield losses (Saini and Aspinall, 1982; Farooq et al., 2011). The United States ranks fourth in the world wheat production, accounting for approximately 55 million metric tons of wheat produced from a harvested area of around 19 million hectares (USDA-NASS, 2017, USDA-FAS, 2016). The majority of wheat grown in the United States is winter wheat, with a large proportion (~57%) produced in the Great Plains (USDA-NASS, 2017). Among different states in the US, Kansas tops the chart both in terms of total wheat area and production. However, grain yield per unit area (productivity) in Kansas (mean yield of 2.76 t ha^{-1}, from 2014 to 2016) is lower than the national average for winter wheat (USDA-NASS, 2017), owing to its extreme weather conditions (Barkley et al., 2014; Lollato and Knapp, 2017). The primary reason for low productivity is because winter wheat grown in Kansas is often exposed to temperatures ≥30 °C during grain filling phase in the months of May and June, which is well beyond the optimum temperature identified for grain filling. Such scenarios are predicted to worsen with increased frequency and magnitude of heat stress exposure associated with a changing climate, which can lead to increased economic loss to wheat growers. Hence,

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https://doi.org/10.1016/j.fcr.2018.03.009
Received 15 September 2017; Received in revised form 11 March 2018; Accepted 12 March 2018
0378-4290/ Published by Elsevier B.V.

quantifying post-flowering heat tolerance in local prominent varieties during the grain filling phase is important and timely.

Heat stress at the grain filling phase induces significant grain yield and quality losses in wheat (Bhullar and Jenner, 1985; Blum et al., 1994; Viswanathan and Khanna-Chopra, 2001; Shah and Paulsen, 2003; Liu et al., 2011; Shirdelmoghanloo et al., 2016a; Mastilovic et al., 2017). Grain weight is a product of rate and duration of grain filling (Gallagher et al., 1976), wherein temperature is a key environmental driver that determines the rate and duration dynamics. High temperatures are known to reduce grain filling duration, thereby reducing the window for translocation of the stored or currently synthesized assimilates into grains, leading to lower grain weight and yield. For every °C increase in temperature above the optimum growth temperature the grain filling duration is shown to reduce by 2.8 d (Chowdhury and Warlaw, 1978; Streck, 2005). Additionally, heat stress during grain fill negatively affects many physiological and biochemical processes including photosynthesis (Blum et al., 1994), membrane integrity and quantum yield of photosystem II (Bhullar and Jenner, 1985). Almost all previous studies quantifying the impact of heat stress and QTL mapping for heat stress during grain filling in wheat have used controlled environment facilities (Stone and Nicolas, 1994; Gibson and Paulsen, 1999; Spiertz et al., 2006; Shirdelmoghanloo et al., 2016a,b) or delayed planting to impose heat stress (Pinto et al., 2016; Pinto et al., 2010; Bennett et al., 2012). In the current study prominent varieties are tested to fill a critical gap in our understanding on the extent to which heat tolerance in these varieties needs to be improved. Due to lack of field based phenotyping facilities, delayed and staggered sowing approach is followed to expose crops to heat stress during critical developmental stages under field conditions (Viswanathan and Khanna-Chopra, 2001). Although this approach provides an opportunity to have the flowering or post-flowering stage of the crop exposed to stress, the overall agronomic performance of the varieties is seriously affected due to their exposure to significantly different environments, compared to the target conditions that they are bred (Bahuguna et al., 2015). In contrary, using the custom built heat tents or similar structures would induce heat stress by increasing the temperatures inside the tents compared to ambient temperatures, facilitating varietal responses within the cropping season under realistic field conditions. One growth chamber and two field experiments were conducted: 1. Determine the level of genetic variability for post-flowering heat tolerance in prominent and recently released winter wheat varieties for Kansas and US Great Plains; 2. Assess chlorophyll index, tissue temperature and agronomic response during post-flowering heat stress exposure in prominent varieties under controlled chambers and field based heat tents; and 3. Identify the most suitable farmer preferred winter wheat variety/s for the warmer conditions observed in the Great Plains region of the United States.

2. Materials and methods

2.1. Crop husbandry and high day temperature stress imposition

2.1.1. Controlled environment (Exp. 1)

The study was carried out in controlled environment chambers at the Department of Agronomy, Kansas State University, Manhattan, Kansas in 2016. This experiment involved seven prominent Kansas winter wheat varieties (Supplementary Table 1) grown under two temperature treatments (control and heat stress). Seeds of each of the seven varieties were sown in 30.5 × 61 cm flat seed trays filled with Sunshine Metro-Mix 380 potting mix (Sun Gro Horticulture, Agawam, MA) and placed in a greenhouse at room temperature. After most seeds had germinated the seed trays were transferred to a vernalization chamber maintained at 5 °C for 6 weeks. Following vernalization, 40 plants of each variety were transplanted into individual 1.6 L pots (10 × 24 cm, MT49 Mini-Treepot) and filled with Sunshine Metro-Mix 380 potting mix. Each pot received 5 g of Scotts Osmocote classic (14-14-14 of N-P-K) and 0.5 g of Scotts Micromax Micronutrients (Hummert International, Topeka, KS) at the time of transplanting. Pots were kept in trays and moved to controlled environment chambers maintained at 25/15 °C maximum day/minimum night temperature. Throughout the experiment, the plants were kept under well-watered conditions by maintaining a water layer of 1 cm in the tray placed below the pots, to avoid confounding effects of water stress.

The main tiller and subsequent two tillers (considered as primary tillers) from each plant were tagged on the day anthesis began. Ten days after the start of anthesis, half of the plants (20 plants) from each variety were transferred to high day temperature (heat stress) growth chambers, which were maintained at 35/15 °C maximum day/minimum night temperature. While the other half (20 plants) remained in the control growth chambers maintained at an optimum 25/15 °C maximum day/minimum night temperature. Both, heat stress and the control growth chambers were maintained at 16/8 (day/night) hour photoperiod, with 900–1000 μmol $m^{-2} s^{-1}$ light intensity at 5 cm above the canopy and 70% relative humidity (RH). Maximum day and minimum night temperatures were maintained for 7 and 8 h respectively, in all the chambers with a transition period of 4.5 h for each transition i.e. maximum day and minimum night temperatures and *vice versa* (Supplementary Fig. S1). Temperature and RH were recorded every 15 min using HOBO UX 100-011 temperature/RH data loggers (Onset Computer Corp., Bourne, Massachusetts) in all growth chambers.

2.2. Field experiments (Field 2016 and Field 2017)

The study was conducted in 2016 and 2017 at Kansas State University (KSU), Agronomy research farm at Manhattan (39°11′N, 96°35′W). Soil type was a Kennebec silt loam. Soil samples were collected at 0–15 cm surface and 15–60 cm subsurface prior to sowing in October 2015 to analyze organic matter (OM), pH, P, K, N [ammonia (NH_3) and nitrate (NO_3)], S, and Cl. Each sample was composed of 15 individual soil cores representing the experimental area. Soils contained 2.3% of OM, with a pH of 5.5, 16.5 ppm of Melich-P, 303 ppm K, 7.8 ppm of NH_4-N and 12.2 ppm of NO_3-N. The experiments included seven commercial varieties bred for Kansas and US Great Plains environments (Supplementary Table 1). These varieties were grown in two temperature treatments (control and heat stress) with four replications in field 2016 and 3 replications in field 2017. In field 2016, under heat stress treatment all the four replications were within a heat tent and in field 2017, there were three independent heat tents. In field 2016, seeds were sown in soil using a Rowseed 1R hand pushed single row seeder (Wintersteiger, Ried im Innkreis, Austria) on 26 October 2015 at 60 seeds per meter row with a row spacing of 19 cm. Whereas, 2017 field experiment was planted using tractor and research plot grain drill with GPS guidance system on 27 October 2017. Each replicate plot per cultivar contained four rows with each row being four-meter in length. The field was irrigated manually with a fan sprinkler attached to a garden hose, two days after planting. During a rain event only heat stress plots (within the heat tent) were irrigated to ensure that both the treatments were not affected by water limitation throughout the experimental period. The total amount of rain fall received during 2016 and 2017 field experimental period was around 155 and 98 mm respectively. In Field 2016, plants were top dressed with 56 kg N ha^{-1} (Urea; 46-0-0) on 29th February 2016. In field 2017, in addition to top dressing with urea the use of tractor driven drill allowed application of Di-Ammonium Phosphate (18-46-0) at a rate of 14.5 kg N ha^{-1} and 39 kg P_2O_5 ha^{-1} as starter dose at the time of planting.

To impose post-anthesis heat stress, specially designed field based heat tents (Prasad et al., 2015, Sunoj et al., 2017) were placed on the established plots approximately ten days after 50% flowering (Image 1). The phenological differences across the seven varieties was not more than six days. The heat tents (5.4 m wide × 7.2 m long × 3.0 m high at the apex) are constructed of galvanized steel framework covered with a