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Performance of bread wheat advanced lines under late sowing and hydric stress during the crop season 2020-2021

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Abstract

Thirty four advanced bread wheat lines and cultivar Borlaug 100 were sown on January 15 and 30, 2021, at the Norman E. Borlaug Experimental Station, in the Yaqui Valley, Sonora, México. Plots consisted of 1 bed 2 m long with two rows and 0.80 m apart with two replications, and a seed density of 100 kg ha^{-1} with two complementary irrigations. Average daily temperature (°C), maximum, minimum, relative humidity, rainfall, heat and cold units were recorded from January 1 to May 15, 2021. The average days for heading of the group was 69 for the first sowing date and 66 for the second one, while days for physiological maturity were 99 and 90, respectively. The average plant height of the group for the first date was 97.5 cm and 94 for the second one; the sister line SOKOLL/5/W15.92/4/PASTOR//HXL7573/2*BAU/3/WBLL1/6/SOKOLL/3/PASTOR//HXL7573/2*BAU (PTSS12SHB00020T-0TOPB-099Y-099B-25Y-020Y-0B) consistently reached the maximum height with 107.5 and 110 cm in each date, respectively. The average grain yield per plot was 294 g; line BAJ #1*2/4/BETTY/3/CHEN/AE.SQ//2*OPATA showed the highest yield with 345.4 g which was above 4.3 t ha^{-1}, followed by SOKOLL/3/PASTOR//HXL7573/2*BAU/4/ASTREB/5/PIHA//WORRAKATTA/2*PASTOR/3/PRL/2*PASTOR, also above 4.3 t ha^{-1}. The average hourly temperature was 18.4 °C with a maximum of 40.8 °C and a minimum of 3.9 °C, and the number of heat and cold units was 203 and 393, respectively.

Keywords: Wheat; *Triticum* spp; Grain yield; Drought stress; Heat stress

1. Introduction

The increment of temperature over a threshold level during a period of time, sufficient to cause a negative irreversible effect on plant growth and development is defined as heat stress [1,2]. High temperature causes a diversity of effects on crops depending upon its duration and the rate of increment, whether it occurs during the day or during the night. This phenomenon affects the wheat plant to varying degrees at different phenological stages, however, it is more harmful during the reproductive phase than during the vegetative phase, due to direct effect on grain number, dry weight as well as grain quality, although the final effect will also depend on the genotype [3,4]. At mid-anthesis, an increase in temperature of about 10 °C might induce a 40 % decrease in grain number per spike [5]. Grain yield in winter cereals may be reduced by high temperatures during the grain-filling stage from 10 to 15 % [6,7]. Wheat is cultivated in tropical or subtropical areas [8], where the temperature during the coolest month of the crop season is higher than 17.5 °C. More than 7 million hectares comply with this condition, located primarily in Southeast Asia, in India and Bangladesh [9], in

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Sub-Saharan Africa [10], Brazil, Thailand, Uganda, Mexico, Sudan, Egypt, Nigeria, and Syria [11]. To comply with the demand of food worldwide in the future, wheat productivity must increase in favorable and marginal environments; plants have developed mechanisms to adapt to heat stress through modifications in their morphological or growth responses, physiological and biochemical pathways, and changes in enzyme reactions. Numerous heat tolerance genes have been identified in wheat, but the more extensive study is needed to increase heat tolerance in crops to satisfy the food demands of the world's growing population. The global food policy needs to prioritize and promote additional joint research and the development of heat-tolerant wheat breeding to ensure the world's food security [5]. Flowering of winter crops in temperate zones must take place with the lowest risk of a frost, therefore, the sowing date is important, since high temperature generally occurs during the grain-filling period; high temperature and low water availability are the most common abiotic stresses in winter cereals [6]. Wheat consumption and importation by developing countries in the warmer regions are factors that lead to the increase of local wheat production [12]. Drought, the lack of ample moisture required for normal plant growth and development to complete the life cycle, is the most devastating environmental stress which affects crop productivity. The main effects in plants are reduced rate of cell division and expansion, leaf size, stem elongation, root proliferation, disturbed stomatal oscillations, affecting severely plant growth and development, and biomass accumulation [13]. The United Nations Development Programme (UNDP) enabled wheat breeders from the International Maize and Wheat Improvement Center (CIMMYT) to expand their research on the generation of high yielding, disease resistant, semi-dwarf wheats adapted to the warmer, subtropical area of the world. Therefore, the Stress Adaptive Trait Yield Nursery (SATYN) was implemented; this nursery is formed with lines for drought-stressed areas and for heat stress conditions, for major spring wheat-growing countries such as Bangladesh, China, Egypt, India, Iran, Mexico, Nepal, and Pakistan [14]. The objective of this work was to evaluate the performance of a set of wheat lines comprising the 10th SATYN, subjected to late sowing, and therefore, exposed to a warmer and shorter crop season with reduced irrigation.

2. Materials and methods

Thirty four advanced bread wheat lines from the 10th Stress Adapted Trait Yield Nurseries (SATYN), which included six groups of sister lines (lines 1 and 2; 4-6; 11-15; 17 and 18; 19-23; and 34 and 35) (Table 1), selected by the International Maize and Wheat Improvement Center´s wheat breeding for their tolerance to stress, were sown on January 15 and 30, 2021, at the Norman E. Borlaug Experimental Station which belongs to the National Institute for Forestry, Agriculture, and Livestock Research, located in block 910 in the Yaqui Valley, Sonora, Mexico (27º22´3.01" N and 109º55´40.22" W) in a clay soil with pH of 7.8. The commercial bread wheat cultivar Borlaug 100 which has shown an average grain yield of 6.1 and 7.0 t ha^{-1} with two and four complementary irrigations, respectively, in experimental plots [15] was used as a check.

Table 1 Advanced bread wheat lines from the 10th Stress Adaptive Trait Yield Nursery from CIMMYT, sown on January 15 and 30, 2021, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico

No.	Pedigree and selection history
1	KS940935.7.1.2/2*PASTOR/4/FRAME//MILAN/KAUZ/3/PASTOR/5/D67.2/PARANA 66.270//AE.SQUARROSA (320)/3/CUNNINGHAM/4/VORB PTSS14Y00103S-0B-099Y-099B-35Y-020Y-0B
2	KS940935.7.1.2/2*PASTOR/4/FRAME//MILAN/KAUZ/3/PASTOR/5/D67.2/PARANA 66.270//AE.SQUARROSA (320)/3/CUNNINGHAM/4/VORB PTSS14Y00103S-0B-099Y-099B-8Y-020Y-0B
3	WBLL4//OAX93.24.35/WBLL1/5/D67.2/PARANA66.270//AE.SQUARROSA(320)/3/ CUNNINGHAM/4/VORB PTSS14Y00135S-0B-099Y-099B-39Y-020Y-0B
4	CROC_1/AE.SQUARROSA(213)//PGO/3/BAV92/4/PIHA//WORRAKATTA/2*PASTOR/3/ PRL/2*PASTOR PTSS14Y00207S-0B-099Y-099B-3Y-020Y-0B
5	CROC_1/AE.SQUARROSA(213)//PGO/3/BAV92/4/PIHA//WORRAKATTA/2*PASTOR/3/ PRL/2*PASTOR PTSS14Y00207S-0B-099Y-099B-4Y-020Y-0B
6	CROC_1/AE.SQUARROSA(213)//PGO/3/BAV92/4/PIHA//WORRAKATTA/2*PASTOR/3/ PRL/2*PASTOR PTSS14Y00207S-0B-099Y-099B-33Y-020Y-0B

7	NAC/5/2*D67.2/PARANA 66.270//AE.SQUARROSA (320)/3/CUNNINGHAM/4/VORB PTSS14B00048T-099Y-099B-15Y-020Y-0B
8	MTRWA92.161/PRINIA/5/SERI*3//RL6010/4*YR/3/PASTOR/4/BAV92/6/W15.92/4/PASTOR//HXL7573/2*BAU/3/WBLL1 PTSS11Y00185S-0B-099Y-099Y-099Y-20Y-020Y-0B
9	CROC_1/AE.SQUARROSA(333)//2*KUTZ PTSS15B00034T-099Y-099M-23Y-0Y-020Y-0B
10	D67.2/PARANA 66.270//AE.SQUARROSA (185)/3/2*KUTZ PTSS15B00036T-099Y-099M-13Y-0Y-020Y-0B
11	SOKOLL/WBLL1/5/D67.2/PARANA66.270//AE.SQUARROSA(320)/3/CUNNINGHAM/4/ VORB PTSS15Y00110S-099B-099Y-099M-5Y-020Y-0B
12	SOKOLL/WBLL1/5/D67.2/PARANA66.270//AE.SQUARROSA(320)/3/CUNNINGHAM/4/ VORB PTSS15Y00111S-099B-099Y-099M-22Y-020Y-0B
13	SOKOLL/WBLL1/5/D67.2/PARANA66.270//AE.SQUARROSA(320)/3/CUNNINGHAM/4/ VORB PTSS15Y00111S-099B-099Y-099M-23Y-020Y-0B
14	SOKOLL/WBLL1/5/D67.2/PARANA66.270//AE.SQUARROSA(320)/3/CUNNINGHAM/4/ VORB PTSS15Y00111S-099B-099Y-099M-2Y-020Y-0B
15	SOKOLL/WBLL1/5/D67.2/PARANA66.270//AE.SQUARROSA(320)/3/CUNNINGHAM/4/ VORB PTSS15Y00111S-099B-099Y-099M-9Y-020Y-0B
16	MEX94.27.1.20/3/SOKOLL//ATTILA/3*BCN/5/D67.2/PARANA66.270//AE.SQUARROSA (320)/3/CUNNINGHAM/4/VORB PTSS15Y00114S-099B-099Y-099M-12Y-020Y-0B
17	SOKOLL/3/PASTOR//HXL7573/2*BAU/4/WBLL4//OAX93.24.35/WBLL1/5/D67.2/PARANA 66.270//AE.SQUARROSA(320)/3/CUNNINGHAM/4/VORB PTSS15Y00138S-099B-099Y-099M-9Y-020Y-0B
18	SOKOLL/3/PASTOR//HXL7573/2*BAU/4/WBLL4//OAX93.24.35/WBLL1/5/D67.2/PARANA 66.270//AE.SQUARROSA(320)/3/CUNNINGHAM/4/VORB PTSS15Y00138S-099B-099Y-099M-5Y-020Y-0B
19	SOKOLL/WBLL1/4/PIHA//WORRAKATTA/2*PASTOR/3/PRL/2*PASTOR PTSS15Y00152S-099B-099Y-099M-24Y-020Y-0B
20	SOKOLL/WBLL1/4/PIHA//WORRAKATTA/2*PASTOR/3/PRL/2*PASTOR PTSS15Y00152S-099B-099Y-099M-3Y-020Y-0B
21	SOKOLL/WBLL1/4/PIHA//WORRAKATTA/2*PASTOR/3/PRL/2*PASTOR PTSS15Y00152S-099B-099Y-099M-11Y-020Y-0B
22	SOKOLL/WBLL1/4/PIHA//WORRAKATTA/2*PASTOR/3/PRL/2*PASTOR PTSS15Y00152S-099B-099Y-099M-1Y-020Y-0B
23	SOKOLL/WBLL1/4/PIHA//WORRAKATTA/2*PASTOR/3/PRL/2*PASTOR PTSS15Y00154S-099B-099Y-099M-12Y-020Y-0B
24	SOKOLL/3/PASTOR//HXL7573/2*BAU/4/WBLL4//OAX93.24.35/WBLL1/5/PIHA//WORRAKATTA/2*PASTOR/3/PRL/2*PASTOR PTSS15Y00175S-099B-099Y-099M-5Y-020Y-0B
25	SOKOLL/3/PASTOR//HXL7573/2*BAU/4/ASTREB/5/PIHA//WORRAKATTA/2*PASTOR/3/PRL/2*PASTOR PTSS15Y00179S-099B-099Y-099M-11Y-020Y-0B

26	SOKOLL/WBLL1/5/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/VEE#5 /4/FRET2/6/PIHA//WORRAKATTA/2*PASTOR/3/PRL/2*PASTOR PTSS15Y00182S-099B-099Y-099M-21Y-020Y-0B
27	BAJ #1*2/4/BETTY/3/CHEN/AE.SQ//2*OPATA PTSS15B00078T-099Y-099M-6Y-020Y-0B
28	STLN/MUNAL #1//2*BORL14 CMSS12B00828T-099TOPY-099M-0SY-42M-0WGY
29	SOKOLL CMSS97M00316S-0P20M-0P20Y-43M-010Y
30	BORLAUG100 F2014 CMSS06Y00605T-099TOPM-099Y-099ZTM-099Y-099M-11WGY-0B-0MEX
31	BAJ #1 CGSS01Y00134S-099Y-099M-099M-13Y-0B
32	WBLL1//PUB94.15.1.12/WBLL1/3/MUCUY PTSS14Y00345S-0B-099Y-099B-29Y-0B
33	MEX94.27.1.20/3/SOKOLL//ATTILA/3*BCN/4/PUB94.15.1.12/WBLL1/5/MUCUY PTSS14Y00328S-0B-099Y-099B-19Y-020Y
34	SOKOLL/5/W15.92/4/PASTOR//HXL7573/2*BAU/3/WBLL1/6/SOKOLL/3/PASTOR//HXL7573/2*BAU PTSS12SHB00020T-0TOPB-099Y-099B-6Y-020Y-0B
35	SOKOLL/5/W15.92/4/PASTOR//HXL7573/2*BAU/3/WBLL1/6/SOKOLL/3/PASTOR//HXL7573/2*BAU PTSS12SHB00020T-0TOPB-099Y-099B-25Y-020Y-0B

Plots consisted of 1 bed 2 m long with two rows and 0.80 m apart with two replications, and a seed density of 100 kg ha^{-1}. Weed control was done manually and two complementary irrigations were applied 45 days after the irrigation for seed germination and the second one 30 days later (75 days after the irrigation for seed germination). The agronomic management was based on the technical recommendations by Figueroa-López *et al*. [16]. The daily average temperature (°C), the maximum and minimum, relative humidity, the number of cold and heat units, and precipitation were recorded from January 16 to May 15, 2021 by the weather station CIANO-910, located in block 910 in the Yaqui Valley [17]; this station belongs to the automated weather station network of Sonora [18]. Cold units were calculated as the temperature > 0.1°C to < 10°C that occurs in a given hour and the heat units as the number of hours with temperature above 30°C [19]. The variables evaluated were: days to heading, days to physiological maturity, plant height (cm), and grain weight (g) from a 0.8 m^2 plot, after harvesting with a sickle; threshing was carried out with a Pullman stationary thresher.

3. Results and discussion

The range of the daily average temperature during the period of evaluation was 10.5-29.8 °C (Figure 1), while for the maximum temperature it was 17.2-40.8 °C and 3.9-20.8 °C for the minimum temperature.

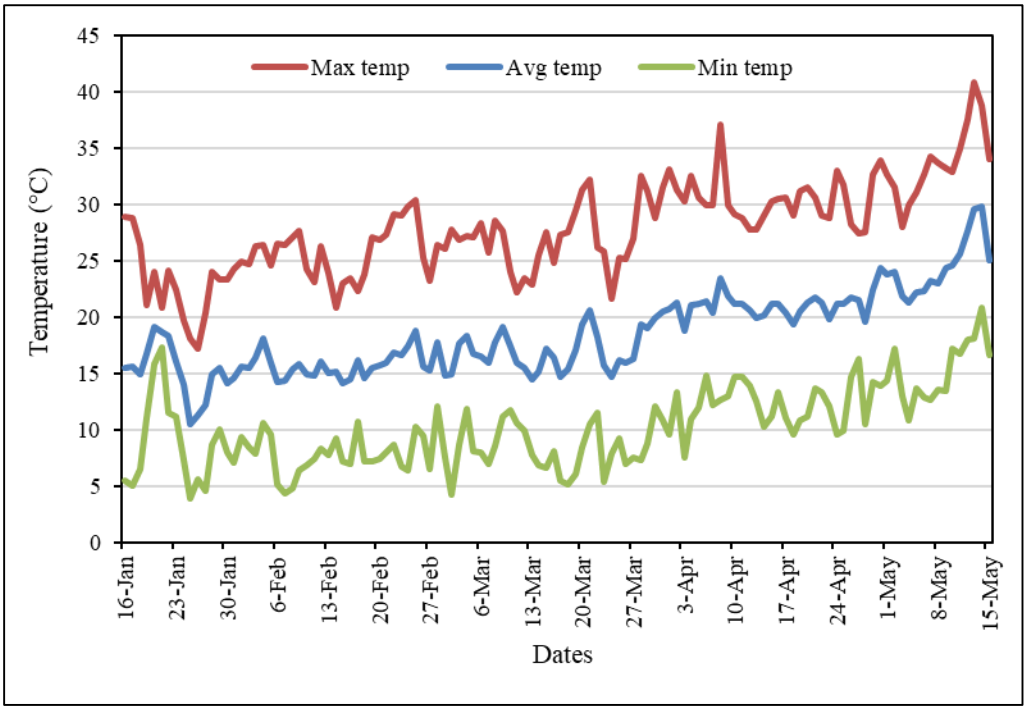

Figure 1 Average temperature from January 16 to May 15, 2021, recorded by the weather station CIANO-910, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico, during the crop season 2020-2021

Maximum temperatures above 30 °C occurred from one to several hours during the following days: February 25 (2 h), March 20 (3), 21 (5), 28 (4), 29 (3), 31 (4), April 1 (5), 2 (4), 3 (1), 4 (5), 5 (4), 8 (8), 15 (1), 16 (2), 17 (2), 19 (4), 20 (5), 21 (4), 24 (7), 25 (7), 29 (6), 30 (8), May 1 (9), 2 (6), 5 (5), 6 (7), 7 (8), 8 (7), 9 (9), 10 (7), 11 (10), 12 (11), 13 (11, 14 (11), 15 (8) (Figure 2). The highest prevalence of heat units during 2020 [20] occurred during April 20 to May 15, while for the 2021, there was more persistence on the occurrence of heat units from March 28 to April 5 and from April 15 to May 15.

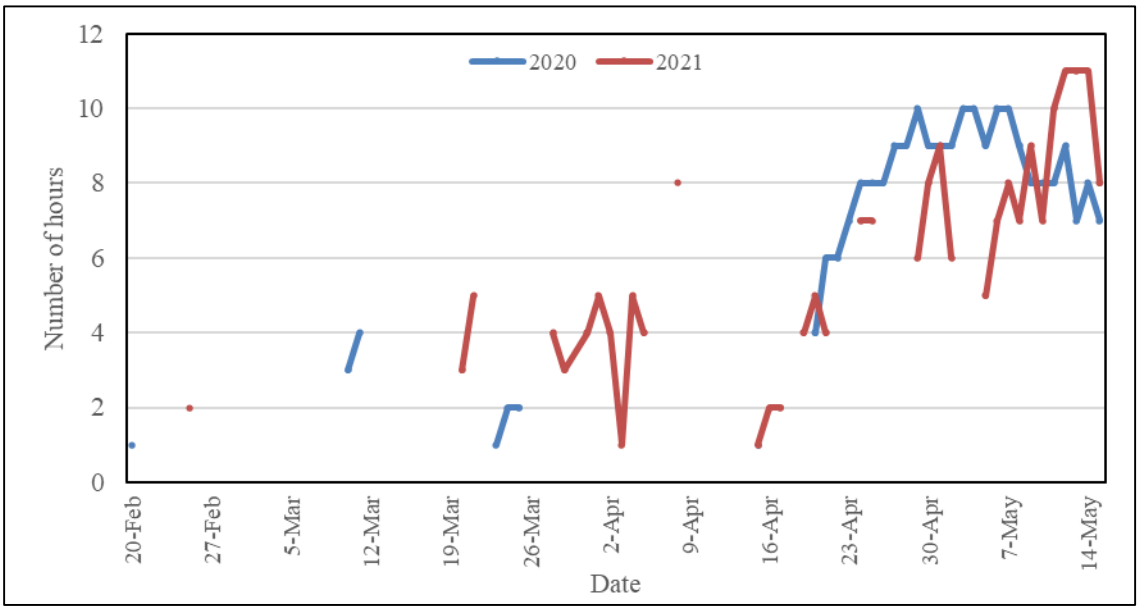

Figure 2 Daily occurrence of heat units from January 16 to May 15, 2021, recorded from the weather station CIANO-910, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico, during the crop seasons 2019-2020 and 2020-2021

Heading dates for the first sowing date occurred from March 21 to 31 and from April 4 to 11 for the second date, therefore, plants in the first date were only exposed to 16 HU distributed across four days during March 21-31, while plants in the second date were exposed to 17 HU distributed across three days, and one of those three had 8 HU; consequently, heat stress might affected flowering [stage 65, 21] to some degree, and so the grain yield final outcome. Continuous hours from two to five on 15 different days with temperature above 30 °C occurred between 12:00 and 16:00 pm, while from six to eleven on 18 different days between 8:00 am and 19:00 pm. Wheat is a cool-season crop whose production is concentrated between latitudes 30-60 °N and 27-40 °S under different climatic areas, but it can be grown beyond these limits, with an optimum growth temperature of about 25 °C [22]. Weeks where the maximum temperature reached more than 30°C in some days and in some hours were February 21-27 with 2 HU, March 14-20 (3), 21-27 (5), March 28-April 3 (21), 4-10 (17), April 11-17 (5), 18-24 (20), April 25-May 1 (30), 2-8 (33), and 9-15 (67); the total heat units accumulated during the period of time that covered this work was 203, being a season with greater number of HU than 2019 with 146 [23], but lower than 2020 with 229 [20]. In relation to cold units, with the exception of weeks April 4-10, 11-17, and May 2-8 and 9-15, the rest of the weeks starting from January 16-23 to March 28-April 3, April 18-24 and April 25-May 1, accumulated cold units ranging from 1 to a maximum of 50 during the week of February 7-13, followed by the weeks of January 24-30 and March 14-20, both with 49 (Figure 3). A total of 393 cold units were recorded during the period of the study. All stages of the wheat plant phenology are sensitive to changes of temperature; high temperatures favor a greater metabolic activity of the plant, as well as the speed up of the physiologic processes that determine its growth and development [24].

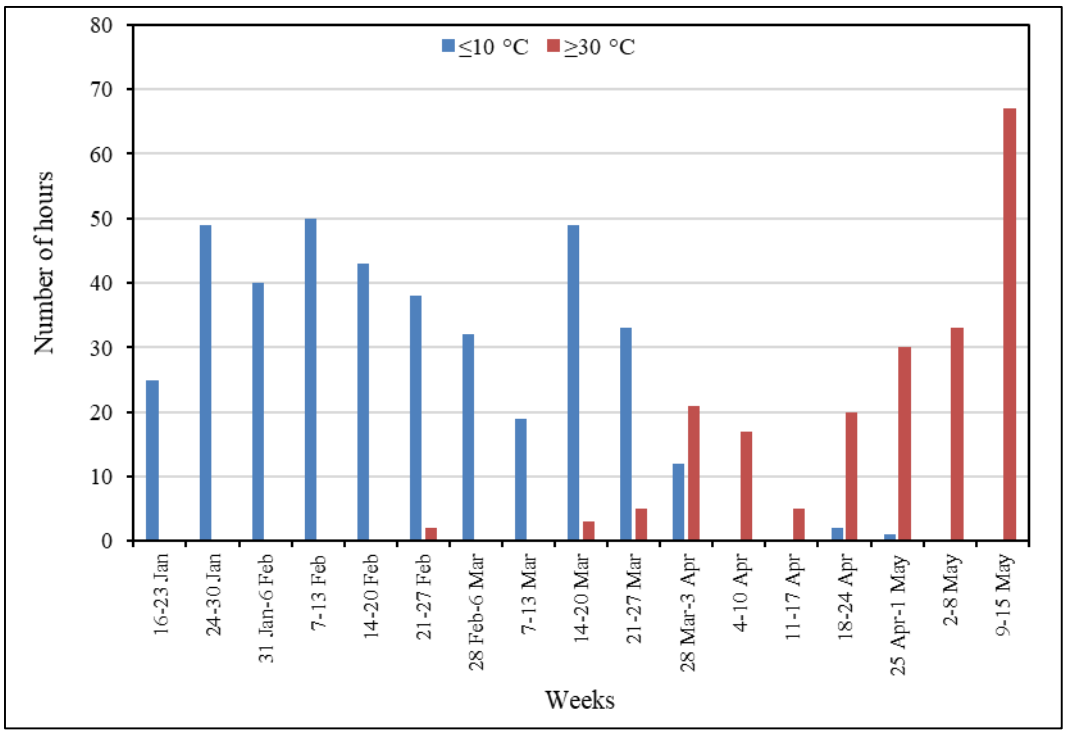

Figure 3 Number of cold and heat units accumulated from January 16 to May 15, 2021, recorded by the weather station CIANO-910, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico, during the crop season 2020-2021

The wheat plant also requires the accumulation of cold units, to prolong its biological cycle, which generally leads to a higher grain yield [19]. During January the daily low temperature range was 4.5-17.3 °C, in February 4.3-12.0 °C, in March 4.2-12.0 °C, in April 7.5-16.2 °C, and in May 10.8-20.8 °C. Recommended wheat sowing dates for southern Sonora are between November 15 to December 15; generally, if sowing is done later, plants will not tiller properly and will be exposed to heat stress [16]. Late sowing with reduced irrigation of the experimental germplasm in this work was focused on exposure to heat stress. The average days to heading of the group of lines and commercial bread wheat cultivar Borlaug 100 was 69 for the first sowing date and 66 for the second; sister lines KS940935.7.1.2/2*PASTOR/4/FRAME//MILAN/KAUZ/3/PASTOR/5/D67.2/PARANA66.270//AE.SQUARROSA(320) /3/CUNNINGHAM/4/VORB (line No. 1, PTSS14Y00103S-0B-099Y-099B-35Y-020Y-0B) and CROC_1/AE.SQUARROSA (213)//PGO/3/BAV92/4/PIHA//WORRAKATTA/2*PASTOR/3/PRL/2*PASTOR (line No. 5, PTSS14Y00207S-0B-099Y-099B-4Y-020Y-0B) headed 65 days after the first sowing date, while cultivar Borlaug 100 (No. 30) and two other lines headed 70 das (Figure 4).

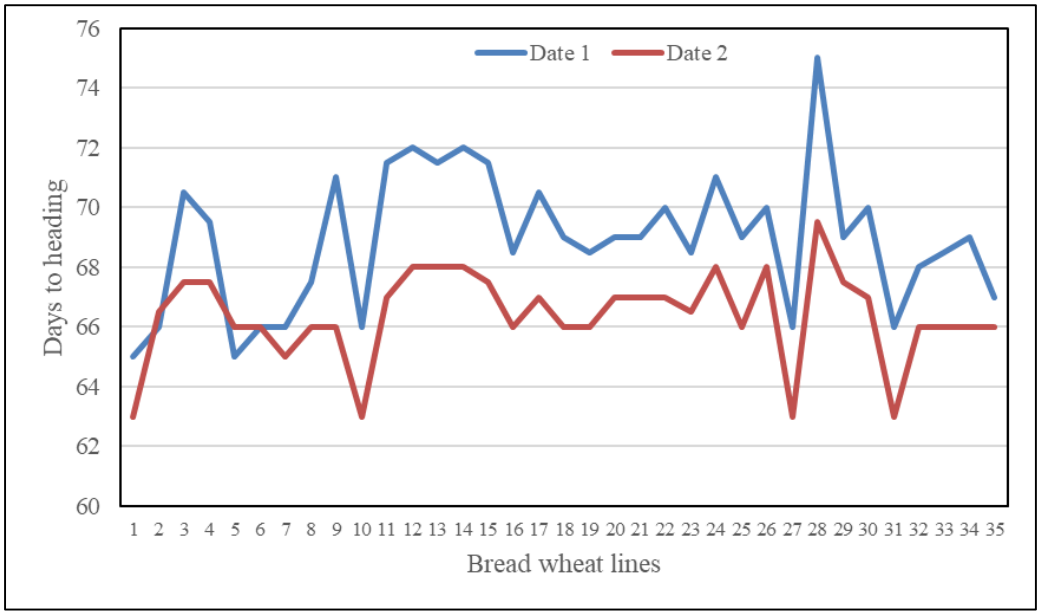

Figure 4 Days to heading bread wheat cultivar Borlaug 100 (No. 30), and 34 advanced bread wheat lines adapted to stress, sown late on January 16 and 30, 2021, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico

Line STLN/MUNAL#1//2*BORL14 (No. 28) headed 70 das. In the second date, there were four lines (No. 1, 10, 27, and 31) that headed 63 das, one (No. 7) 65, and twelve (No. 5, 6, 8, 9, 16, 18, 19, 25, 32-35) that headed 66 das. Lines that had a two day difference or less for heading during the first and second dates were No. 1, 2, 4, 5, 6, 7, 8, 20, 21, 23, 26, 29, 32, and 35, while those with a larger difference of 2.5-3 days were No. 3, 10, 16, 18, 19, 22, 24, 25, 27, 30, 31, 33, and 34, with 3.5-4 days difference were No. 12, 13, 14, 15, and 17, and with a 4.5-5.5 difference were: No. 9, 11 and 28; the highest difference of five days was shown by line MTRWA92.161/PRINIA/5/SERI*3 //RL6010/4*YR/3/PASTOR/4/ BAV92/6/W15.92/4/PASTOR//HXL7573/2*BAU/3/WBLL1 (No. 9) and STLN/ MUNAL#1//2*BORL14 (No. 28). The average plant height of the group was 97.5 cm for the first sowing date and 94 cm for the second (Figure 5).

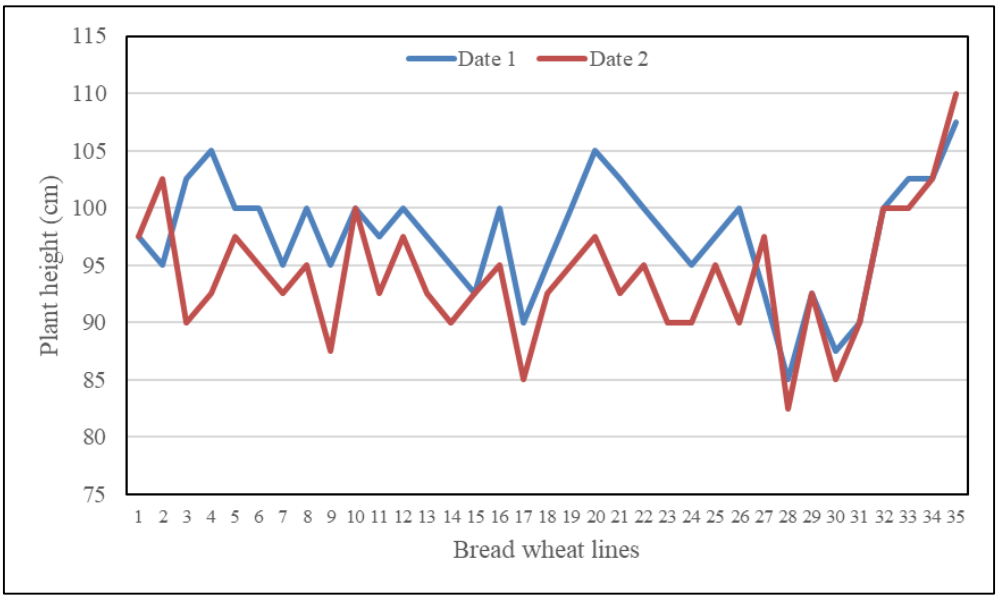

Figure 5 Plant height of bread wheat cultivar Borlaug 100 (No. 30), and 34 advanced bread wheat lines adapted to stress, sown late on January 16 and 30, 2021, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico

Sister line SOKOLL/5/W15.92/4/PASTOR//HXL7573/2*BAU/3/WBLL1/6/SOKOLL/3/PASTOR//HXL7573/2*BAU (PTSS12SHB00020T-0TOPB-099Y-099B-25Y-020Y-0B, No. 35) was the tallest in the first date with 107.5 cm, followed by sister line SOKOLL/WBLL1/4/PIHA//WORRAKATTA/2*PASTOR/3/PRL/2*PASTOR (PTSS15Y00152S-099B-099Y-099M-3Y-020Y-0B, No. 20) with 105 cm, and by lines No. 4, 22, 34-36 with 102.5, while cultivar Borlaug 100 (No. 30) was the second shortest with 87.5 cm. In the second date, sister line SOKOLL/5/W15.92/4/PASTOR//HXL7573/2*BAU /3/WBLL1/6/SOKOLL/3/PASTOR//HXL7573/2*BAU (PTSS 12SHB00020T-0TOPB-099Y-099B-25Y-020Y-0B, No. 35) was the tallest with 110 cm, followed by lines 2 and 34 wih 102.5 cm, while sister line SOKOLL/3/PASTOR//HXL7573/ 2*BAU/4/WBLL4//OAX93.24.35/WBLL1/5/D67.2/PARANA66.270//AE.SQUARROSA(320)/3/CUNNINGHAM/4/ VORB (PTSS15Y00138S-099B-099Y-099M-9Y-020Y-0B, No. 17), and cultivar Borlaug 100 (No. 30) were the shortest with 85 cm. There were several lines which did not show any difference in height in both dates, like lines No. 1, 10, 15, 29, 31, 32, and 34 (Figure 5); lines No. 3-9, 11-14, 16-26, 28, 30, and 33 were taller in the first date than in the second date, being the highest difference 12.5 cm in line WBLL4//OAX93.24.35/WBLL1/5/D67.2/PARANA66.270//AE. SQUARROSA(320)/3/CUNNINGHAM/4/VORB (No. 3) and sister line CROC_1/AE.SQUARROSA(213)//PGO/3/BAV92 /4/PIHA//WORRAKATTA/2*PASTOR/3/PRL/2*PASTOR (PTSS14Y00207S-0B-099Y-099B-3Y-020Y-0B, No. 4). Lines taller in the second date than in the first date were No. 2, 27, and 35. Fuentes-Dávila *et al*. [25] reported that during the 2016-2017 wheat season, a group of lines adapted to stress as well as the two cultivars used in that work, showed an average of 68 days to heading and 60 cm for plant height; during the wheat season 2017-2018, another group of lines showed an average of 69 days for heading and 84 cm for plant height [26], in 2018-2019, another group of lines showed an average of 75 days for heading and 92 cm for plant height [23], while in 2019-2020 another group of lines showed an average of 66 days for heading and 83 cm for plant height [20]. Cultivar Borlaug 100 had 68 days for heading and 60 cm height in 2017, 69 days for heading and 75 cm height in 2018, in 2019, it had 74 days for heading and an average height of 85 cm, in 2020 it had 64 days for heading and 75 cm for plant height, and in 2021 it had 69 days for heading and 86 cm for plant height. In the span of those five years, results indicate that climatic condition were more stressful in 2017 as reported by Fuentes-Dávila *et al*. [25], since the highest average temperature from January to the middle of May was higher than in 2018, 2019, 2020, and 2021 which was partly reflected in days to heading and plant height (Table 2). The total average temperature during the 2017 period was 33.24 °C, 29.03 in 2018, 18.26 °C in 2019, 19.09 °C in 2020, and 18.4 °C in 2021. The average physiological maturity of the group of lines and cultivar Borlaug 100 in this study occurred after 99 days for the first sowing date and 90 for the second with a range of 96 to 104 and 87 to 95, respectively (Figure 6).

Table 2 Average monthly temperatures during January to the middle of May in five years in the Yaqui Valley, Sonora, Mexico, and days to heading and plant height of selected germplasm with tolerance to drought and heat

Year	Average temperature (°C)					Days to heading (avg)	Plant height (cm)
	January	February	March	April	May		
2017	28.22	31.26	32.97	37.76	36.0	68	60
2018	26.39	25.02	28.40	31.71	33.64	69	84
2019	15.65	15.42	17.84	20.72	22.25	74	92
2020	16.70	16.70	18.00	20.88	24.94	66	83
2021	15.13	15.79	16.99	21.06	24.56	68	96

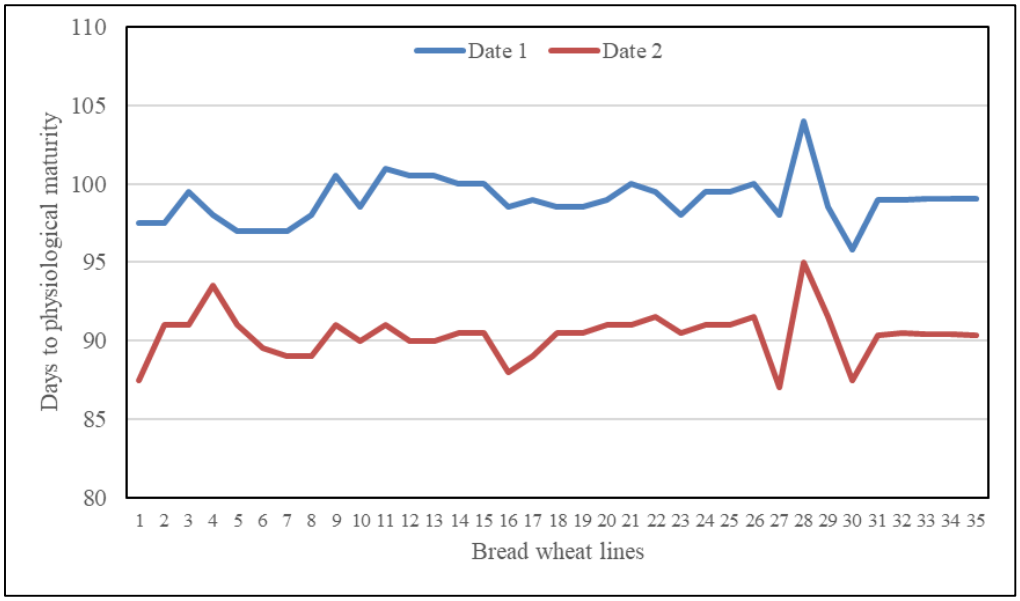

Figure 6 Days to physiological maturity of bread wheat cultivar Borlaug 100 (No. 30), and 34 advanced bread wheat lines adapted to stress, sown late on January 16 and 30, 2021, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico

The average grain weight per plot of the group in the first sowing date was 288.9 g and 299.8 in the second (Figure 7); in the first date, line STLN/MUNAL#1//2*BORL14 (No. 28) showed the highest weight with 397 g, followed by the line SOKOLL/3/PASTOR//HXL7573/2*BAU/4/WBLL4//OAX93.24.35/WBLL1/5/PIHA//WORRAKATTA/2*PASTOR/3/PRL/2*PASTOR (No. 24) with 383.4 g, while sister line CROC_1/AE.SQUARROSA(213)//PGO/3/BAV92/4/PIHA//WORRAKATTA/2*PASTOR/3/PRL/2*PASTOR (PTSS14Y00 207S-0B-099Y-099B-4Y-020Y-0B, No. 5) and BAJ #1 (No. 31), showed the lowest grain weight with 199.4 and 200.4 g, respectively.

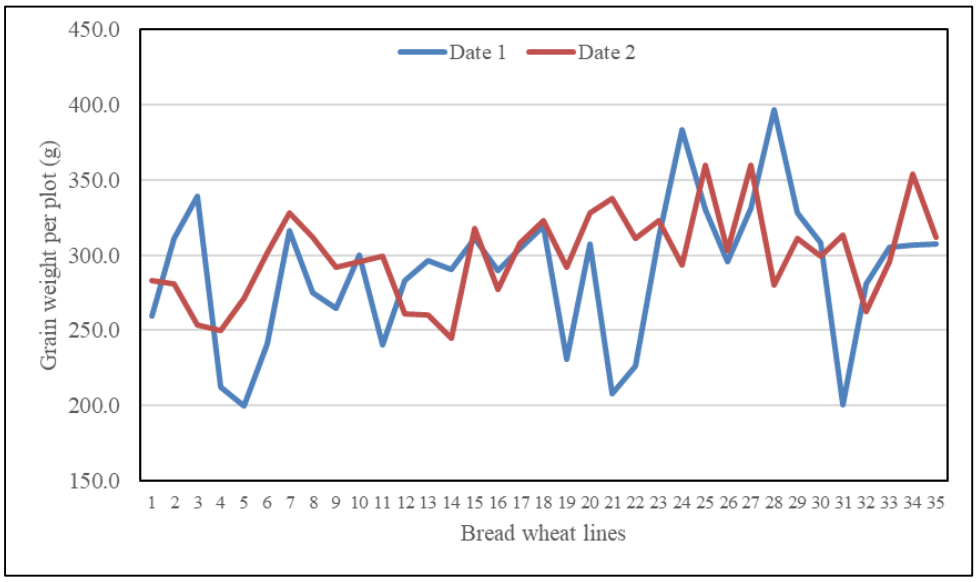

Figure 7 Grain weight per plot of bread wheat cultivar Borlaug 100 (No. 30), and 34 advanced bread wheat lines adapted to stress, sown late on January 16 and 30, 2021, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico.

In the second date, line BAJ #1*2/4/BETTY/3/CHEN/AE.SQ//2*OPATA (No. 27) showed the highest grain weight per plot with 359.9 g, followed by SOKOLL/3/PASTOR//HXL7573/2*BAU/4/ASTREB/5/PIHA//WORRAKATTA/2*PASTOR/3/PRL/2*PASTOR (No. 25) with 359.5 g, while sister lines SOKOLL/WBLL1/5/D67.2/PARANA 66.270//AE.SQUARROSA(320)/3/CUNNINGHAM/4/VORB (PTSS15Y00111S-099B-099Y-099M-2Y-020Y-0B, No. 14) and

CROC_1/AE.SQUARROSA(213)//PGO/3/BAV92/4/PIHA//WORRAKATTA/2*PASTOR/3/PRL/2*PASTOR (PTSS14Y00207S-0B-099Y-099B-3Y-020Y-0B, No. 4) showed the lowest grain weight with 244.8 and with 249.6 g, respectively. The stability shown by cultivar Borlaug 100 in evaluations similar to the present work, from 2019 to 2020, where it was estimated a grain yield from 4.2 to 5.0 t ha^{-1} [20,23,25,26], was not observed in 2021 since the grain yield estimated was 3.8 t ha^{-1}. The HU that occurred during heading, might have accounted for this low grain yield. Heat stress causes important physiological and morphological responses in a plant by reducing seed germination and seedling growth, cell turgidity and water-use efficiency; it disturbs cellular functions generating excessive reactive oxygen species leading to oxidative stress; leaf senescence is enhanced; photosynthesis is reduced, photosynthetic enzymes are deactivated, and chloroplasts are damaged; assimilate translocation and duration and growth rate of grains are limited with the consequent reduction of grain the number [27]. Despite this, Borlaug 100 has also shown good adaptability by the grain yield obtained in five out of six regions throughout Mexico, overcoming three other commercial bread wheat cultivars by as much as 41 % [28]. Lines with a difference equal or greater than 100 g of grain weight per plot between the first and second sowing dates were: sister line SOKOLL/WBLL1/4/PIHA//WORRAKATTA/2*PASTOR/3/PRL/2*PASTOR (PTSS15Y00152S-099B-099Y-099M-11Y-020Y-0B, No. 21), STLN/MUNAL#1//2*BORL14 (No. 28), and BAJ #1 (No. 31), while those with a difference between 50 and 99 g were: SOKOLL/3/PASTOR//HXL7573/2*BAU/4/WBLL4//OAX93.24.35/WBLL1/5/PIHA//WORRAKATTA/2*PASTOR/3/PRL/2*PASTOR (No. 24), WBLL4//OAX93.24.35/WBLL1/5/D67.2/PARANA66.270//AE.SQUARROSA(320)/3/CUNNINGHAM/4/VORB (No. 3), sister line SOKOLL/WBLL1/4/PIHA//WORRAKATTA/2*PASTOR/3/PRL/2*PASTOR (PTSS15Y00152S-099B-099Y-099M-1Y-020Y-0B, No. 22), sister line CROC_1/AE.SQUARROSA(213)//PGO/3/BAV92/4/PIHA//WORRAKATTA/2*PASTOR/3/PRL/2*PASTOR (PTSS14Y00207S-0B-099Y-099B-4Y-020Y-0B, No. 5), sister line SOKOLL/WBLL1/4/PIHA//WORRAKATTA/2*PASTOR/3/PRL/2*PASTOR (PTSS15Y00152S-099B-099Y-099M-24Y-020Y-0B, No. 19), sister line CROC_1/AE.SQUARROSA(213)//PGO/3/BAV92/4/PIHA//WORRAKATTA/2*PASTOR/3/PRL/2*PASTOR (PTSS14Y00207S-0B-099Y-099B-33Y-020Y-0B, No. 6), and sister line SOKOLL/WBLL1/5/D67.2/PARANA66.270//AE.SQUARROSA(320)/3/CUNNINGHAM/4/VORB (PTSS15Y00110S-099B-099Y-099M-5Y-020Y-0B, No. 11). Twenty two lines showed greater grain weight per plot in the second date, while twelve, including cultivar Borlaug 100, in the first date. Lines with the best agronomic type consistent in both dates were: STLN/MUNAL#1//2*BORL14, sister line SOKOLL/WBLL1/5/D67.2/PARANA66.270//AE.SQUARROSA(320)/3/CUNNINGHAM/4/VORB (PTSS15Y00111S-099B-099Y-099M-9Y-020Y-0B, No. 15), SOKOLL/WBLL1/5/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2/6/PIHA//WORRAKATTA/2*PASTOR/3/PRL/2*PASTOR (No. 26), and SOKOLL. The temperature that prevailed during the period of the study which had an average monthly range of 15.1 to 24.5 °C and an overall average of 18.4 °C, was rather similar as that reported for the years 2019 [23] and 2020 [20], however, the heat stress exerted during heading (Figures 2 and 3) [29] might have caused lower grain yield per plot in the group of lines that comprised the 10th SATYN. On the other hand, two complementary irrigations to the group of lines caused a drought stress, which affects all plant development stages from germination, vegetative and reproductive growth to grain filling and maturation of the crop [30]. It also reduces nitrogen uptake efficiency and utilization by plants. The severe low nutrient uptake is due to impaired membrane permeability and active transport, so that the transpiration rate is reduced resulting in repressed root absorbing power. Because of stomatal closure, the CO2 intake is reduced, and inside the stomata, a high level of oxygen produces reactive oxygen species, caused by the partial reduction of oxygen, and causes rupturing of membranes which become leaky, thereby affecting respiration, photosynthesis, and the overall development of the plant. Double ridge to anthesis stage is the most sensitive growth period to water deficit regarding wheat grain yield, affecting negatively the number of spikelets and kernels per spike. Water deficit might decrease wheat grain yield from 17 to 70% [30]. According to Díaz-Ceniceros *et al*. [31], cultivar Borlaug 100 may produce a grain yield of 8.797 t ha^{-1} under full irrigation (four complementary irrigations), while under reduced irrigation, it may yield 4.2 t ha^{-1} [18b] or 3.8 t ha^{-1}, as it was the case in this work.

4. Conclusion

The average days for heading of thirty four advanced bread wheat lines and bread wheat cultivar Borlaug 100 was 69 days for the first sowing date and 66 for the second, while days for physiological maturity were 99 and 90, respectively.

The average plant height of the group for the first and second sowing dates was 97.5 and 94, respectively; sister line SOKOLL/5/W15.92/4/PASTOR//HXL7573/2*BAU/3/WBLL1/6/SOKOLL/3/PASTOR//HXL7573/2*BAU (PTSS12SHB00020T-0TOPB-099Y-099B-25Y-020Y-0B) consistently reached the maximum height with 107.5 and 110 cm in each date, respectively.

The average grain yield per plot was 294 g; line BAJ#1*2/4/BETTY/3/CHEN/AE.SQ//2*OPATA showed the highest yield with 345.4 g which was above 4.3 t ha^{-1}, followed by SOKOLL/3/PASTOR//HXL7573/2*BAU/4/ASTREB/5/PIHA//WORRAKATTA/2* PASTOR/3/PRL/2*PASTOR, also above 4.3 t ha^{-1}.

The average hourly temperature was 18.4 °C with a maximum of 40.8 °C and a minimum of 3.9 °C; the average relative humidity was 64.3 %; there were 10.8 mm of precipitation, and the number of heat and cold units was 203 and 393, respectively.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

The authors declare that No conflict of interest.

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