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Performance of bread wheat advanced lines under late sowing and hydric stress during the crop season 2021-2022

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Abstract

Thirty-eight advanced bread wheat lines and cultivar Borlaug 100 were sown on January 15 and 30, 2022, 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 15 to May 15, 2022. The average days for heading of the group was 68.7 for the first sowing date and 64.7 for the second one, while days for physiological maturity were 102 and 94, respectively. The average plant height of the group for the first date was 95 cm and 83 for the second one; the sister line CI7260//2*KACHU*2/FRNCLN (PTSS16B00053T-099Y-099M-7Y-020Y-0B-0Y) showed the highest average height with 97.5 cm. The average grain yield per plot was 350 g; sister line SOKOLL/3/PASTOR//HXL7573/2*BAU/4/WBLL4//OAX93.24.35/WBLL1/5/MUTUS*2/CHONTE (PTSS16Y 00213S-0B-099Y-099M-13Y-020Y-0B-0Y) showed the highest average yield with 418 g which was above 5.2 t ha^{-1}, followed by SOKOLL/3/PASTOR//HXL7573/2*BAU/5/CROC_1/AE.SQUARROSA(205)//BORL95 /3/PRL/SARA //TSI/VEE#5/4/FRET2/6/SHORTENEDSR26TRANSLOCATION//2*WBLL1*2/KKTS/3/ BECARD which corresponded to 5.19 t ha^{-1}. The average hourly temperature was 18.3 °C with a maximum of 38.3 °C and a minimum of 2.3 °C, the average relative humidity was 62.3 %, and the number of heat and cold units was 236 and 489, respectively.

Keywords: Wheat; *Triticum* spp; Grain Yield; Drought Stress; Heat Stress

1. Introduction

The world has witnessed severe heatwaves and drought stress in recent decades, especially in major wheat-producing regions, such as Australia, Western Europe, Russia, United States, India, and Pakistan [1]. 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 [2,3]. 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. It affects the wheat plant to varying degrees at different phenological stages, but it is more harmful during the reproductive than 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 [4,5]. At mid-anthesis, an increase in temperature of about 10 °C might induce a 40 % decrease in grain number per spike [6]. Grain yield in winter cereals may be reduced by high temperatures during the grain-filling stage from 10 to 15 % [7,8]. Wheat is cultivated in tropical or subtropical areas [9], where the temperature during the coolest month of the crop season is higher than 17.5 °C. There are more than 7 million hectares under this condition, located

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primarily in Southeast Asia, in India and Bangladesh [10], in Sub-Saharan Africa [11], Brazil, Thailand, Uganda, Mexico, Sudan, Egypt, Nigeria, and Syria [12]. In order 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 a 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 [6]. 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 [7]. Wheat consumption and importation by developing countries in the warmer regions are factors that lead to the increase of local wheat production [13]. 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. Drought stress occurs when the amount of water reaching the plant roots may not be enough for the transpiration of the leaves, leading to a reduction in water potential and cell dehydration. 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 [14,15]. 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 [16]. The objective of this work was to evaluate the performance of a set of wheat lines comprising the 11th SATYN, subjected to late sowing, and therefore, exposed to a warmer and shorter crop season with reduced irrigation.

2. Materials and methods

Thirty eight advanced bread wheat lines from the 11th Stress Adapted Trait Yield Nursery (SATYN), which included eight groups of sister lines (lines 2-5; 7-8; 11-12; 13 and 15-16; 21-22; 23-25; 28-29; and 34-37) (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, 2022, 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 [17] was used as a check.

Table 1 Advanced bread wheat lines from the 11th Stress Adaptive Trait Yield Nursery from CIMMYT, sown on January 15 and 30, 2022, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico.

No	Pedigree and selection history
1	SOKOLL CMSS97M00316S-0P20M-0P20Y-43M-010Y
2	KS940935.7.1.2/2*PASTOR/4/FRAME//MILAN/KAUZ/3/PASTOR/5/KUTZ PTSS17Y00001S-0B-099Y-099M-6Y-0Y
3	KS940935.7.1.2/2*PASTOR/4/FRAME//MILAN/KAUZ/3/PASTOR/5/KUTZ PTSS17Y00001S-0B-099Y-099M-11Y-0Y
4	KS940935.7.1.2/2*PASTOR/4/FRAME//MILAN/KAUZ/3/PASTOR/5/KUTZ PTSS17Y00001S-0B-099Y-099M-20Y-0Y
5	KS940935.7.1.2/2*PASTOR/4/FRAME//MILAN/KAUZ/3/PASTOR/5/KUTZ PTSS17Y00001S-0B-099Y-099M-23Y-0Y
6	SOKOLL/3/PASTOR//HXL7573/2*BAU/4/CROC_1/AE.SQUARROSA (224)//OPATA/3/SOKOLL/5/BAJ #1 PTSS17Y00185S-0B-099Y-0M-10Y-0Y

7	SOKOLL/3/PASTOR//HXL7573/2*BAU/4/CROC_1/AE.SQUARROSA(224)//OPATA/3/ SOKOLL/5/KACHU*2/FRNCLN PTSS17Y00186S-0B-099Y-0M-2Y-0Y
8	SOKOLL/3/PASTOR//HXL7573/2*BAU/4/CROC_1/AE.SQUARROSA(224)//OPATA/3/ SOKOLL/5/KACHU*2/FRNCLN PTSS17Y00186S-0B-099Y-0M-4Y-0Y
9	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
10	SOKOLL/3/PASTOR//HXL7573/2*BAU/4/PARUS/PASTOR/5/KACHU*2/FRNCLN PTSS17Y00188S-0B-099Y-0M-8Y-0Y
11	FRTL/SOKOLL//KACHU*2/FRNCLN PTSS17Y00195S-0B-099Y-0M-25Y-0Y
12	FRTL/SOKOLL//KACHU*2/FRNCLN PTSS17Y00195S-0B-099Y-0M-32Y-0Y
13	MILAN/KAUZ//PRINIA/3/BAV92/4/WBLL1*2/KUKUNA/5/KACHU*2/FRNCLN PTSS17Y00209S-0B-099Y-0M-16Y-0Y
14	BORLAUG100 F2014 CMSS06Y00605T-099TOPM-099Y-099ZTM-099Y-099M-11WGY-0B-0MEX
15	MILAN/KAUZ//PRINIA/3/BAV92/4/WBLL1*2/KUKUNA/5/KACHU*2/FRNCLN PTSS17Y00209S-0B-099Y-0M-25Y-0Y
16	MILAN/KAUZ//PRINIA/3/BAV92/4/WBLL1*2/KUKUNA/5/KACHU*2/FRNCLN PTSS17Y00209S-0B-099Y-0M-34Y-0Y
17	VORB//PARUS/PASTOR/4/MUTUS//KIRITATI/2*TRCH/3/WHEAR/KRONSTAD F2004 PTSS17Y00217S-0B-099Y-099M-17Y-0Y
18	WORRAKATTA/2*PASTOR/4/MUTUS//KIRITATI/2*TRCH/3/WHEAR/KRONSTAD F2004 PTSS17Y00241S-0B-099Y-099M-41Y-0Y
19	WBLL1/6/CMH79A.955/4/AGA/3/4*SN64/CNO67//INIA66/5/NAC/7/QUAIU #1 PTSS17Y00278S-0B-099Y-099M-29Y-0Y
20	W15.92/4/PASTOR//HXL7573/2*BAU/3/WBLL1/5/SOKOLL/WBLL1 PTSS17Y00284S-0B-099Y-0M-22Y-0Y
21	KAPUDE/AE.SQUARROSA (341)//2*KUTZ PTSS17B00013T-099Y-099M-21Y-0Y
22	KAPUDE/AE.SQUARROSA (341)//2*KUTZ PTSS17B00013T-099Y-099M-23Y-0Y
23	CETA/AE.SQUARROSA (1013)//2*KACHU*2/FRNCLN PTSS17B00096T-099Y-0M-6Y-0Y
24	CETA/AE.SQUARROSA (1013)//2*KACHU*2/FRNCLN PTSS17B00096T-099Y-0M-13Y-0Y
25	CETA/AE.SQUARROSA (1013)//2*KACHU*2/FRNCLN PTSS17B00096T-099Y-0M-21Y-0Y
26	ARLIN_1/AE.SQUARROSA (237)//2*KACHU*2/FRNCLN PTSS17B00099T-099Y-0M-18Y-0Y

27	PASTOR//HXL7573/2*BAU/3/WBLL1/4/MUTUS*2/CHONTE PTSS16Y00202S-0B-099Y-099M-3Y-020Y-0B-0Y
28	SOKOLL/3/PASTOR//HXL7573/2*BAU/4/WBLL4//OAX93.24.35/WBLL1/5/MUTUS*2/CHONTE PTSS16Y00207S-0B-099Y-099M-11Y-020Y-0B-0Y
29	SOKOLL/3/PASTOR//HXL7573/2*BAU/4/WBLL4//OAX93.24.35/WBLL1/5/MUTUS*2/CHONTE PTSS16Y00207S-0B-099Y-099M-13Y-020Y-0B-0Y
30	SOKOLL/WBLL1/4/SHORTENEDSR26TRANSLOCATION//2*WBLL1*2/KKTS /3/BECARD PTSS16Y00230S-0B-099Y-099M-38Y-020Y-0B-0Y
31	SOKOLL/3/PASTOR//HXL7573/2*BAU/5/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2/6/SHORTENEDSR26TRANSLOCATION//2*WBLL1*2/KKTS /3/BECARD PTSS16Y00234S-0B-099Y-099M-5Y-020Y-0B-0Y
32	SOKOLL/3/PASTOR//HXL7573/2*BAU/4/SOKOLL/WBLL1/5/KACHU*2/FRNCLN PTSS16Y00261S-0B-099Y-099M-32Y-020Y-0B-0Y
33	SOKOLL/3/PASTOR//HXL7573/2*BAU/4/WBLL4//OAX93.24.35/WBLL1/5/KACHU*2/FRNCLN PTSS16Y00262S-0B-099Y-099M-10Y-020Y-0B-0Y
34	CI7260//2*KACHU*2/FRNCLN PTSS16B00053T-099Y-099M-4Y-020Y-0B-0Y
35	CI7260//2*KACHU*2/FRNCLN PTSS16B00053T-099Y-099M-7Y-020Y-0B-0Y
36	CI7260//2*KACHU*2/FRNCLN PTSS16B00053T-099Y-099M-31Y-020Y-0B-0Y
37	CI7260//2*KACHU*2/FRNCLN PTSS16B00053T-099Y-099M-36Y-020Y-0B-0Y
38	CMH82.575/CMH82.801/3/PASTOR//HXL7573/2*BAU PTSS17GHB01919S-61GHB-0GHB-0GHB-0GHB-0B-0Y
39	WBLL1//PUB94.15.1.12/WBLL1/3/MUCUY PTSS14Y00345S-0B-099Y-099B-29Y-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.* [18]. The daily average temperature (°C), the maximum and minimum, relative humidity, the number of cold and heat units, and precipitation were recorded from January 15 to May 15, 2022 by the weather station CIANO-910, located in block 910 in the Yaqui Valley [19]; this station belongs to the automated weather station network of Sonora [20]. 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 [21]. The variables evaluated were: days to heading, days to physiological maturity, plant height (cm), a thousand grain weight (g), 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 11.7-26.3 °C (Figure 1), while for the maximum temperature it was 19.3-38.3 °C and 2.4-18.0 °C for the minimum temperature. Maximum temperatures above 30 °C occurred from one to several hours during the following days: February 13 (2 h), March 14 (1), 15 (1), 19 (1), 23 (4), 24 (4), 25 (5), 27 (1), 31 (2), April 6 (3), 7 (6), 8 (1), 14 (3), 15 (2), 16 (7), 17 (7), 18 (8), 19 (6), 20 (5), 21 (7), 24 (4), 25 (7), 26 (8), 27 (8), 28 (8), 29 (3), 30 (7), May 1 (5), 2 (6), 3 (6), 4 (4), 5 (7), 6 (9), 7 (8), 8 (8), 9 (9), 10 (9), 11 (10), 12 (9), 13 (8), 14 (9), 15 (8) (Figure 2). The highest prevalence of heat units during 2021 [22] occurred from

March 28 to April 5 and from April 15 to May 15, while for 2022, there was more persistence on the occurrence of heat units from April 6 to May 15. Heading dates for the first sowing date occurred from March 17 to 30 and from April 5 to 12 for the second date, therefore, plants in the first date were only exposed to 15 HU distributed across five days during March 19-27, while plants in the second date were exposed to 10 HU distributed across three days, and one of those three had 6 HU; consequently, heat stress might affected flowering [stage 65, 23] to some degree, and so the grain yield final outcome. Continuous hours from two to five on 18 different days with temperature above 30 °C occurred between 10:00 and 16:00 pm, while from six to ten on 24 different days between 9:00 am and 18:00 pm.

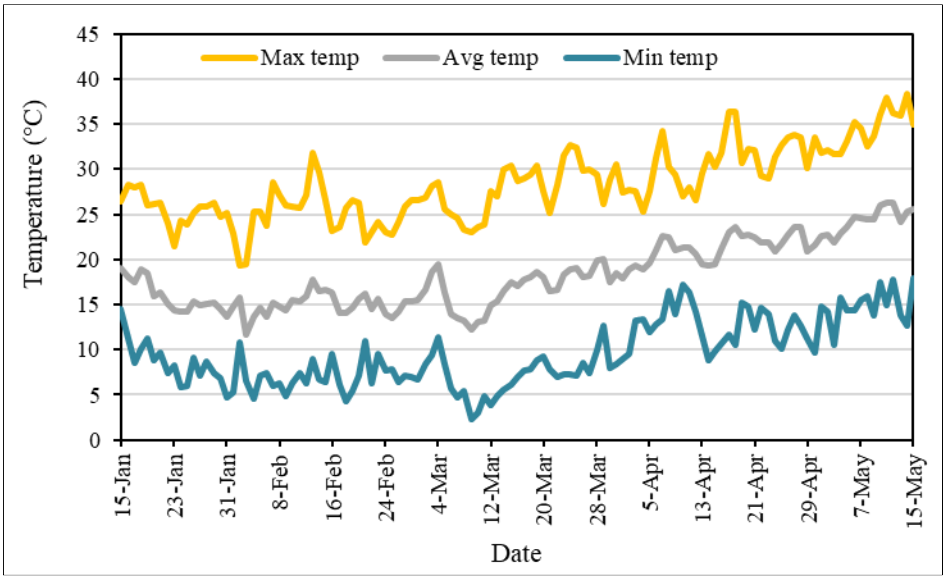

Figure 1 Average temperature from January 15 to May 15, 2022, recorded by the weather station CIANO-910, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico, during the crop season 2021-2022

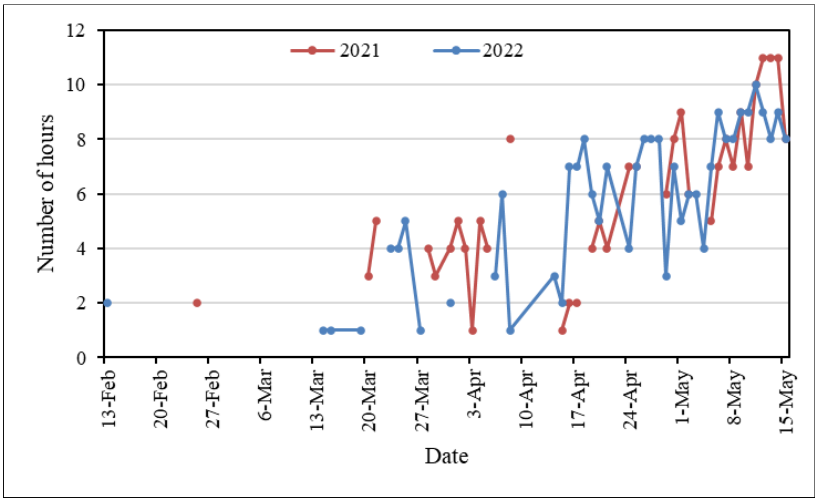

Figure 2 Daily occurrence of heat units from January 15 to May 15, 2022, recorded by the weather station CIANO-910, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico, during the crop seasons 2020-2021 and 2021-2022

Weeks where the maximum temperature reached more than 30 °C in some days and in some hours were February 13-19 with 2 HU, March 13-19 (3), 20-26 (13), March 27-April 2 (3), April 3-9 (10), 10-16 (12), 17-23 (33), 24-30 (45), May 1-7 (45), 8-15 (70); the total heat units accumulated during the period of time that covered this work was 236, being a season with greater number of HU than 2021 with 203 [22], but lower than 2020 with 229 [24]. In relation to cold units, with the exception of weeks April 3-9, 17-23, and May 1-7 and 8-15, the rest of the weeks starting from January 15-22 to March 27-April 2, April 10-16 and April 24-30, accumulated cold units ranging from 2 to a maximum of 72 during the week of March 6-12, followed by the weeks of February 6-12 and January 30-February 5, with 62 and 59, respectively

(Figure 3). A total of 489 cold units were recorded during the period of the study. All the phenological stages of the wheat plant are sensitive to temperature fluctuation; 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 [25], and although wheat is a cool-season crop whose production is concentrated between latitudes 30-60 °N and 27-40 °S under different climatic areas, it can be grown beyond these limits, with an optimum growth temperature of about 25 °C [26].

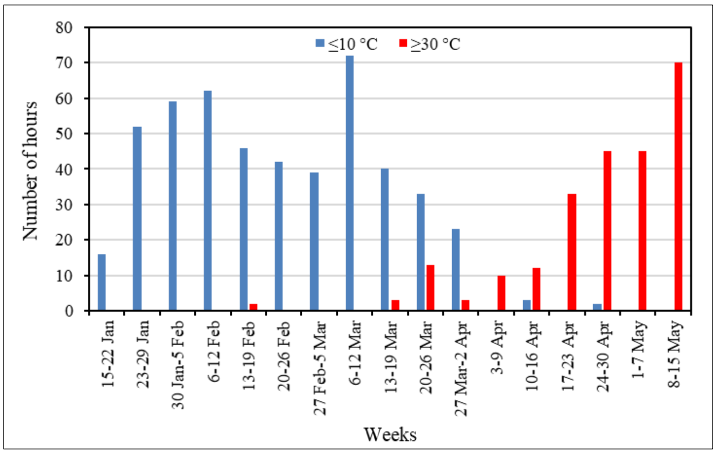

Figure 3 Number of cold and heat units accumulated from January 15 to May 15, 2022, recorded by the weather station CIANO-910, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico, during the crop season 2021-2022

The wheat plant requires the accumulation of cold units to prolong its biological cycle, which generally leads to a higher grain yield [21]. During January the daily low temperature range was 4.6-14.5 °C, in February 4.3-10.9 °C, in March 2.4-12.6 °C, in April 8.8-17.1 °C, and in May 10.5-17.9 °C. Sowing dates recommended for wheat in 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 [18]. 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 68.7 for the first sowing date and 64.7 for the second; line CMH82.575/CMH82.801/3/PASTOR//HXL7573/2*BAU (No. 38) headed 72 days after the first sowing date, while cultivar Borlaug 100 (No. 14) headed 71 das, and sister line MILAN/KAUZ//PRINIA/3/BAV92/4/WBLL1*2/KUKUNA/5/KACHU*2/FRNCLN (PTSS17Y00209S-0B-099Y-0M-25Y-0Y, No. 15) 62 das (Figure 4).

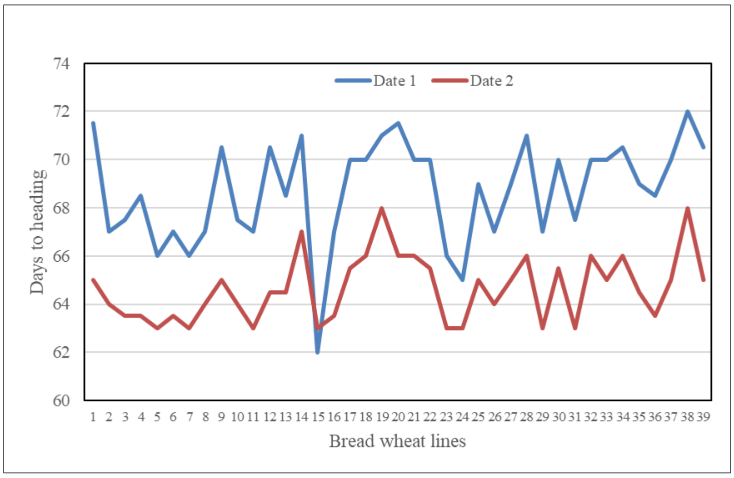

Figure 4 Days to heading of bread wheat cultivar Borlaug 100 (No. 14), and 38 advanced bread wheat lines adapted to stress, sown late on January 15 and 30, 2022, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico

In the second date, lines WBLL1/6/CMH79A.955/4/AGA/3/4*SN64/CNO67//INIA66/5/NAC/7/QUAIU #1 (No. 19) and CMH82.575/CMH82.801/3/PASTOR//HXL7573/2*BAU (No. 38) headed 68 das, lines No. 5, 7, 11, 15, 23, 24, 29, and 31, headed 63 das, while cultivar Borlaug 100 (No. 14) 67 das. Lines that had a three day difference or less for heading during the first and second dates were No. 2, 5, 7, 8, 15, 19, 23, 24, and 26, while those with a larger difference of 3.5-4.5 days were No. 3, 6, 10, 11, 13, 14, 16, 17, 18, 21, 22, 25, 27, 29-32, 34, 35, and 38, with 5-6.5 days difference were No. 1, 4, 9, 12, 20, 28, 33, 36, 37, and 39. The highest difference of 6 and 6.5 five days was shown by sister line FRTL/SOKOLL//KACHU*2/FRNCLN (PTSS17Y00195S-0B-099Y-0M-32Y-0Y, No. 12) and SOKOLL (No. 1), respectively. The average plant height of the group was 95 cm for the first sowing date and 83 cm for the second (Figure 5).

Figure 5 Plant height of bread wheat cultivar Borlaug 100 (No. 14), and 38 advanced bread wheat lines adapted to stress, sown late on January 15 and 30, 2022, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico

Sister line CI7260//2*KACHU*2/FRNCLN (PTSS16B00053T-099Y-099M-7Y-020Y-0B-0Y, No. 35) was the tallest in the first date with 107.5 cm, followed by lines No. 3, 5, 10, 29, 30, and 36 with 100 cm, while cultivar Borlaug (No. 14) showed 87.5 cm. In the second date, there were six lines with the maximum height of 90 cm (No. 9, 28, 29, 34, 36 and 39), while sister line SOKOLL/3/PASTOR//HXL7573/2*BAU/4/CROC_1/AE.SQUARROSA(224)//OPATA/3/SOKOLL /5/KACHU*2/FRNCLN (PTSS17Y00186S-0B-099Y-0M-4Y-0Y, No. 8) and cultivar Borlaug 100 (No. 14) showed a height of 75 cm. All the lines and cultivar Borlaug 100 showed differences in height between the first sowing date and the second one, and in all cases, the first date was taller with a range of 7.5 to 20 cm. Lines with the maximum difference of 20 cm were No. 2, 5, 8, and 35, cultivar Borlaug 100 had a difference of 12.5 cm. During the crop seasons 2016-2017 to 2020-2021, the groups of lines that comprised the SATYN have shown an average heading days of 69 with a range of 66 to 74, and an average height of 83 cm with a range of 60 to 96 [22,24,27,28,29]. During the same time, cultivar Borlaug 100 had an average heading days of 69 days with a range of 64 to 74, and an average height of 76 cm with a range of 60 to 86. Despite the rather similar monthly average temperature in 2021 and 2022 (Table 2), the average grain weight per plot was higher in 2022 with 350 g (4.37 t ha^{-1}), while it was 294 (3.67 t ha^{-1}) in 2021 [22]. The occurrence of heat units during 2021 was higher during the heading-flowering of the wheat plant than in 2022.

Table 2 Average monthly temperatures recorded by the weather station CIANO B-910, during mid-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		
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
2022	15.91	15.00	16.82	21.25	24.36	67	89

The average physiological maturity of the group of lines and cultivar Borlaug 100 in this study occurred after 102 days for the first sowing date and 94 for the second, with a range of 97 to 105 and 90 to 96, respectively (Figure 6).

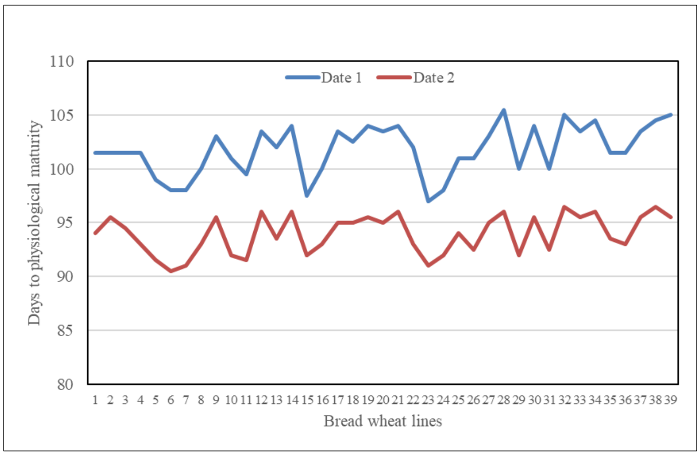

Figure 6 Days to physiological maturity of bread wheat cultivar Borlaug 100 (No. 14), and 38 advanced bread wheat lines adapted to stress, sown late on January 15 and 30, 2022, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico

The average a thousand grain of the group in the first sowing date was 39.5 g and 39.7 in the second (Figure 7); in the first date, line ARLIN_1/AE.SQUARROSA (237)//2*KACHU*2/FRNCLN (No. 26) showed the highest weight with 45.8 g, followed by the line SOKOLL/3/PASTOR//HXL7573/2*BAU/5/CROC_1/AE.SQUARROSA (205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2/6/SHORTENED SR26 TRANSLOCATION//2*WBLL1*2/ KKTS/3/BECARD (No. 31) with 44.9 g, and sister line MILAN/KAUZ//PRINIA/3/BAV92/4/WBLL1*2/KUKUNA/5/KACHU*2/FRNCLN (PTSS17Y00209S-0B-099Y-0M-25Y-0Y, No. 15) with 44.4 g, while sister line FRTL/SOKOLL//KACHU*2/FRNCLN (PTSS17Y00195S-0B-099Y-0M-32Y-0Y, No. 12), showed the lowest grain weight with 30.5 g. In the second date, the line SOKOLL/3/PASTOR//HXL7573/2*BAU/5/CROC_1/AE.SQUARROSA (205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2/6/SHORTENEDSR26TRANSLOCATION//2*WBLL1*2/KKTS/3/BECARD (No. 31) showed the highest a thousand grain weight with 46.4 g, followed by sister line CI7260//2*KACHU*2/FRNCLN (PTSS16B00053T-099Y-099M-31Y-020Y-0B-0Y, No. 36) with 45 g, and SOKOLL/3/PASTOR//HXL7573/2*BAU/4/PARUS/PASTOR/5/KACHU*2/FRNCLN (No. 10) with 43 g; line W15.92/4/PASTOR//HXL7573/2*BAU/3/WBLL1/5/SOKOLL/WBLL1 (No. 20) showed the lowest a thousand grain weight with 34.5 g.

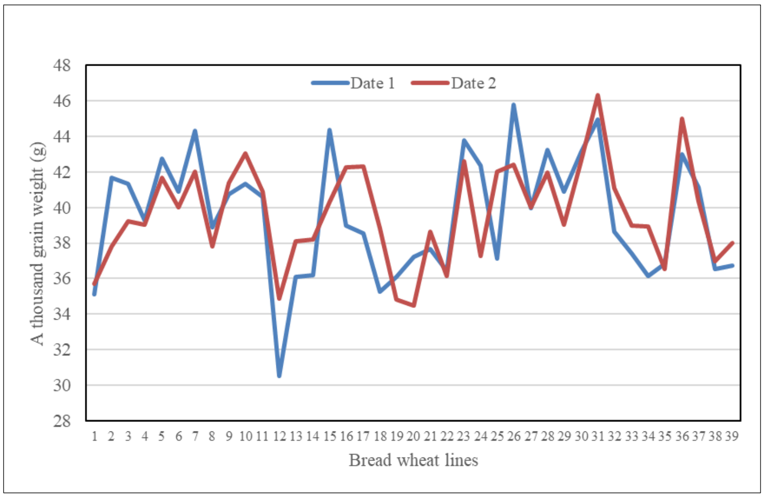

Figure 7 A thousand grain weight of bread wheat cultivar Borlaug 100 (No. 14), and 38 advanced bread wheat lines adapted to stress, sown late on January 15 and 30, 2022, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico

The average grain weight per plot of the group in the first sowing date was 380 g and 320 in the second (Figure 8); in the first date, line SOKOLL/3/PASTOR//HXL7573/2*BAU/5/CROC_1/AE.SQUARROSA(205)//BORL95/3/ PRL/SARA //TSI/VEE#5/4/FRET2/6/SHORTENEDSR26TRANSLOCATION//2*WBLL1*2/KKTS/3/BECARD (No. 31) showed the highest weight with 465 g, followed by the sister line SOKOLL/3/PASTOR//HXL7573/2*BAU/4/WBLL4// OAX93.24.35/WBLL1/5/MUTUS*2/CHONTE (PTSS16Y00207S-0B-099Y-099M-11Y-020Y-0B-0Y, No. 28) with 460 g, while sister line FRTL/SOKOLL//KACHU*2/FRNCLN (PTSS17Y00195S-0B-099Y-0M-32Y-0Y, No. 12), showed the lowest grain weight with 290 g. In the second date, sister line SOKOLL/3/PASTOR//HXL7573/2*BAU/4/WBLL4 //OAX93.24.35/WBLL1/5/MUTUS*2/CHONTE (PTSS16Y00213S-0B-099Y-099M-13Y-020Y-0B-0Y, No. 29) showed the highest grain weight per plot with 395 g, followed by W15.92/4/PASTOR//HXL7573/2*BAU/3/WBLL1/5/SOKOLL /WBLL1 (No. 20), SOKOLL/3/PASTOR//HXL7573/2*BAU/5/CROC_1/AE.SQUARROSA (205)//BORL95/3/PRL/SARA //TSI/VEE#5/4/FRET2/6/SHORTENEDSR26TRANSLOCATION//2*WBLL1*2/KKTS/3/BECARD (No. 31), and WBLL1 // PUB94.15.1.12/WBLL1/3/MUCUY (No. 39) with 365 g. Sister line FRTL/SOKOLL//KACHU*2/FRNCLN (No. 12) as in the first date, showed the lowest grain yield per plot with 225 g.

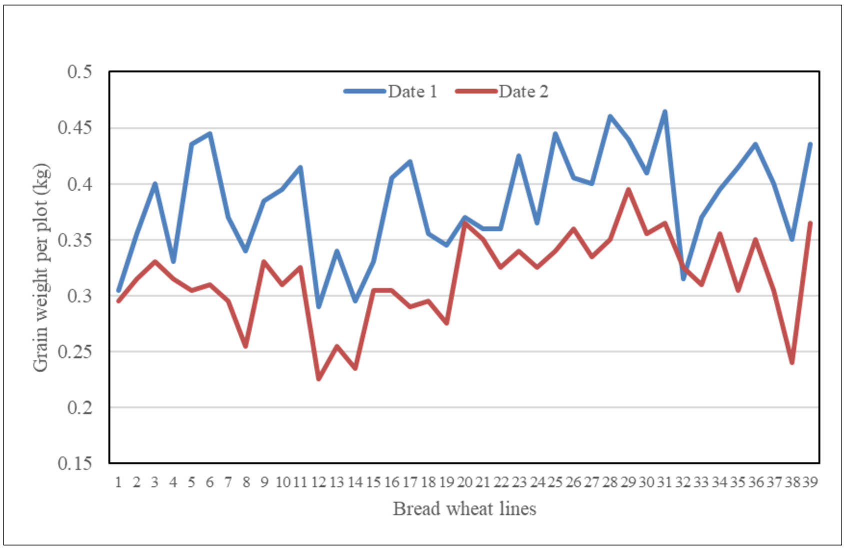

Figure 8 Grain weight per plot of bread wheat cultivar Borlaug 100 (No. 14), and 38 advanced bread wheat lines adapted to stress, sown late on January 15 and 30, 2022, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico

The stability shown by cultivar Borlaug 100 in previous evaluations similar to this work, during 2017, 2018, and 2020 where it was estimated a grain yield from 4.3 to 5.0 t ha^{-1} [24,27,28], was not observed in 2021 [22] as well as in the present work, since the grain yield estimated was 3.8 and 3.3 t ha-1, respectively. 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 [30]. 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 % [31]. With the exception of line SOKOLL/3/PASTOR//HXL7573/2*BAU/4/SOKOLL/WBLL1/5/KACHU*2/FRNCLN (No. 32), the rest showed higher grain yield in the first date than in the second one. Ten lines showed a difference equal or greater than 100 g of grain weight per plot between the first and second sowing dates, being SOKOLL/3/PASTOR//HXL7573/2*BAU /4/CROC_1/AE.SQUARROSA (224)//OPATA/3/SOKOLL/5/BAJ #1 the line with the greatest difference of 140 g, followed by sister line KS940935.7.1.2/2*PASTOR/4/FRAME//MILAN/ KAUZ/3/PASTOR/5/KUTZ (PTSS17Y00001S-0B-099Y-099M-23Y-0Y, No. 5), and VORB//PARUS/PASTOR/4/ MUTUS//KIRITATI/2*TRCH/3/WHEAR/KRONSTAD F2004 (No. 17) with 130 g difference. Lines with a difference of 100 to 110 g were: No. 16, 25, 28, 31, 35, 37, and 38, while 18 had a difference between 50 and 99 g. Lines with the best agronomic type consistent in both dates were: sister lines KAPUDE/AE.SQUARROSA (341)//2*KUTZ (PTSS15Y00111S-099B-099Y-099M-9Y-020Y-0B (PTSS17B00013T-099Y-099M-21Y-0Y, No. 21), and CI7260//2*KACHU*2/FRNCLN (PTSS16B00053T-099Y-099M-7Y-020Y-0B-0Y, No. 35). The temperature that prevailed during this work with an average monthly range of 15.0 to 24.4 °C and an overall average of 18.3 °C, was rather similar as that reported for the years 2019 [29], 2020 [24], and 2021 [22], however, the heat stress exerted during heading (Figure 2) [32] might have caused lower grain yield per plot in the group of lines that comprised the 10th SATYN in 2021. The two complementary irrigations caused drought stress on the wheat plants, affecting all the stages of development, the vegetative and reproductive growth to grain filling and maturation of the crop [33]. Nitrogen uptake efficiency is reduced as well as its 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. Stomatal closure causes the reduction in CO_2 intake, 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 % [33]. The check cultivar used in this work Borlaug 100, has been the main bread wheat cultivar in the Yaqui Valley, with a sown area of 9,309 to 44,381 ha from the crop season 2018-2019 to 2021-2022 [34,35,36,37]; it may produce a grain yield of 8.797 t ha^{-1} under full irrigation (four complementary irrigations) [38], while under reduced irrigation, it may yield 4.3 t ha^{-1} [29], 3.8 t ha^{-1} [22] or 3.3 t ha^{-1}, as it was the case in this work.

4. Conclusion

The average days for heading of thirty-eight advanced bread wheat lines and bread wheat cultivar Borlaug 100 was 68.7 days for the first sowing date and 64.7 for the second, while days for physiological maturity were 102 and 94, respectively.

The average plant height of the group for the first date was 95 cm and 83 for the second one; the sister line CI7260//2*KACHU*2/FRNCLN (PTSS16B00053T-099Y-099M-7Y-020Y-0B-0Y) showed the highest average height with 97.5 cm.

The average grain yield per plot was 350 g; sister line SOKOLL/3/PASTOR//HXL7573/2*BAU/4/WBLL4// OAX93.24.35/WBLL1/5/MUTUS*2/CHONTE (PTSS16Y 00213S-0B-099Y-099M-13Y-020Y-0B-0Y) showed the highest average yield with 418 g which was above 5.2 t ha^{-1}, followed by SOKOLL/3/PASTOR//HXL7573/2*BAU/5/ CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2/6/SHORTENEDSR26 TRANSLOCATION//2*WBLL1*2/KKTS/3/ BECARD, which corresponded to 5.19 t ha^{-1}.

The average hourly temperature was 18.3 °C with a maximum of 38.3 °C and a minimum of 2.3 °C; the average relative humidity was 62.3 %; there were 1.7 mm of precipitation, and the number of heat and cold units was 236 and 489, respectively.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that No conflict of interest.

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