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Performance of advanced bread wheat lines and cultivars under late sowing during the crop season 2022-2023

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Abstract

Thirty-nine advanced bread wheat lines and cultivars Borlaug 100 and CIANO M2018 were sown on January 15 and 30, 2023, at the Norman E. Borlaug Experimental Station, in the Yaqui Valley, Sonora, Mexico. 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, 2023. The average days for heading of the group was 72 for the first sowing date and 67 for the second one, while days for physiological maturity were 106 and 99, respectively. The average plant height of the group for the first date was 90.3 cm and 80.5 for the second one; the 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 showed the highest average height with 97.5 cm. The average a thousand grain weight was 36.8 g; the line TACUPETOF2001/6/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2/5/CIRO16 showed the highest average TGW with 46.2 g. The average grain yield per plot was 380 g; sister line VORB//PARUS/PASTOR/4/MUTUS//KIRITATI/2*TRCH/3/WHEAR/KRONSTADF2004 (PTSS17Y00217S-0B-099Y-099M-35Y-0Y) showed the highest average yield with 504 g which corresponded to 6.30 t ha^{-1}, followed by SOKOLL/WBLL1/5/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2/6/SOKOLL/3/ PASTOR//HXL7573/2*BAU/5/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2 with 466 g (5.82 t ha^{-1}). The average hourly temperature was 17.4 °C with a maximum of 34.7 °C and a minimum of 2.6 °C, the average relative humidity was 60.6 %, there were 81.7 mm of precipitation, and the number of heat and cold units was 187 and 510, respectively.

Keywords: Wheat; Triticum SPP; Grain Yield; Drought Stress; Heat Stress

1. Introduction

In recent decades, the world has experienced increasingly severe heatwaves and drought conditions, particularly in key wheat-producing regions, such as Australia, Western Europe, Russia, United States, India, and Pakistan [1,2]. Heat stress is defined as an increase in temperature beyond a critical threshold for a sufficient duration that causes irreversible negative effect on plant growth and development [3,4]. High temperatures impact crops in various ways, depending on

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the duration, the rate of temperature increase, and whether the stress occurs during the day or night. In wheat, the effect of heat stress varies across phenological stages, with the reproductive phase being more sensitive than the vegetative phase. This heightened sensitivity is due to direct impact on grain number, dry weight as well as grain quality. However, the extent of damage also depends on the specific genotype [5,6]. An increase in temperature of approximately 10 °C during mid-anthesis can lead to a reduction of up to 40 % in the number of grains per spike [7]. In winter cereals, exposure to high temperatures during the grain-filling stage may result in a grain yield reduction ranging from 10 to 15 % [8,9]. Wheat is cultivated in tropical or subtropical areas [10], 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 primarily in Southeast Asia, in India and Bangladesh [11], in Sub-Saharan Africa [12], Brazil, Thailand, Uganda, Mexico, Sudan, Egypt, Nigeria, and Syria [13]. To meet the rising global demand for food, wheat productivity must be enhanced in both favorable and marginal environments. Wheat plants have evolved various adaptive mechanisms to cope with heat stress, including morphological and growth adjustments, physiological and biochemical changes, and alterations in enzyme activity. Although numerous heat tolerance genes have been identified in wheat, further in-depth research is essential to improve heat resilience in crops. Strengthening global food security will require coordinated research efforts and targeted breeding programs to develop heat-tolerant wheat cultivars, which should be prioritized within international food policy agendas [7]. In temperate regions, the flowering of winter crops must occur with minimal risk of frost, making the timing of sowing a critical factor. This is especially important as high temperatures typically coincide with the grain-filling period. Among winter cereals, high temperature and limited water availability are the most prevalent abiotic stresses affecting yield and crop performance [8]. Wheat consumption and importation by developing countries in the warmer regions are factors that lead to the increase of local wheat production [14]. Drought, defined as the insufficient availability of moisture required for normal plant growth and completion of the life cycle, is one of the most damaging environmental stresses impacting crop productivity. It occurs when water supply to the roots is inadequate to meet transpiration demands of the leaves, resulting in reduced water potential and cell dehydration. The primary effects of drought stress in plants include decreased rates of cell division and expansion, reduced leaf size, limited stem elongation, inhibited root proliferation, and disturbed stomatal regulation. Collectively, these physiological disruptions severely impair plant growth, development, and overall biomass accumulation [15,16]. The United Nations Development Programme (UNDP) played a pivotal role in supporting the efforts of wheat breeders at the International Maize and Wheat Improvement Center (CIMMYT) by providing the necessary resources and institutional backing to broaden their research scope. This collaboration enabled scientists to focus on developing high-yielding, disease-resistant, semi-dwarf wheat varieties specifically adapted to the warmer, subtropical regions of the world. These areas, often characterized by challenging growing conditions such as high temperatures, variable rainfall, and increased disease pressure, had previously been underserved by traditional wheat breeding programs. The partnership between UNDP and CIMMYT significantly accelerated the global dissemination of improved wheat varieties, contributing not only to enhanced food security in developing countries, but also to the modernization of wheat production systems in climates vulnerable to the effects of climate change [17]. Therefore, the Stress Adaptive Trait Yield Nursery (SATYN) was implemented which 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 [18]. The objective of this work was to evaluate the performance of a set of wheat lines comprising the 12th SATYN, subjected to late sowing, and therefore, exposed to a warmer and shorter crop season with reduced irrigation.

2. Materials and methods

Thirty nine advanced bread wheat lines from the 12th Stress Adapted Trait Yield Nursery (SATYN), which included nine groups of sister lines (lines 6 and 17; 8 and 23; 9, 25, and 30; 11 and 34; 14, 15, and 24; 16 and 41; 20 and 28; 35 and 40; 37 and 39) (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, 2023, at the Norman E. Borlaug Experimental Station (CENEB) 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 F2014 [19] was used as a check. In experimental plots, it demonstrated average grain yields of 6.1 and 7.0 t ha^{-1} with two and four complementary irrigations, respectively. Cultivar CIANO M2018 was also included for comparison. Although it showed an average of 1.58 y 6.27 % higher grain yields than Borlaug 100 F2014 under four and two complementary irrigations, respectively, over three cropping seasons at CENEB [20], and yielded 7.19, 3.25, and 4.90 % more under four complementary irrigations in trials conducted in the states of Sonora, Sinaloa, and Baja California, a separate study reported that Borlaug 100 F2014 outperformed CIANO M2018 by 1.47 ha^{-1} [21]

Table 1 Advanced bread wheat lines from the 12th Stress Adaptive Trait Yield Nursery from CIMMYT, sown on January 15 and 30, 2023, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico

No	Pedigree and selection history
1	GARZA/BOY//AE.SQUARROSA (1037)/4/MUTUS//KIRITATI/2*TRCH/3/WHEAR/KRONSTAD F2004 PTSS17Y00417S-0B-099Y-099M-24Y-0Y
2	SOKOLL/WESTONIA/6/PFAU/MILAN/5/CHEN/AEGILOPSSQUARROSA(TAUS)//BCN/3/VEE#7/BOW/4/PASTOR PTSS17Y00316S-0B-099Y-099M-24Y-0Y
3	BORL14/BAJ #1 PTSS18Y00002S-0B-099Y-099B-23Y-0B
4	XIN-CHU-1-ST118/6/2*SOKOLL/3/PASTOR//HXL7573/2*BAU/5/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2 PTSS16B00009T-099Y-099M-099Y-7Y-099GOBW-0Y
5	NINGA #1 CMSA11Y00507S-099Y-099M-099NJ-099NJ-19WGY-0B
6	VORB//PARUS/PASTOR/4/MUTUS//KIRITATI/2*TRCH/3/WHEAR/KRONSTADF2004 PTSS17Y00217S-0B-099Y-099M-49Y-099GCBW-0Y
7	GARZA/BOY//AE.SQUARROSA(1037)/4/MUTUS//KIRITATI/2*TRCH/3/WHEAR/KRONSTADF2004 PTSS17Y00417S-0B-099Y-099M-9Y-0Y
8	ARLIN_1/AE.SQUARROSA(237)/4/MUTUS//KIRITATI/2*TRCH/3/WHEAR/KRONSTADF2004 PTSS17Y00422S-0B-099Y-099M-47Y-0Y
9	GARZA/BOY//AE.SQUARROSA(294)/4/MUTUS//KIRITATI/2*TRCH/3/WHEAR/KRONSTADF2004 PTSS17Y00415S-0B-099Y-099M-29Y-0Y
10	CIANO M2018 CMSS12B00828T-099TOPY-099M-0SY-42M-0WGY
11	MILAN/KAUZ//DHARWARDRY/3/BAV92/6/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/ VEE#5/4/FRET2/5/CIRO16 PTSS18Y00075S-0M-099Y-099M-26Y-0B

12	SOKOLL/WBLL1/5/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2/6/
	SOKOLL/3/PASTOR//HXL7573/2*BAU/5/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//
	TSI/VEE#5/4/FRET2
	PTSS16Y00140S-0B-099Y-099M-7Y-0Y

13	SORA/AE.SQUARROSA(617)//2*BORL14 PTSS18B00005T-099Y-099M-15Y-0B
14	68.111/RGB-U//WARD/3/FGO/4/RABI/5/AE.SQUARROSA(191)/6/MUTUS//KIRITATI/2*TRCH/3/ WHEAR/KRONSTADF2004 PTSS17Y00426S-0B-099Y-099M-37Y-0Y
15	68.111/RGB-U//WARD/3/FGO/4/RABI/5/AE.SQUARROSA(191)/6/MUTUS//KIRITATI/2*TRCH/3/ WHEAR/KRONSTAD F2004 PTSS17Y00426S-0B-099Y-099M-7Y-0Y
16	MEX94.27.1.20/3/SOKOLL//ATTILA/3*BCN/4/PUB94.15.1.12/WBLL1/5/MUCUY

	PTSS14Y00329S-0B-099Y-099B-33Y-020Y
17	VORB//PARUS/PASTOR/4/MUTUS//KIRITATI/2*TRCH/3/WHEAR/KRONSTADF2004 PTSS17Y00217S-0B-099Y-099M-35Y-0Y
18	TACUPETOF2001/6/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2/5/CIRO16 PTSS18Y00070S-0M-099Y-099M-18Y-0B
19	GARZA/BOY//AE.SQUARROSA(1037)/4/MUTUS//KIRITATI/2*TRCH/3/WHEAR/KRONSTAD F2004 PTSS17Y00417S-0B-099Y-099M-12Y-0Y
20	CHEN/AE. SQ//WEAVER/3/SSERI1/4/MUTUS//KIRITATI/2*TRCH/3/WHEAR/KRONSTADF2004 PTSS17Y00237S-0B-099Y-099M-48Y-0Y
21	MILAN/KAUZ//DHARWARDRY/3/BAV92/4/BORL14 PTSS18Y00059S-0M-099Y-099M-8Y-0B
22	BORLAUG100 F2014 CMSS06Y00605T-099TOPM-099Y-099ZTM-099Y-099M-11WGY-0B-0MEX
23	ARLIN_1/AE.SQUARROSA(237)/4/MUTUS//KIRITATI/2*TRCH/3/WHEAR/KRONSTADF2004 PTSS17Y00422S-0B-099Y-099M-33Y-0Y
24	68.111/RGBU//WARD/3/FGO/4/RABI/5/AE.SQUARROSA(191)/6/MUTUS//KIRITATI/2*TRCH/3/WHEAR/ KRONSTADF2004 PTSS17Y00426S-0B-099Y-099M-33Y-0Y
25	GARZA/BOY//AE.SQUARROSA (294)/4/MUTUS//KIRITATI/2*TRCH/3/WHEAR/KRONSTADF2004 PTSS17Y00415S-0B-099Y-099M-22Y-0Y
26	SOKOLL/WBLL1/5/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2/7/SOKOLL/3/PASTOR//HXL7573/2*BAU*2/6/OASIS/5*BORL95/5/CNDO/R143//ENTE/MEXI75/3/AE.SQ/4 /2*OCI PTSS18Y00169S-0M-099Y-099M-27Y-0B
27	SOKOLL/3/PASTOR//HXL7573/2*BAU/4/WBLL4//OAX93.24.35/WBLL1/5/D67.2/PARANA66.270//AE.SQUARROSA(320)/3/CUNNINGHAM/4/VORB PTSS14Y00013S-0B-099Y-099B-17Y-020Y-0B
28	CHEN/AE. SQ//WEAVER/3/SSERI1/4/MUTUS//KIRITATI/2*TRCH/3/WHEAR/KRONSTADF2004 PTSS17Y00237S-0B-099Y-099M-31Y-0Y
29	TUR.180085/QUAIU #1 PTSS17Y00260S-0B-099Y-099M-3Y-0B-0Y
30	GARZA/BOY//AE.SQUARROSA(294)/4/MUTUS//KIRITATI/2*TRCH/3/WHEAR/KRONSTADF2004 PTSS17Y00415S-0B-099Y-099M-25Y-0Y
31	SOKOLL/3/PASTOR//HXL7573/2*BAU/5/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2/7/SOKOLL/3/PASTOR//HXL7573/2*BAU*2/6/OASIS/5*BORL95/5/CNDO/R143//ENTE/MEXI75/3/AE.SQ/4/2*OCI PTSS18Y00165S-0M-099Y-099M-5Y-0B
32	SOKOLL CMSS97M00316S-0P20M-0P20Y-43M-010Y
33	CETA/AE.SQUARROSA(1011)/4/MUTUS//KIRITATI/2*TRCH/3/WHEAR/KRONSTADF2004 PTSS17Y00427S-0B-099Y-099M-65Y-0Y

34	MILAN/KAUZ//DHARWARDRY/3/BAV92/6/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/ VEE#5/4/FRET2/5/CIRO16 PTSS18Y00075S-0M-099Y-099M-5Y-0B
35	REDING//PUB94.15.1.12/WBLL1 PTSS18Y00234S-0M-099Y-099M-5Y-0B
36	REEDLING-GL5A_1/QUAIU PTSS18Y00248S-0M-2Y-0B-2Y-0B
37	REEDLING-GW6A_3/3/SERI/BAV92//PUB94.15.1.12/WBLL1 PTSS18Y00244S-0M-099Y-099M-2Y-0B
38	C80.1/3*QT4118//KAUZ/RAYON/3/2*TRCH/7/CMH79A.955/4/AGA/3/4*SN64/CNO67//INIA66/5/NAC/6/RIALTO/8/WBLL1*2/KURUKU/9/BOKOTA/10/WBLL1//PUB94.15.1.12/WBLL1/3/MUCUY PTSS18Y00022S-0B-099Y-099B-16Y-0B
39	REEDLING-GW6A_3/3/SERI/BAV92//PUB94.15.1.12/WBLL1 PTSS18Y00244S-0M-099Y-099M-19Y-0B
40	REDING//PUB94.15.1.12/WBLL1 PTSS18Y00234S-0M-099Y-099M-4Y-0B
41	MEX94.27.1.20/3/SOKOLL//ATTILA/3*BCN/4/PUB94.15.1.12/WBLL1/5/MUCUY PTSS14Y00329S-0B-099Y-099B-33Y-020Y

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*. [22]. 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, 2023 by the weather station CIANO-910, located in block 910 in the Yaqui Valley [23]; this station belongs to the automated weather station network of Sonora [24]. Cold units (CU) were calculated as the temperature > 0.1 °C to < 10 °C that occurs in a given hour and the heat units (HU) as the number of hours with temperature above 30 °C [25]. 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 13.4-22.0 °C (Figure 1), while for the maximum temperature it was 24.8-34.7 °C and 2.6-9.3 °C for the minimum temperature. Maximum temperatures above 30 °C occurred from one to several hours during the following days: March 11 (2 h), 12 (3), 13 (2), 14 (2), April 1 (2), 2 (3), 8 (4), 9 (5), 10 (4), 11 (6), 12 (2), 16 (5), 17 (4), 19 (4), 20 (4), 21 (6), 22 (7), 23 (6), 26 (5), 27 (7), 28 (5), 29 (8), 30 (7), May 1 (4), 4 (4), 5 (5), 6 (7), 7 (8), 8 (8), 9 (8), 10 (7), 11 (7), 12 (6), 13 (6), 14 (6), 15 (8) (Figure 2). As in crop season 2021-2022 [26], there was more persistence on the occurrence of heat units from April 6 to May 15, although in 2022 the occurrence of heat units was higher during February 13 to March 31 than in 2023. Heading dates for the first sowing date occurred from March 26 to April 1 and from April 3 to 12 for the second date. Plants from the first sowing date were exposed only to 2 HU on April 1; in contrast, plants from the second date experienced 21 HU over five days, with one of those days accounting for 6 HU. As a result, plants from the second date were likely exposed to greater heat stress during flowering [Zadoks stage 65, 27], which may have affected grain yield to some extent.

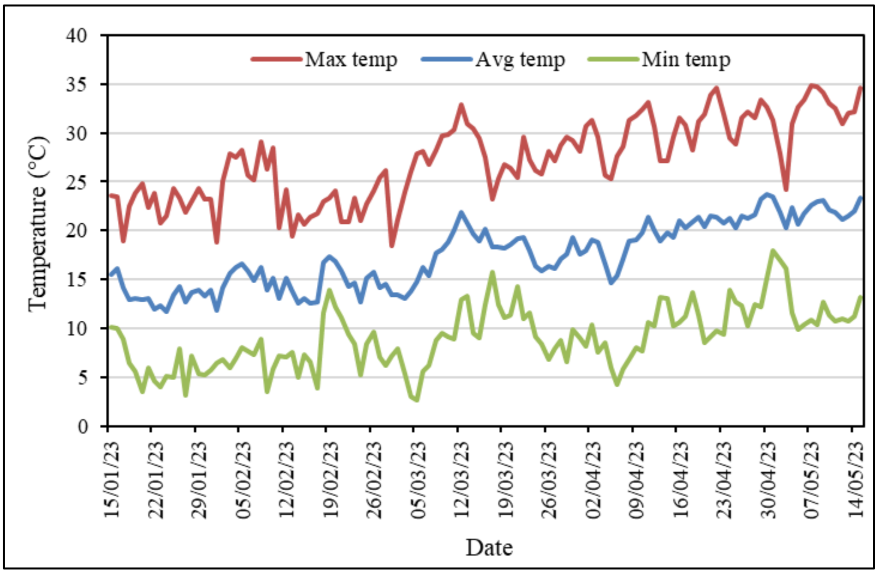

Figure 1 Average daily temperature from January 15 to May 15, 2023, recorded by the weather station CIANO-910, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico, during the crop season 2022-2023

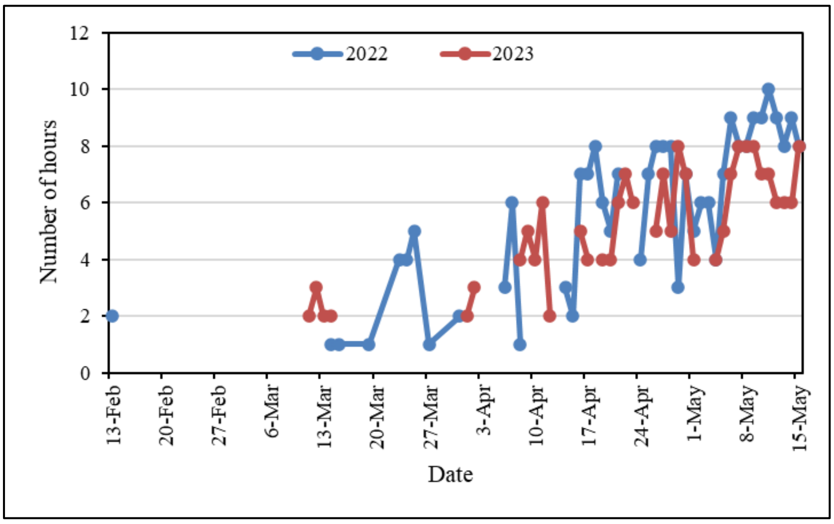

Figure 2 Daily occurrence of heat units from January 15 to May 15, 2023, recorded by the weather station CIANO-910, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico, during the crop seasons 2021-2022 and 2022-2023

Continuous hours from two to five on 19 different days with temperature above 30 °C occurred between 11:00 and 16:00 pm, while from six to eight on 17 different days between 10:00 am and 17:00 pm. Weeks where the maximum temperature reached more than 30 °C in some days and in some hours were March 5-11 (2), 12-18 (7), March 26-April 1 (2), April 2-8 (7), 9-15 (17), 16-22 (30), 23-29 (31), April 30-May 6 (27), 7-13 (50), 14-15 (14). The total heat units accumulated during the period of time that covered this work was 187, being a season with a lower number of HU than 2020, 2021, and 2022 with 229, 203 236, respectively [26,28,29]. In relation to cold units, with the exception of week May 7-13 and May 14 and 15, the rest of the weeks starting from January 15-21 to April 30-May 6, accumulated cold units ranging from 1 to a maximum of 68 during the week of January 22-28, followed by the weeks of January 29-February 4 and February 26-March 4, with 64 and 53, respectively (Figure 3). A total of 510 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 [30], 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 [31].

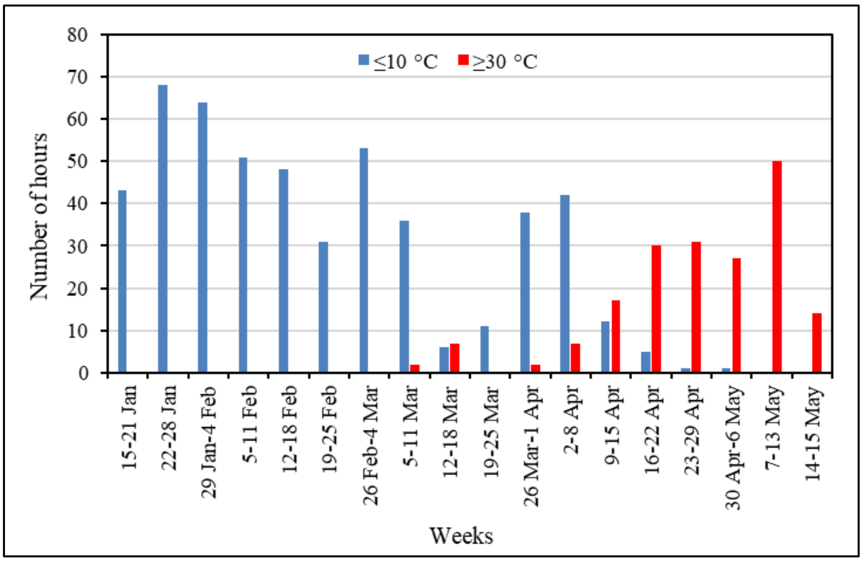

Figure 3 Number of cold and heat units accumulated from January 15 to May 15, 2023, recorded by the weather station CIANO-910, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico, during the crop season 2022-2023

The wheat plant requires the accumulation of cold units to prolong its biological cycle, which generally leads to a higher grain yield [25]. During January the daily low temperature range was 3.1-10.1 °C, in February 3.5-13.8 °C, in March 2.6-15.8 °C, in April 4.2-15.1 °C, and in May 9.8-17.9 °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 [22]. 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 cultivars Borlaug 100 F2014 and CIANO M2018 was 72 for the first sowing date and 67 for the second. In the first sowing date, CIANO M2018 was the latest entry to reach heading, occurring 75 days after sowing (das), Borlaug 100 F2014 with 71 das, while lines No. 31, 36, and 40 were the earliest to head with 60 das (Figure 4).

Figure 4 Days to heading of bread wheat cultivars CIANO M2018 (No. 10) and Borlaug 100 F2014 (No. 22), and 39 advanced bread wheat lines adapted to stress, sown late on January 15 and 30, 2023, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico

In the second date, lines SOKOLL/WBLL1/5/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2/7/SOKOLL/3/PASTOR//HXL7573/2*BAU*2/6/OASIS/5*BORL95/5/CNDO/R143//ENTE/MEXI75/3/AE.SQ/4/2*OCI (No. 26) headed 71 das, CIANO M2018 and Borlaug 100 F2014 in 70 and 68 das, respectively, while TACUPETOF2001/6/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2/5/CIRO16 (No. 18) in 63 days. Lines that had a three day difference or less for heading during the first and second dates were No. 1, 2, 6, 19, 26, 32, 35, 37, 38, 40, 41, and Borlaug 100 F2014; those with a larger difference of 3.5-4.5 days were No. 3, 4, 5, 7, 9, 15, 16, 17, 20, 21, 23, 25, 27, 28, 31, 33, 36, and 39; and with 5-7 day difference were No. 8, 11-14, 18, 24, 29, 30, 34, and CIANO M2018. The highest difference of 6.5 and 7 days were shown by sister line MILAN/KAUZ//DHARWARDRY/3/BAV92/6/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2/5/CIRO16 (PTSS18Y00075S-0M-099Y-099M-26Y-0B, No. 11) and TACUPETOF2001/6/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2/5/CIRO16 (No. 18), respectively. The average plant height of the group was 90.3 cm for the first sowing date and 80.5 cm for the second (Figure 5).

Figure 5 Plant height of bread wheat cultivars CIANO M2018 (No. 10) and Borlaug 100 F2014 (No. 22), and 39 advanced bread wheat lines adapted to stress, sown late on January 15 and 30, 2023, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico

Lines TACUPETOF2001/6/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2/5/ CIRO16 (No. 18) and SOKOLL/3/PASTOR//HXL7573/2*BAU/4/WBLL4//OAX93.24.35/WBLL1/5/D67.2/PARANA66.270//AE.SQUARROSA (320)/3/CUNNINGHAM/4/VORB (No. 27) were the tallest in the first date with 102.5 cm, followed by lines No. 9 and 17 with 100 cm, while cultivars CIANO M2018 (No. 10) and Borlaug 100 F2014 (No. 22) showed 90 and 82.5 cm, respectively. Line BORL14/BAJ #1 (No. 3) was the shortest with 77.5 cm. In the second date, line No. 27 was the tallest with 92.5 cm and lines No. 3, 13, and 30 as well as both cultivars were the shortest with 72.5 cm. With the exception of sister line REDING//PUB94.15.1.12/WBLL1 (PTSS18Y00234S-0M-099Y-099M-4Y-0B, No. 40), the rest of lines and both cultivars 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 5 to 20 cm. Sister line No. 40 showed the same height in both dates. Sister line MILAN/KAUZ//DHARWARDRY/3/BAV92/6/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2/5/CIRO16 (No. 11) showed the maximum difference with 20 cm, followed by lines No. 9 and 19 as well as cultivar CIANO M2018 with 17.5 cm, while cultivar Borlaug 100 F2014 had a difference of 10 cm. Between the 2016-2017 and 2021-2022 crop seasons, the SATYN line groups exhibited an average heading days of 68.6, ranging from 66 to 74 days, and an average plant height of 84 cm, with a range of 60 to 96 cm [26,28,29,32,33,34]. Over the same period, cultivar Borlaug 100 F2014 showed an average heading days of 69 with a range of 64 to 74, and an average height of 77 cm, ranging from 60 to 86 cm. The average heading days and plant height in crop season 2022-2023 fell within the range of the previous seasons (Table 2).

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, 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
2023	13.47	14.70	17.50	19.92	22.08	69	85

Although the monthly average temperatures in 2021 and 2022 were rather similar, the average grain weight per plot was higher in 2022 [26], reaching 350 g (equivalent to 4.37 t ha^{-1}), compared to 294 (3.67 t ha^{-1}) in 2021 [28]. This difference may be attributed to higher heat unit accumulation during the heading-flowering stages of the wheat plant in 2021, which likely induced greater stress on the crop compared to 2022. The average physiological maturity of the group of lines and cultivars Borlaug 100 F2014 and CIANO M2018 in this study occurred after 106 days for the first sowing date and 99 for the second, with a range of 102 to 117 and 97 to 104, respectively (Figure 6).

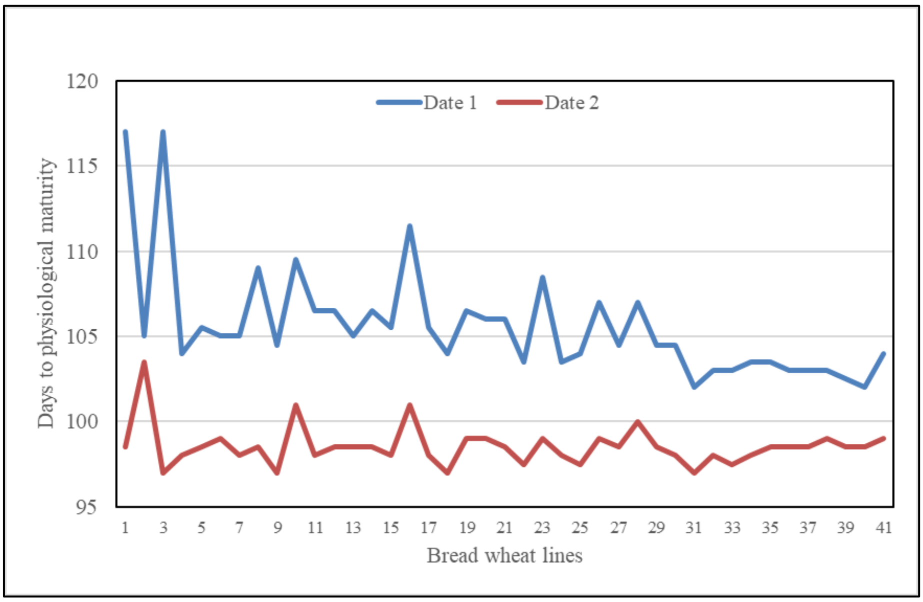

Figure 6 Days to physiological maturity of bread wheat cultivars CIANO M2018 (No. 10) and Borlaug 100 F2014 (No. 22), and 39 advanced bread wheat lines adapted to stress, sown late on January 15 and 30, 2023, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico

The average a thousand grain weight of the group in the first sowing date was 38.9 g and 34.7 in the second (Figure 7). In the first date, line NINGA#1 (No. 5) showed the highest weight with 48.1 g, followed by the line TACUPETO F2001/6/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2/5/CIRO16 (No. 18) with 47.3 g, and sister line 68.111/RGB-U//WARD/3/FGO/4/RABI/5/AE.SQUARROSA(191)/6/MUTUS//KIRITATI/2*TRCH/3/WHEAR/KRONSTADF2004 (PTSS17Y00426S-0B-099Y-099M-7Y-0Y, No. 15) with 46.9 g, while line SORA/AE.SQUARROSA(617)//2*BORL14 (No. 13), showed the lowest grain weight with 23.5 g. In the second date, line No. 18 showed the highest a thousand grain weight with 45.0 g, followed by line SOKOLL/3/PASTOR//HXL7573/2*BAU /5/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2/7/SOKOLL/3/PASTOR// HXL7573/2*BAU*2/6/OASIS/5*BORL95/5/CNDO/R143//ENTE/MEXI75/3/AE.SQ/4/2*OCI (No. 31) with 43.1 g; sister line GARZA/BOY//AE.SQUARROSA(294)/4/MUTUS//KIRITATI/2*TRCH/3/WHEAR/KRONSTADF2004 (PTSS17Y00415S-0B-099Y-099M-25Y-0Y, No. 30) showed the lowest a thousand grain weight with 25.6 g.

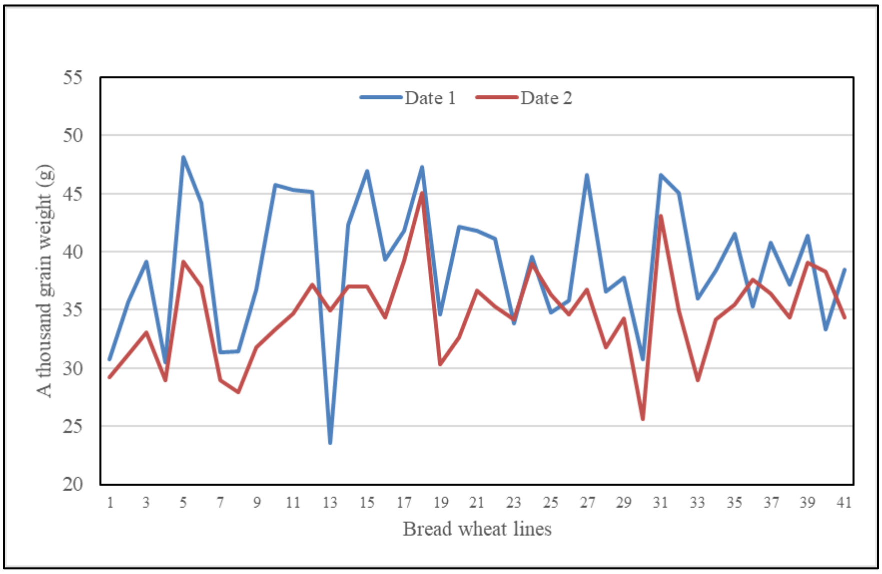

Figure 7 A thousand grain weight of bread wheat cultivars CIANO M2018 (No. 10) and Borlaug 100 F2014 (No. 22), and 39 advanced bread wheat lines adapted to stress, sown late on January 15 and 30, 2023, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico

The average grain weight per plot of the group in the first sowing date was 450 g and 320 in the second (Figure 8). In the first date, sister line VORB//PARUS/PASTOR/4/MUTUS//KIRITATI/2*TRCH/3/WHEAR/KRONSTADF2004 (PTSS17Y00217S-0B-099Y-099M-35Y-0Y, No. 17) showed the highest weight with 583 g, followed by the line SOKOLL/WBLL1/5/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2/6/SOKOLL/3/ PASTOR//HXL7573/2*BAU/5/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2 (No. 12) with 560 g, while line SORA/AE.SQUARROSA (617)//2*BORL14 (No. 13), showed the lowest grain weight with 270 g. In the second date, the same sister line No. 17 showed the highest grain weight per plot with 425 g, followed by sister line 68.111/RGB-U//WARD/3/FGO/4/RABI/5/AE.SQUARROSA(191)/6/MUTUS//KIRITATI/2*TRCH/3/WHEAR/ KRONSTADF2004 (PTSS17Y00426S-0B-099Y-099M-33Y-0Y, No. 24) with 385 g, and SOKOLL/3/PASTOR//HXL7573/ 2*BAU/4/WBLL4//OAX93.24.35/WBLL1/5/D67.2/PARANA66.270//AE.SQUARROSA(320)/3/CUNNINGHAM/4/ VORB (No. 27) with 382 g. Cultivar CIANO M2018 (No. 10) showed the lowest grain yield per plot with 255 g, while lines No. 8 and 30 showed 260 g.

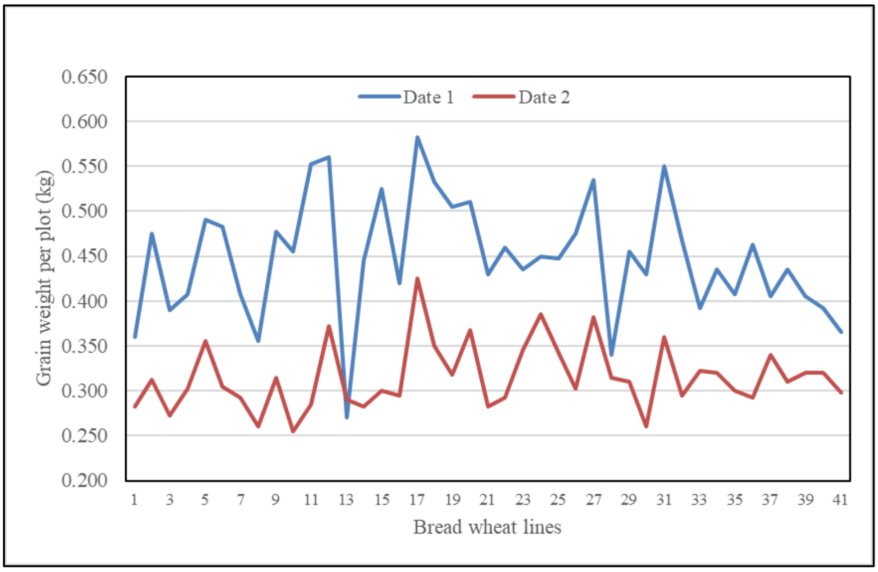

Figure 8 Grain weight per plot of bread wheat cultivars CIANO M2018 (No. 10) and Borlaug 100 F2014 (No. 22), and 39 advanced bread wheat lines adapted to stress, sown late on January 15 and 30, 2023, at the Norman E. Borlaug Experimental Station in the Yaqui Valley, Sonora, Mexico

The year 2023, during the crop season 2022-2023, showed the lowest average monthly temperature since 2018-2019, with a maximum contrasting difference of 3.23 °C in January, 2 °C in February, 0.5 °C in March, 1.33 °C in April, and 2.86 °C in May (Table 2). This phenomenon partly contributed to an average grain yield per plot of 380 g, equivalent to 4.75 t ha^{-1}, as well as for cultivar Borlaug 100 F2014 with an average grain yield of 376 g (equivalent to 4.70 t ha^{-1}), which surpassed its grain yield of 2022 by 1.4 t ha^{-1}. The HU that occurred during heading, might have accounted for the low grain yield obtained in some of the previous crop seasons. Heat stress triggers significant physiological and morphological responses in plants. It reduces seed germination and seedling growth, decreases cell turgidity and water-use efficiency, and disrupts cellular functions by generating excessive reactive oxygen species (ROS), leading to oxidative stress. It also accelerates leaf senescence, impairs photosynthesis through deactivation of photosynthetic enzymes and damage chloroplasts, and limits assimilate translocation. As a results, both the duration and growth rate of grains are reduced, ultimately decreasing grain number [35]. Borlaug 100 F2014 has demonstrated good adaptability, achieving higher grain yields in five out of six regions across Mexico. It outperformed other commercial wheat cultivars by up to 41 % [36]. With the exception of line SORA/AE.SQUARROSA (617)//2*BORL14 (No. 13), the other 38 lines and the cultivars showed higher grain yield in the first date than in the second one. Ten lines showed a difference lower than 100 g of grain weight per plot between the first and second sowing dates, twenty-seven between 100 and 199 g, and three equal or greater than 200 g. The greatest difference was shown by sister line MILAN/KAUZ//DHARWARDRY/3/BAV92/6/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2/5/CIRO16 (PTSS18Y00075S-0M-099Y-099M-26Y-0B, No. 11) with 268 g, followed by sister line 68.111/RGB-U//WARD/3/FGO/4/RABI/5/AE.SQUARROSA(191)/6/MUTUS//KIRITATI/2*TRCH/3/WHEAR/KRONSTADF2004 (PTSS17Y00426S-0B-099Y-099M-7Y-0Y, No. 15) with 225 g, and cultivar CIANO M2028 with 200 g. Lines with the best agronomic type consistent in both dates were: sister lines MEX94.27.1.20/3/SOKOLL//ATTILA/3*BCN/4/PUB94.15.1.12/WBLL1/5/MUCUY (PTSS14Y00329S-0B-099Y-099B-33Y-020Y, No. 16), and CHEN/AE.SQ//WEAVER/3/SSERI1/4/MUTUS//KIRITATI/2*TRCH/3/WHEAR/KRONSTADF2004 (PTSS17Y00237S-0B-099Y-099M-48Y-0Y, No. 20). The temperature that prevailed during this work had an average monthly range of 13.4 to 22.0 °C and an overall average of 17.4 °C. This season showed the lowest average monthly temperatures since 2018-2019 which in partly contributed to higher grain yields, but also in this crop season, 81.7 mm of precipitation were recorded primarily with 13.7 mm on March 17, and 52.1 mm on March 18. The purpose of the two complementary irrigations is to cause drought stress on the wheat plants, which affects all the stages of development, the vegetative and reproductive growth to grain filling and maturation of the crop [37]. Nitrogen uptake efficiency and its utilization by plants is primarily due to impaired membrane permeability and disrupted active transport mechanisms, leading to lower transpiration rates and diminished root absorption capacity. Additionally, stomatal closure limits CO_2 intake, while the accumulation of oxygen inside the stomata promotes the formation of oxygen species (ROS) through partial oxygen reduction. These ROS cause membrane damage, resulting in leakage that adversely impacts respiration, photosynthesis, and overall plant development. In wheat, the growth stage from double ridge to anthesis stage is particularly sensitive to water deficit. Drought stress during this critical period negatively affects spikelet and kernel formation, leading to a substantial reduction in grain yield, ranging from 17 to as much as 70 % [37]. 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 2022-2023 [38,39,40,41,42], it may produce a grain yield of 8.797 t ha-1 under full irrigation (four complementary irrigations) [43], while under reduced irrigation, it may yield 3.3 t ha-1 [26] or 4.7 t ha-1, as it was the case in this work.

4. Conclusion

The average days for heading of thirty-nine advanced bread wheat lines and bread wheat cultivars Borlaug 100 F2014 and CIANO M2018 was 72 days for the first sowing date and 67 for the second, while days for physiological maturity were 106 and 99, respectively.

The average plant height of the group for the first date was 90.3 cm and 80.5 for the second one; the 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 showed the highest average height with 97.5 cm.

The average a thousand grain weight was 36.8 g; the line TACUPETO F2001/6/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2/5/CIRO16 showed the highest average TGW with 46.2 g.

The average grain yield per plot was 380 g; sister line VORB//PARUS/PASTOR/4/MUTUS//KIRITATI/2*TRCH/3/WHEAR/KRONSTADF2004 (PTSS17Y00217S-0B-099Y-099M-35Y-0Y) showed the highest average yield with 504 g which corresponded to 6.30 t ha^{-1}, followed by SOKOLL/WBLL1/5/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2/6/SOKOLL/3/PASTOR//HXL7573/2* BAU/5/CROC_1/AE.SQUARROSA(205)//BORL95/3/PRL/SARA//TSI/VEE#5/4/FRET2 with 466 g (5.82 t ha^{-1}).

The average hourly temperature was 17.4 °C with a maximum of 34.7 °C and a minimum of 2.6 °C, the average relative humidity was 60.6 %, there were 81.7 mm of precipitation, and the number of heat and cold units was 187 and 510, respectively.

The 65.8 mm precipitation that occurred prior to the heading stage of the wheat crop contributed to an increase in grain yield of both lines and cultivars, surpassing the yields observed in previous crop seasons.

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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