SCIENTIFIC NOTE

Global warming is reducing the tillering capacity and grain yield of wheat in Yaqui Valley, Mexico

El calentamiento está reduciendo la capacidad de macollamiento y el rendimiento de grano en trigo en el Valle del Yaqui, México

Denisse Morales-Coronado[1], Leandris Argentel-Martínez[1,2], Luciano Castro-Espinoza[1]*, Marco Gutiérrez-Coronado[1], Juan Garibaldi-Chávez[1], and José Ortiz-Enríquez[3]

ABSTRACT

The effect of temperature variations recorded in eight meteorological stations in Yaqui Valley, Sonora, Mexico, on the tillering capacity and grain yield of wheat variety CIRNO C2008 in the growing cycles December 2016-May 2017 and December 2017-May 2018 was studied. In one of the sites, the crop canopy temperature was increased by +2°C with a T-FACE system (warming) based on the temperature recorded in the nearest meteorological station. With the two experimental variants, the abscisic (ABA) and gibberellic (GA) acid hormones were determined during tillering (initial tillering: 30 d after emergence and final tillering: 45 d after emergence) to explain their contribution to the tillering capacity response. A temperature variability of 1°C was observed in the cycle December 2017-May 2018, as compared to the previous cycle and between the evaluated sites. As a result of the temperature increase effect, the tiller number was significantly reduced. The experimental warming caused a highly significant decrease in the ABA content and an increase in the GA. The temperature variation found in Yaqui Valley had a negative and significant correlation with the grain yield in both experiment crop cycles, which demonstrated that global warming is reducing the tillering capacity and grain yield of wheat in Yaqui Valley.

Key words: climate change, gibberellic acid, abscisic acid.

RESUMEN

Se estudió el efecto de las variaciones de temperatura registradas en ocho estaciones meteorológicas del Valle del Yaqui, Sonora, México, en la capacidad de macollamiento y el rendimiento de grano de la variedad de trigo CIRNO C2008, en dos ciclos de cultivo. En uno de los sitios, la temperatura del dosel del cultivo se incrementó en 2°C por medio de un sistema T-FACE (calentamiento) usando como control la temperatura registrada en la estación meteorológica más cercana. En estos dos tratamientos, se determinaron las hormonas ABA y GA al inicio y final del macollamiento para explicar su contribución a la capacidad de macollamiento. Como resultado, se encontró una variabilidad de temperatura de 1°C en el ciclo de diciembre de 2017 a mayo de 2018 con respecto al anterior y también entre los sitios evaluados. Por efecto del aumento de la temperatura disminuyó el número de hijos. El contenido de ABA disminuyó por efecto del calor mientras que el de GA aumentó. La variación de temperatura encontrada en el Valle del Yaqui correlacionó negativamente con el rendimiento de grano en ambos ciclos de cultivos, demostrando que el calentamiento está reduciendo la capacidad de macollamiento y el rendimiento del grano de trigo en el Valle del Yaqui.

Palabras clave: cambio climático, ácido giberélico, ácido abscisico.

Introduction

High temperatures cause considerable changes in plant morphology, cellular dynamism and hormonal relationships, which modify growth patterns (Argentel *et al.*, 2017), creating heat stress when plants do not overcome the minimum tolerance index (Mahalingam, 2015). A single heat shock during growth may cause irreversible damage to plant physiology and yield (Valluru *et al.*, 2017; Garatuza *et al.*, 2018). Many species, such as wheat, need cold hours (also called heat units) to complete critical phenophases (Ganem *et al.*, 2014); for example, at least 300 cold hours are needed for good tillering. The tillering capacity is directly correlated with yield; however, both depend on temperature (Argentel *et al.*, 2017). The tillering phenophase is hormonally regulated by the relationship between abscisic (ABA) and gibberellic (AG) acids, with temperature variations being the abiotic factor that contributes most to hormonal imbalances (Xie *et al.*, 2016). Currently, in some high producing regions,

Received for publication: 23 October, 2018. Accepted for publication: 15 January, 2019

Doi: 10.15446/agron.colomb.v37n1.75736

[1] Instituto Tecnológico de Sonora. 5 de febrero, 818 Sur, Col. Centro, Cd. Obregón, Sonora, México.
[2] Tecnológico Nacional de México, Instituto Tecnológico del Valle del Yaqui, Calle 600, Block 611, Bácum, 85275 San Ignacio Río Muerto, Sonora, México.
[3] Campo Experimental "Norman Borlaug", Carretera Norman E. Borlaug-INIFAP, Ciudad Obregón, Sonora, México.
* Corresponding author: castro.luciano58@gmail.com

such as Yaqui Valley, Sonora, Mexico, where more than 39% of the domestic wheat production occurs, significant changes in temperature patterns are viewed as evidence of climate change (Lares *et al.,* 2016). This phenomenon, according to parametrized models, will limit the tillering capacity and, consequently, modify the genetic-productive expression potential of wheat (Argentel *et al.,* 2017). For this reason, the present study aimed to evaluate the effect of temperature variability on the tillering capacity and grain yield in eight representative sites in Yaqui Valley during two crop cycles, comparing them to that obtained with an experimental warming of +2°C in the ambient canopy temperature (Garatuza *et al.,* 2018) using the CIRNO C2008 wheat variety.

Material and methods

Experiment area location

The experiment was carried out during the growing seasons of 2016-2017 and 2017-2018 (December-May) under field conditions using a calculus surface of one ha in seven representative sites in Yaqui Valley, Sonora, Mexico, where agro-meteorological stations belonging to the INIFAP (Instituto Nacional de Investigaciones Forestales Agrícolas y Pecuarias) are located (Fig. 1). These stations record the data of agroclimatic variables, mainly the temperature of the region.

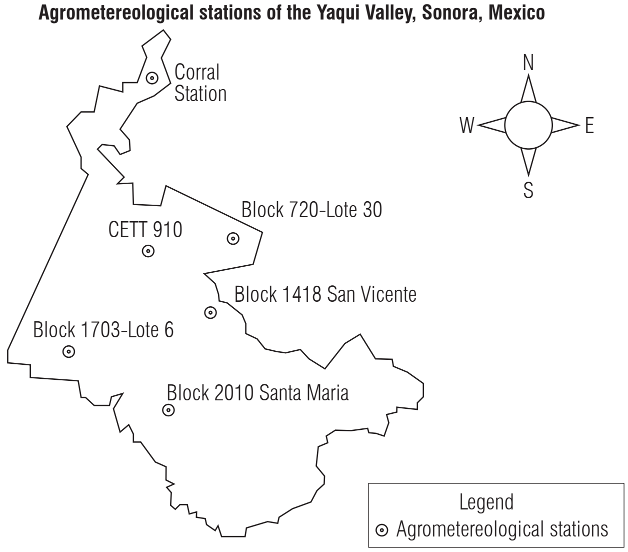

FIGURE 1. Distribution of experimental sites and their respective meteorological stations in Yaqui Valley.

To simulate a site with the maximum temperature (+2°C) predicted for this region, the canopy temperature was increased +2°C with respect to the ambient canopy temperature, at one site in order to evaluate the effect of global warming on the tillering capacity, yield components, and hormonal concentrations during the tillering phenophase. The experimental warming was carried out at the Experimental Technology Transfer Center (CETT-910) of the Instituto Tecnologico de Sonora (ITSON) located in Yaqui Valley at: 27°22'0.4" N and 109°54'50.6" W (UTM: 607393.24 m E; 3027508.34 m N), which is a representative place for wheat crops in Yaqui Valley.

Temperature control

The temperature database was supplied by seven climatological stations located in the experiment sites. The digital memory of the meteorological station records readings every 10 min and provides integrated data by hour and day, averaging the temperature and calculating the thermal sum (heat hours, cold hours) with the maximum and minimum threshold temperature of 10°C and 0°C, respectively, following the methodology of thermal sums of Confalone and Navarro (1999). These data are available at http://www.siafeson.com/remas/index.php.

For the maximum predicted temperature value for the region (warming), a T-FACE system was used (Kimball, 2015), which consisted of raising the crop canopy temperature by 2°C using six thermal radiators per plot (FTE-1000 model, 1000W, 240 V, 245 mm long x 60 mm wide, built by Mor Electric Company Heating Association Inc. Comstock Park, MI, USA) on eight equilateral triangular structures, with sides of 5.2 m. Two radiators were installed on each side of the triangular structures, forming a hexagon, which raised the temperature in a 3 m diameter circle for each plot. To control the temperature, infrared temperature sensors (IRTS Apogee Instruments Inc., Logan, UT, USA) were pointed to each plot at an inclination degree of 45° from the soil horizontal surface, covering a circle with a r = 1.5 m at the center of each plot (Garatuza *et al.,* 2018). The IRTS were registered in a datalogger (CR1000 Campbell Sci, Inc. Logan, UT, USA), which sent a voltage signal to an interface (MAI-05V, Avatar Instruments).

Variety, seeding and crop management

In all sites, the CIRNO C2008 wheat variety was used. This variety is classified as crystalline or hard wheat. It originated from selection in segregating populations of SOOTY-9 / RASCON-37 // CAMAYO crossbreed, carried out at the International Center of Maize and Wheat Improvement (CIMMYT). This variety was released for cropping in 2008 and is widely used in Mexico, particularly in the northwest. The grain yield has reached 5.6 t ha^{-1} and 6.3 t ha^{-1} with two and three irrigations, respectively, at an irrigation rate of 14 cm when this variety was released in Sonora. This variety, after eight years of being released for crops in southern Sonora, has shown a high yield genetic stability (Argentel *et al.,* 2018).

The seeding was done with a sowing machine (SUB-24) on 8-14 December 2016 and 7-14 December 2016 on vertisol soils (Bockheim *et al.,* 2014) with a seeding density of 170 kg ha^{-1}. The background fertilization, in both experiment crop cycles, was done with a standard of 250 kg ha^{-1} of Urea + 100 kg ha^{-1} of monoammonium phosphate fertilizer (MAP, 11-52-00). Three irrigation treatments were applied during the crop cycle. Nitrogen fertilizer was also applied at a dose of 50 kg ha^{-1} of Urea during the first and second irrigation treatments (growth and tillering phenophases). All irrigation treatments were applied with an average water depth of 14 cm and an irrigation interval of 25 d.

During both crop cycles, the presence of the foliage aphid (*Schizaphis graminum*) was observed, and the Muralla Max® pesticide (a.i. Imidacloprid + Betaciflutrin) was applied at a rate of 0.20 L ha^{-1} in the tillering phenophase. Also, a slight presence of broadleaf weeds was observed, which were controlled manually before the irrigation treatments.

Evaluated variables

The tillering capacity was evaluated according to the number of tillers around a principal plant. The final tiller count was done at 45 d after germination.

ABA and GA concentration at the site of maximum temperature (Warming treatment)

For the ABA and GA determination at 15 and 30 d after germination, the methodology of Ortiz *et al.* (2001) was used. Leaf tissue (10 g fresh weight) was collected and immediately frozen in liquid nitrogen. The frozen leaf tissue was freeze-dried for 48 h, ground and extracted in distilled deionized water with an extraction ratio of 1:40 (dry weight: mL water) at 4°C. The ABA and GA concentrations of the extract were determined using high performance liquid chromatography (Wang *et al.,* 2016).

Grain yield

The grain yield (t ha^{-1}) was determined at each experiment site based on a square meter using 16 replicates.

Statistical analysis

For the tillering capacity and grain yield variables, the mean and standard deviation of each treatment (experiment sites) were determined. The differences between the sites were detected with analysis of variance based on a randomized effect linear model (Fisher, 1937). Additionally, a Tukey post-hoc test for $P<0.05$ and $P<0.01$ was applied (Tukey, 1960). To analyze the temperature effect on the grain yield, simple regression was used. The hormonal concentration was compared using a parametric theoretical distribution for t-student quantitative continuous variables (Gosset, 1917) using 16 samples per treatment. For all data analyses, the professional statistical software STATISTICA 11.2 (StatSoft, 2008) was used.

Results and discusion

Wide temperature variability between the studied sites was observed, with a 1°C difference in 2017-18, as compared to the previous cycle. This is an important result that demonstrated a temperature increase in Yaqui Valley that evidences climate change. The site effect explained 95% of the temperature variation according to the randomized effect linear model used for the analysis of variance, while only 2% of the total variability was explained by crop cycle effect. There was not significant interaction between the sites and crop cycles (Fig. 2).

Some reports state that significant variation and increases (about 2°C) have been predicted for several latitudes for the next 50 years, including this area (the semiarid region of Mexico) (Garatuza-Payan *et al.,* 2018). However, in the last crop cycle, the total variability was 1°C.

The tillering capacity experienced significant variation between the sites in both crop cycles, with a reduction in all sites as a result of the temperature variation (Fig. 3).

The hormonal relationship was significantly affected by the warming effect, which shows that temperature increases favor GA synthesis and inhibit ABA synthesis; this hormonal response limited the tillering capacity (Fig. 4).

Some studies have explained that tillering cessation and number of total tillers is regulated by many biochemical, physiological, genetic and environmental factors (Xu *et al.,* 2016). Phytotechnical factors, such as plant density (through an increase in seed density during sowing), can also affect the total tiller number (Pinto *et al.,* 2017).

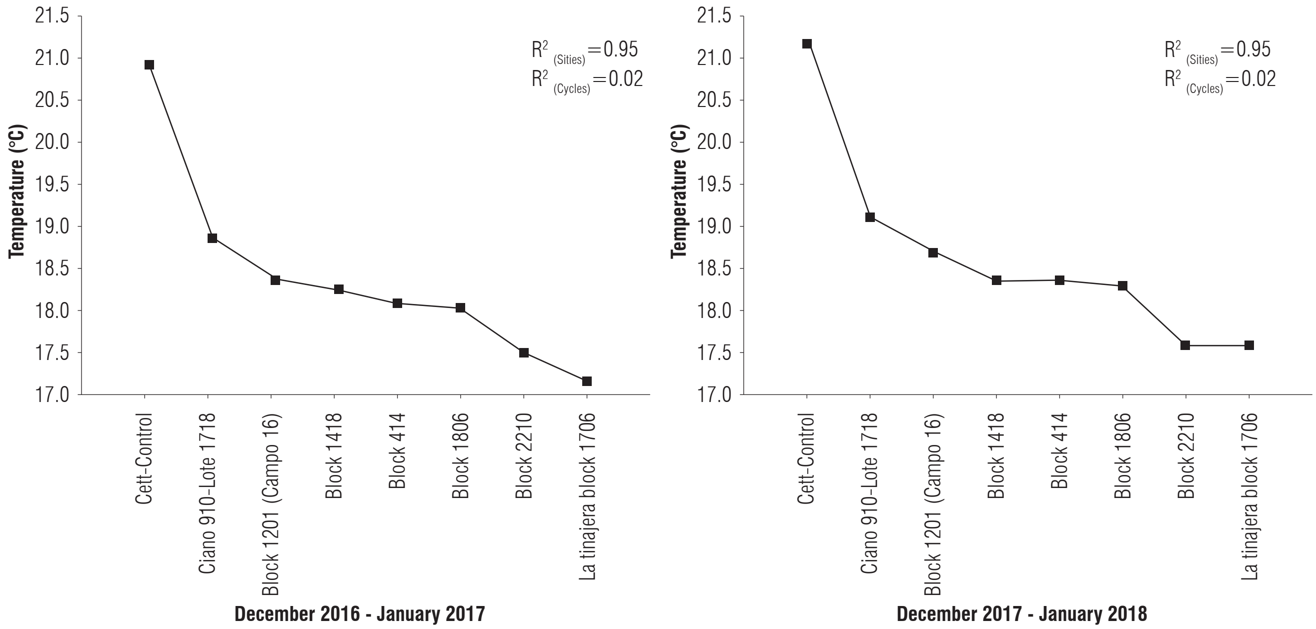

FIGURE 2. Temperature variability at eight experiment sites in Yaqui Valley during the crop cycles December 2016 - January 2017 and December 2017 - January 2018 (tillering phenophase of wheat). R^2: coefficient of determination without adjustment for the sites and crop cycles. Squares represent mean ± standard deviation.

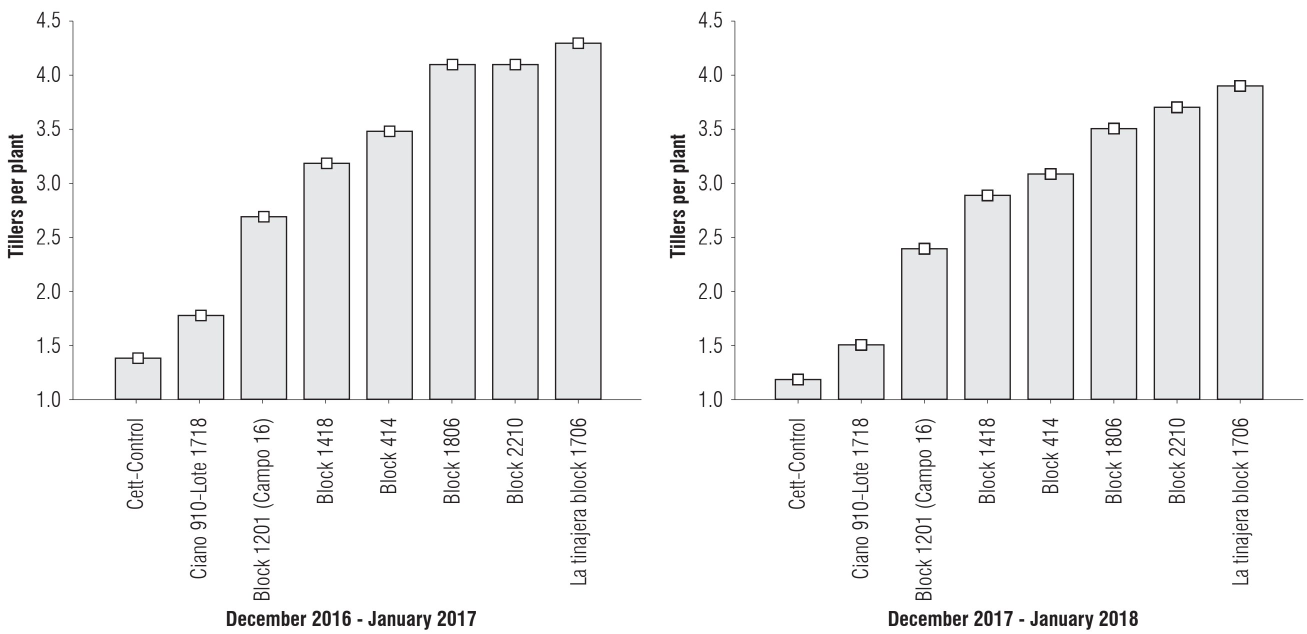

FIGURE 3. Tillering capacity in the evaluated sites in Yaqui Valley during the 2016-17 and 2017-18 crop cycles: A. December 2016 to January 2017, and B. December 2017 to January 2018. R^2: coefficient of determination without adjustment for the sites = 0.96, and crop cycles = 0.04. CV: coefficient of variation for sites = 8.32, and for crop cycles = 1.46. Squares represent mean ± standard deviation.

The tillering capacity in wheat determines plant canopy size (Sattar *et al.*, 2015), photosynthetic area and, more importantly, the number of spikes and full grains per spike (Garatuza *et al.*, 2018).

During the tillering phenophases, there were highly significant differences in the amount of cold hours between the evaluated sites and crop cycles (P = 0.015); CETT-910 (experimental warming) had the least cold hours.

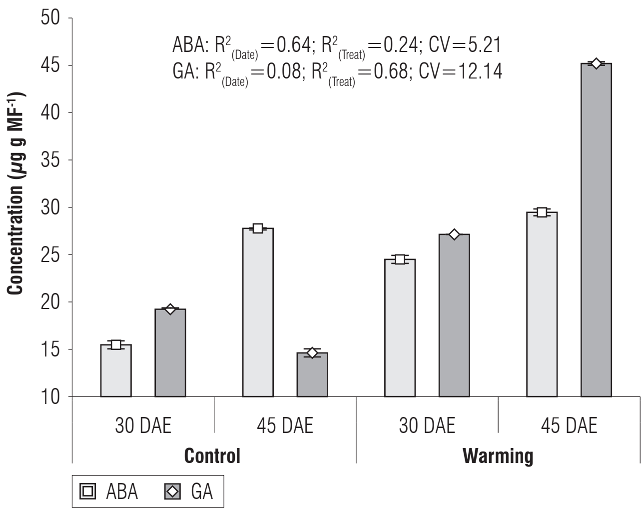

FIGURE 4. ABA and GA content at 30 and 45 d after emergence (tillering phenophases) evaluated in the higher temperature site (crop canopy +2°C) and control site in Yaqui Valley (mean of both 2016-2017 and 2017-2018 crop cycles). R^2: coefficient of determination without adjustment for the phenophases and treatments; CV: coefficient of variation.

Nevertheless, a reduction greater than 30% was observed in cycle 2017-18 with respect to 2016-17. The site effect contributed to 78% of the total variability in the cold hours; however, the crop cycles contributed only 18%. A significant interaction between the sites and crop cycles effects was observed (P = 0.002), which contributed 4% to the total variability (Fig. 5). These results, according to Espinosa *et al.* (2018), demonstrated that the tillering capacity was reduced by the reduction of cold hours in both evaluated crop cycles.

Historically, it has been shown that between 300 and 850 cold hours per season provide a yield near the genetic-productive potential of the varieties, with the greatest contribution to grain yield seen during the first stages, until the tillering phenophase (Zou *et al.,* 2017). Currently, the number of cold hours or heat units is the basis of research in various regions around the world under the context of climate change (Kaur and Kaur, 2017). These studies focus mainly on gene identification and introgression for adaptability to cold hour reductions and on the achievement of hormonal stability during initial growth until the tillering phenophase (Pinto *et al.,* 2017).

Grain yield

The temperature variation showed a negative and significative correlation with grain yield in both experiment crop cycles (Fig. 6). The observed general yield decrease was fit at 92% with the linear model used for the statistical process in the crop cycle 2016-17 and at 51% in the second crop cycle.

Mean temperature values of 18.4°C and 18.66°C were observed during crop phenology in the 2016-17 and 2017-18 crop cycles, respectively. The regression equations were

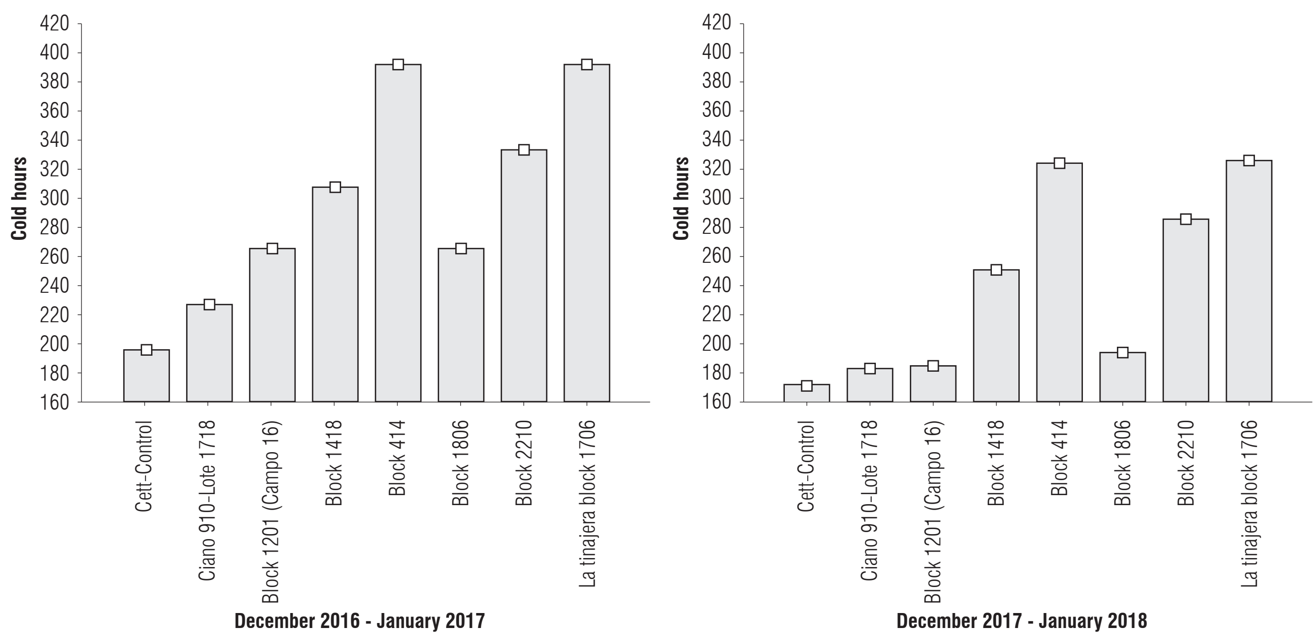

FIGURE 5. Cold hours during the December 2016 - January 2017 and December 2017 - January 2018 crop cycles. R^2: coefficient of determination without adjustment for the sites = 0.78, for cycles = 0.18 and their interaction = 0.04; CV: coefficient of variation = 29.72; Squares represent mean ± standard deviation.

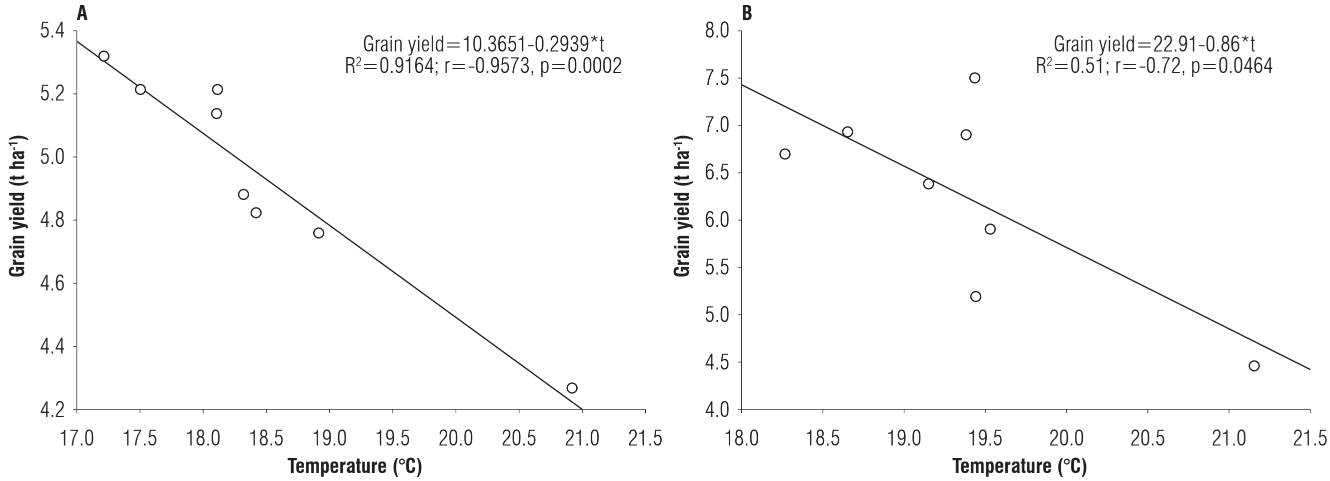

FIGURE 6. A. Effect of temperature on the grain yield during the 2016-2017, and B. 2017-2018 crop cycles. R^2: coefficient of determination without adjustment; r: regression coefficient; p: probability.

used to determine the theoretical temperature values that affected yield at 30%, between the temperature and grain yield. The first crop cycle had a theoretical temperature value of 23.7°C, whereas the second cycle had a value of 22.9°C, demonstrating a greater sensitivity of the wheat to temperature increases in the crop cycle 2017-18.

Warming stresses may cause a grain yield reduction through a reduction of spike number per m^2 (Shirdelmoghanloo *et al.,* 2016) and an increase of non-viable pollen production, which makes grain formation difficult (Siebers *et al.,* 2017). Currently, increased seed densities are used to overcome the temperature effect on tillering capacity reductions in a productive manner in agronomic practices (Lazzaro *et al.,* 2018), which greatly increase seeding costs (Chandra *et al.,* 2017).

Conclusions

A temperature variability of 1°C was observed between the 2016-17 and 2017-18 crop cycles.

The tiller number was significantly reduced from four to one tiller in both evaluated crop cycles.

The warming caused a significant decrease in the ABA content and an increase in the GA, which corroborated its contribution to the wheat tillering capacity reduction in Yaqui Valley.

Although the 2017-18 crop cycle had a higher grain yield, the temperature increase had a negative and significant effect on the grain yield at all evaluated sites and crop cycles in Yaqui Valley, Mexico.

Literature cited

Argentel-Martinez, L., J. Garatuza-Payan, M. Armendariz-Ontiveros, E.A. Yepez-Gonzalez, M. Garibaldi-Chavez, E.J. Ortiz-Enriquez, and J. Gonzalez-Aguilera. 2018. Physiological and agronomic traits of hard wheat CIRNO variety C2008 confirm its genetic stability. Agrociencia *52*(3), 419-435.

Argentel-Martinez, L., J. Garatuza-Payan, M. Armendariz-Ontiveros, E.A. Yepez-Gonzalez, M. Garibaldi-Chavez, E.J. Ortiz-Enriquez, and J. Gonzalez-Aguilera. 2017. Estrés térmico en cultivo del trigo. Implicaciones fisiológicas, bioquímicas y agronómicas. Cultivos Tropicales 38(1), 57-67.

Asseng, S., D. Cammarano, B. Basso, U. Chung, P.D. Alderman, K. Sonder, and D.B. Lobell. 2017. Hot spots of wheat yield decline with rising temperatures. Global Change Biol. 23(6), 2464-2472. Doi: 10.1111/gcb.13530

Bockheim, J.G., A.N. Gennadiyev, A.E. Hartemink, and E.C. Brevik. 2014. Soil-forming factors and Soil Taxonomy. Geoderma 226, 231-237. Doi: 10.1016/j.geoderma.2014.02.016

Chandra, K., R. Prasad, P. Thakur, K. Madhukar, and L.C. Prasad. 2017. Heat tolerance in wheat - A key strategy to combat climate change through molecular markers. Int. J. Curr. Microbiol. App. Sci. 6(3), 662-675. Doi: 10.20546/ijcmas.2017.603.077

Confalone, A.E. and D.M. Navarro. 1999. Comparación de modelos de tiempo térmico para maíz. Rev. Brasil. Agromet. 7(2), 207-211.

Espinosa-Espinosa, J.L., E. Palacios-Vélez, L.C.A. Tijerina-Chávez, A. Ortiz-Solorio, A. Exebio-García, and C. Landeros-Sánchez. 2018. Factores que afectan la producción agrícola bajo riego: cómo medirlos y estudiar su efecto. Tecnol. Cienc. Agua 9(2), 175-191. Doi: 10.24850/j-tyca-2018-02-07

Fisher, R.A. 1937. The design of experiments. Oliver and Boyd, Edinburgh, London.

Ganem, D.G., M.A. Equiza, M. Lorenzo, and J. Tognetti. 2014. Cambios en la anatomía epidérmica foliar de cereales de clima templado en respuesta al frío. Revista Facultad de Agronomía 113(2), 157-164.

Garatuza-Payan J., L. Argentel-Martinez, E.A. Yepez, and T. Arredondo. 2018. Initial response of phenology and yield components of wheat (*Triticum durum* L., CIRNO C2008) under experimental warming field conditions in the Yaqui Valley. PeerJ 6:e5064. Doi: 10.7717/peerj.5064

Gosset, E. 1917. Another differences calculus based on standard deviation and confidence interval. Statistical References 26: 66-72.

Kaur, A. and P. Kaur. 2017. Effect of elevated temperature regimes on phenological development of wheat (*Triticum aestivum* L.). Agricult. Res. J. 54(1), 132-135. Doi: 10.5958/2395-146X.2017.00026.6

Kimball, B.A. 2015. Using canopy resistance for infrared heater control when warming open-field plots. Agron. J. 107(3), 1105-1112. Doi: 10.2134/agronj14.0418

Lares-Orozco, M.F., A. Robles-Morúa, E.A. Yepez, and R.M. Handler. 2016. Global warming potential of intensive wheat production in the Yaqui Valley, Mexico: a resource for the design of localized mitigation strategies. J. Clean. Prod. 127, 522-532. Doi: 10.1016/j.jclepro.2016.03.128

Lazzaro, M., A. Costanzo, D.H. Farag, and P. Bàrberi. 2017. Grain yield and competitive ability against weeds in modern and heritage common wheat cultivars are differently influenced by sowing density. Ital. J. Agron. 12, 343-349. Doi: 10.4081/ija.2017.901

Mahalingam, R. 2015. Consideration of combined stress: a crucial paradigm for improving multiple stress tolerance in plants. pp. 1-25. In: Mahalingam, R. (ed). Combined stresses in plants, physiological, molecular, and biochemical aspects. Springer International Publishing, Switzerland. Doi: 10.1007/978-3-319-07899-1

Ortiz, L.Y., A. López, C.G. de Encizo, and V.J. Flórez. 2001. Determinación del ácido abscísico en papa (*Solanum* sp.) como respuesta a bajas temperaturas. Agron. Colomb. 18(1-3), 31-38.

Pinto, R.S., G. Molero, and M.P. Reynolds. 2017. Identification of heat tolerant wheat lines showing genetic variation in leaf respiration and other physiological traits. Euphytica 213(3), 76. Doi: 10.1007/s10681-017-1858-8

Sattar, A., M.M. Iqbal, A. Areeb, Z. Ahmed, M. Irfan, R.N. Shabbir, and S. Hussain. 2015. Genotypic variations in wheat for phenology and accumulative heat unit under different sowing times. J. Environ. Agric. Sci. 2(8), 1-8.

Shirdelmoghanloo, H., D. Cozzolino, I. Lohraseb, and N. Collins. 2016. Truncation of grain filling in wheat (*Triticum aestivum*) triggered by a brief heat stress during early grain filling: association with senescence responses and reductions in stem reserves. Funct. Plant Biol. 43(10), 919-930. Doi: 10.1071/FP15384

Siebers, M.H., R.A. Slattery, C.R. Yendrek, A.M. Locke, D. Drag, E.A. Ainsworth, and D.R. Ort. 2017. Simulated heat waves during maize reproductive stages alter reproductive growth but have no lasting effect when applied during vegetative stages. Agric. Ecosyst. Environ. 240, 162-170. Doi: 10.1016/j.agee.2016.11.008

StatSoft. 2008. STATISTICA (data analysis software system), version 8.0. URL: www.statsoft.com (accessed 30 May 2018).

Tukey, J.W. 1960. A survey of sampling from contaminated distributions. p. 448-485. In: Olkin I. (ed). Contribution to probability and statistics: Essays in honor to Harold Hotelling, Stanford University Press, USA.

Valluru, R., M.P. Reynolds, W.J. Davies, and S. Sukumaran. 2017. Phenotypic and genome-wide association analysis of spike ethylene in diverse wheat genotypes under heat stress. New Phytol. 214(1), 271-283. Doi: 10.1111/nph.14367

Wang, L.L., X.Y. Chen, Y. Yang, Z. Wang, and F. Xiong. 2016. Effects of exogenous gibberellic acid and abscisic acid on germination, amylases, and endosperm structure of germinating wheat seeds. Seed Sci. Technol. 44(1), 64-76. Doi: 10.15258/sst.2016.44.1.09

Xie, Q., S. Mayes, and D.L. Sparkes. 2016. Optimizing tiller production and survival for grain yield improvement in a bread wheat × spelt mapping population. Ann. Bot. 117(1), 51-66. Doi: 10.1093/aob/mcv147

Xu, T., N. Bian, M. Wen, J. Xiao, C. Yuan, A. Cao, and H. Wang. 2016. Characterization of a common wheat (*Triticum aestivum* L.) high-tillering dwarf mutant. Theor. Appl. Genet. 1-12. Doi: 10.1007/s00122-016-2828-6

Zou, J., K. Semagn, M. Iqbal, A. N'Diaye, H. Chen, M. Asif, and H. Randhawa. 2017. Mapping QTLs controlling agronomic traits in the 'Attila' × 'CDC Go' spring wheat population under organic management using 90K SNP array. Crop Sci. 57(1), 365-377. Doi: 10.2135/cropsci2016.06.0459