Magna Scientia Advanced Research and Reviews
eISSN: 2582-9394
Cross Ref DOI: 10.30574/msarr
Journal homepage: https://magnascientiapub.com/journals/msarr/

(Research Article)

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Impact of temperature variation on the productivity of beans, maize and wheat in southern Sonora, Mexico

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Magna Scientia Advanced Research and Reviews, 2025, 15(02), 051-062

Publication history: Received 18 October 2025; revised on 24 November 2025; accepted on 26 November 2025

Article DOI: https://doi.org/10.30574/msarr.2025.15.2.0137

Abstract

Rising global temperatures are a major constraint on food crop production. This study evaluated thermal variability in southern Sonora, Mexico, and its effect on physiological components associated with wheat, maize, and bean yields. For this purpose, records obtained over 20 agricultural seasons of wheat under furrow irrigation and during three seasons of beans and maize under drip irrigation were used. Daytime and nighttime hourly temperatures were analyzed for the period between October and May, from the 2004-2005 season to 2024-2025. Climate risk was determined by an analysis of extreme temperature values (≤ 4 °C and ≥ 33 °C), considered thresholds associated with physiological and structural damage to the plant and its reproductive organs. The results show that the average daytime temperature increased by 2.8, 2.4 and 3.0 °C during the months of October to December, respectively; while from January to May the increases were 1.5, 2.2, 2.4, 3.1 and 2.7 °C. In contrast, nighttime temperatures showed increases of 0.5, 0.1 and 0.4 °C for the months of October to December, respectively, but decreased by 1.3, 0.5, 0.4, 0.2 and 0.7 °C between January and May. An increased risk of frost was observed during January, a condition that could significantly affect bean and maize crops. Overall, this change in the temperature regime between fall and spring suggests the need to adjust sowing dates and optimize irrigation scheduling to mitigate the effects on agricultural yield.

Keywords: Wheat; *Triticum aestivum*; *Triticum durum*; Bean; *Phaseolus vulgaris*; Maize; *Zea mays*; Temperature variation

1. Introduction

Global climate change is accentuating the temperature increase in some places more than others [1,2]. Félix *et al*. [3] indicate that the southern agricultural region of the state of Sonora is experiencing very significant temperature changes, affecting crops sown from fall to spring, which is the crop season with the highest productive activity. Southern Sonora plants an average of 270,000 hectares annually with various crops, most notably wheat (*Triticum aestivum* L. and *T. durum* Desf.), which accounts for 61.95 % of the national production [4]. Bean (*Phaseolus vulgaris* L.) production occurs in two seasons: fall and spring in the Districts 038 Navojoa-Mayo Valley and 041 Cajeme-Yaqui Valley, and the

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south of the state contributes 70 to 80 % of the total area allocated in the state of Sonora [5]. In southern Sonora, maize cultivation has been supported by several technologically based sowing-date recommendations. For the spring season, sowing from March 1 to 31 is advised, while summer sowing is recommended during the second half of August [6]; additionally, Ortega *et al*. [7] propose sowing in June. For the fall-winter season, Cota Agramont *et al*. [8] recommend sowing from the second week of August through September 10 to avoid frost damage, and suggest sowing sweet maize for canning between October and February. More recently, Valenzuela Borbón *et al*. [9] have recommended December sowing, noting high yield potential and low risk of frost for the hybrids currently grown in the region. They also report that October-November sowing may produce the highest grain yields, although it is associated with a substantially greater frost risk. From 2003 to 2017, maize (*Zea mays* L.) yielded an average of 6.67 t ha^{-1}, and from 2018 onwards, the average production per hectare increased, with farmers now obtaining an average of 11.7 t ha^{-1} [10]. This is due to the yield potential offered by the November and December sowing dates and the use of newly introduced hybrids. This option is growing in area because it is more profitable than wheat and other crops. Temperature is considered the most important factor promoting plant development from emergence to flowering and maturity [11] and affecting growth processes [12]. In contrast, relative humidity is fundamental during all active stages for phytopathogens; the temperature-humidity interaction establishes the methodology for forecasting important diseases [13] and is related to the number, weight, and quality of the grain [14]. The objective of this work was to analyze the impact of the temperature on bean, maize, and wheat crops during the productive stage, in order to adjust the sowing date and the irrigation timing.

2. Materials and methods

To assess temperature trends in southern Sonora, hourly climate records from 2000 to 2025 were analyzed for the months of October through May, encompassing the fall-spring agricultural seasons. From this database, the trend in mean monthly temperature, both daytime and nighttime, was calculated, as well as the number of accumulated hours per month that exceeded or fell below the thermal thresholds of ≥ 33 °C (heat hours) and ≤ 4 °C (cold hours). Previously, Félix-Valencia *et al*. [15] had defined that 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. The thermal trend was determined by a simple linear regression analysis, considering statistical significance at $p < 0.05$. Additionally, the agronomic and phenological information on wheat, maize, and beans obtained from commercial fields located in the southern region of the state of Sonora, Mexico, was analyzed. For wheat, the agricultural seasons between 2004 and 2024 were considered, with a total of approximately 50 commercial fields. For beans, the 2023 spring season (two commercial fields) and the 2023-2024 fall season (two commercial fields) were evaluated. For maize, the 2022-2023 fall-winter season was analyzed in 18 commercial fields. In wheat, the following variables were determined: vegetative growth, number of ears per plant, number of grains per ear, weight of 1000 grains, and grain quality characteristics. In beans (spring and fall seasons), agronomic variables related to reproductive efficiency were recorded: number of flowers and pods shed, pods without grain, number of grains per pod, proportion of grains damaged by pests or diseases associated with humidity and temperature, and specific grain weight. In addition, canopy temperature and relative humidity were recorded using a digital sensor (OMEGA OM-EL-USB-2 datalogger) installed at foliage level. In maize, the following variables were evaluated: foliar and structural damage caused by high temperatures, the proportion of stalks with or without an ear, the size and health of the ears, and the total weight of the grain. Extreme temperature levels were validated through correlation analysis with production and visible damage to leaves, stems, ears, cobs, and pods, as appropriate for each crop.

3. Results and discussion

3.1. Temperature trend

Analysis of hourly temperature records from 2000 to 2025 showed a generalized increase in the average temperature of southern Sonora from autumn to spring (Table 1). Daytime temperatures showed a sustained increase in all months, with values ranging from +1.5 °C in January to +3.1 °C in April, while nighttime temperatures showed moderate increases from October to December (+0.1 °C to +0.5 °C) and decreases from January to May (-0.2 °C to -1.3 °C). Taken together, these variations indicate an average annual increase in the daily temperature ranging between 0.1 and 1.7 °C, therefore, there has been colder nights and warmer days in the last two decades.

Table 1 Average increase in the daytime, nighttime and average temperature (°C) in southern Sonora, Mexico, during the years 2000 to 2025

Month	Daytime temperature (°C)	Nighttime temperature (°C)	Average (°C)
October	2.8	0.5	1.6
November	2.4	0.1	1.3
December	3.0	0.4	1.7
January	1.5	-1.3	0.1
February	2.2	-0.5	0.8
March	2.4	-0.4	1.0
April	3.1	-0.2	1.4
May	2.7	-0.7	1.0

The increase in temperature fluctuations observed in southern Sonora is also reflected in the behavior of extreme temperature thresholds (Table 2). Linear trends indicate an increase in annual hours with temperatures ≥ 33 °C, particularly in the months of October (4.25 h $year^{-1}$) and May (1.92 h $year^{-1}$), followed by April (0.87 h $year^{-1}$) and November (0.52 h $year^{-1}$). In contrast, hours with temperatures ≤ 4 °C showed a stable or slightly negative trend, with the greatest reductions in December (-0.37 h $year^{-1}$).

Table 2 Annual trend (h $year^{-1}$) of thermal thresholds ≤ 4 °C and ≥ 33 °C during the fall to spring growing months in southern Sonora, Mexico, from the years 2000 to 2025

Month	Temperature ≤ 4 °C	Temperature ≥ 33 °C
October	-0.011	4.250
November	-0.007	0.520
December	-0.370	0.010
January	0.170	0.000
February	0.000	0.040
March	0.100	-0.052
April	0.020	0.870
May	0.000	1.920

A summary of the annual trend in temperature thresholds is presented in Figure 1, which shows the behavior of extreme temperature events recorded during the analyzed period. The results show that the accumulation of hours with temperatures ≥ 33 °C occurs mainly in October, November, April, and May, increasing the potential for thermal risk to crops sown during these months. In contrast, the period between December and March is considered a low risk period, coinciding with more favorable conditions for plant development from sowing to physiological maturity, primarily for winter crops, such as wheat among others.

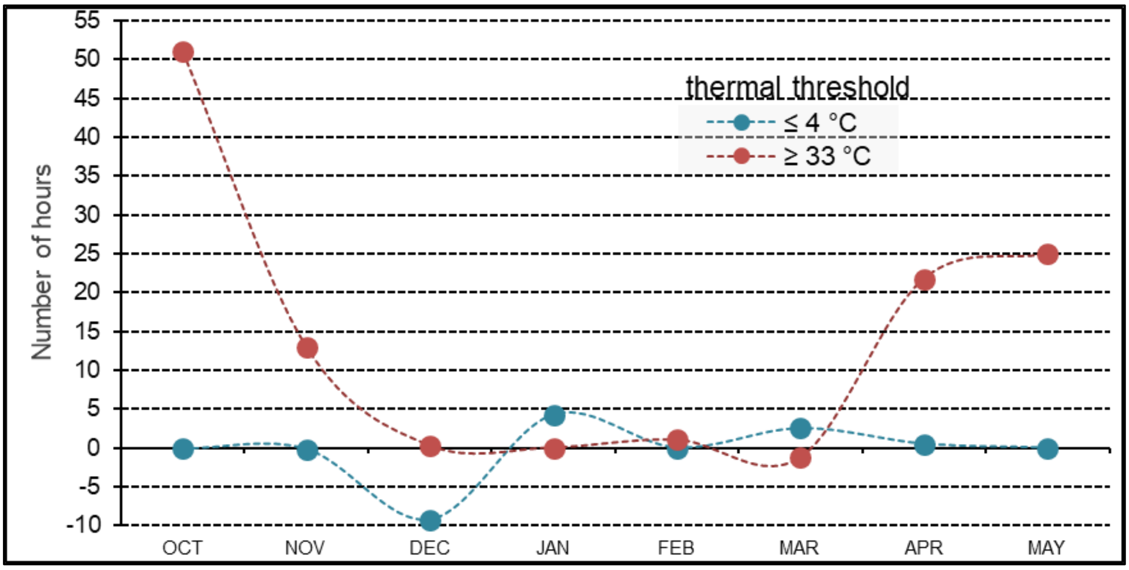

Figure 1 Accumulation of hours of thermal thresholds ≤ 4 °C and ≥ 33 °C during the years 2000 to 2025 in southern Sonora, Mexico

The trend observed in Figure 1 confirms an increase in the frequency of extreme temperature events, implying a greater risk of heat stress in fall and spring crops in the southern region of Sonora. Crop damage can manifest physically when temperatures reach or exceed the critical limits of 0 °C and 40 °C [16]. Likewise, prolonged exposure to suboptimal temperatures, close to these thresholds, can generate physiological stress and affect key processes such as photosynthesis, flowering and grain filling [17,18,19]. These results indicate that the upward temperature trend observed in the period 2000-2025 could translate, in the short and medium term, into greater risks of yield reduction, in accordance with what Ferris *et al*. [20] pointed out regarding the effects of the temperature increase, on the productivity of fall and spring crops.

3.2. Record of damage to fall, winter, and spring crops

3.2.1. Fall bean

The increase in the thermal threshold ≥ 33 °C during October and November is associated with greater flower and pod abortion in the first third of the plant (Figure 2), due to thermal stress that interferes with fertilization and pod setting.

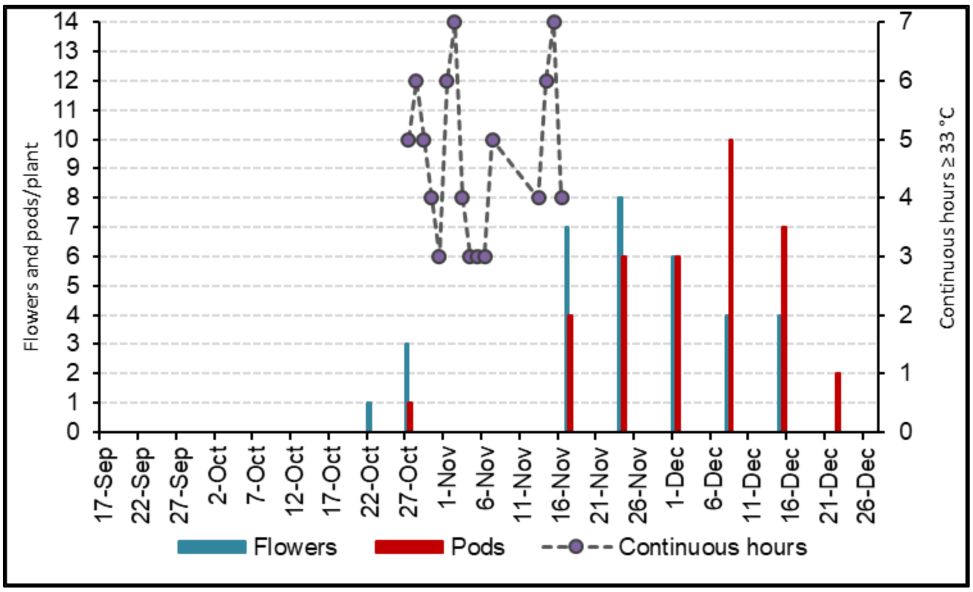

Figure 2 Flower and pod abortion in the Pinto Saltillo bean variety, associated with continuous periods of temperature ≥33 °C

Conversely, reducing the number of hours ≤ 4 °C in December can favor grain filling in the middle and lower thirds of the plant, as temperatures remain more stable during the reproductive development stage. Meanwhile, the first 15 days of January represent the greatest risk of frost in the region, although in some years this cold period can extend until the end of January or the beginning of February. Therefore, the fall sowing date must be carefully planned to minimize the crop's exposure to critical temperatures during flowering and grain filling. The results indicate that the productivity of fall beans is highly sensitive to thermal conditions and irrigation management (Table 3). A significant positive correlation was observed between pod production per square meter and temperature (r = 0.706), as well as with the applied irrigation sheet (r = 0.653). Similarly, grain yield showed a positive relationship with both temperature (r = 0.722) and irrigation sheet (r = 0.627), suggesting that moderately high temperatures and adequate water availability favor the reproductive development and grain filling. In contrast, the percentage of pods without grain showed a high negative correlation with temperature (r = -0.963), indicating that extreme thermal conditions or inadequate irrigation may increase pod abortion.

Table 3 Correlation coefficients between the agronomic variables irrigation sheet and temperature (°C), measured by a datalogger in fall beans

Variable	Irrigation sheet (cm)	Temperature (°C), sensor
Pod production/m2	0.653	0.706
Pods without grain (%)	-0.138	-0.963
Grain yield (kg/ha)	0.627	0.722

3.2.2. Spring bean

The risk from temperatures ≤ 4 °C is greatest during the first 15 days of January, a critical period for germination and crop establishment. However, the greatest thermal risk this season corresponds to temperatures ≥ 33 °C, which increase from April onwards and have a progressively greater impact as the sowing date is delayed from mid-January. This thermal increase during the flowering and pod filling stages increases the detachment of developing pods (< 2 cm) and grain abortion, reducing the number and weight of harvestable pods. Monterroso and Wien [19] reported that exposure to 35 °C for 10 hours over two consecutive days during the flowering stage, resulted in an 82 % abscission of pods smaller than 2 cm, as well as pollen dehydration. Similarly, Rainey and Griffiths [21] observed that day/night temperatures of 33/30 °C led to average reductions of 83, 63, 47, and 73 % in the number of seeds, number of pods, mean seed weight, and seeds per pod, respectively, across 24 evaluated common bean genotypes. The interaction between temperature and accumulated humidity, resulting from inadequate irrigation management, significantly affected grain development and quality in a commercial field in Block-2228 of the Yaqui Valley, where one section was sown on March 3 and another on March 27. The March 27 sowing showed 18.82 % less in grain with consumption quality, 13.63 % more in grain without consumption quality and 49.38 % more in undeveloped grain. Figure 3 shows the differences in the number of hours and duration of high-temperature periods between two commercial bean fields evaluated, which coincide with the crop fruiting stage. The thermal impact was more severe in the field located in block 2228, established with a late sowing date (March 27), where more continuous periods of temperatures higher than 33 °C occurred during the season than in the field located in block 2110, where the lowest statistical performance was recorded (Table 4), a lower number of pods with grain and a decrease in grain weight, which also resulted in a significant reduction in the commercial quality of the grain (Figure 4).

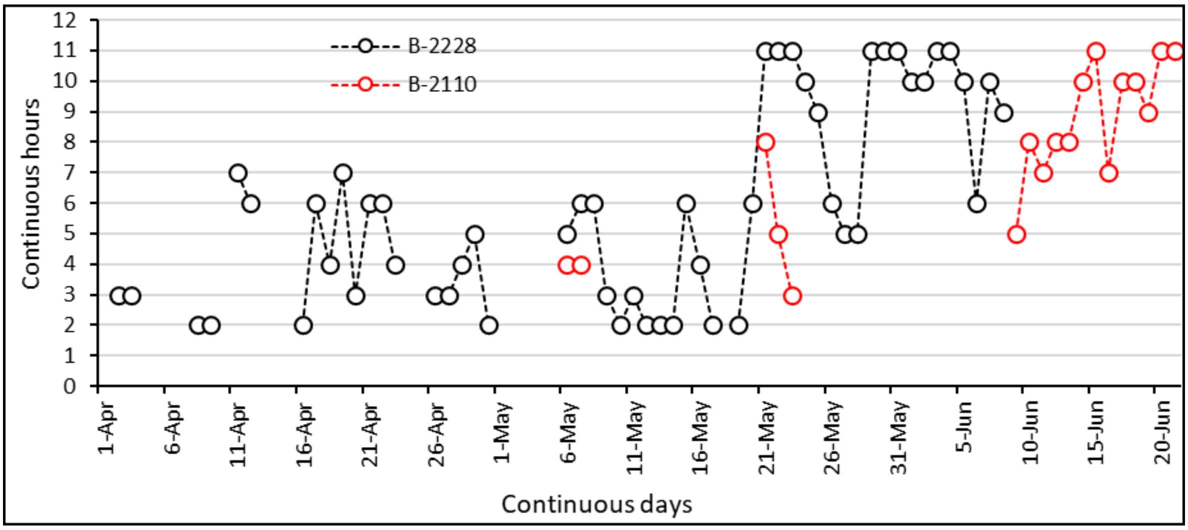

Figure 3 Continuous hours and days of temperature ≥ 33 °C, recorded within two commercial bean fields, in the Yaqui Valley, Sonora, Mexico, during the spring of 2023

Table 4 Average grain yield by sowing date in two commercial bean fields, in the Yaqui Valley, Sonora, Mexico

Field	Sowing date	Average grain yield (t ha^{-1})	Mean comparison
B-2110	09-mar	3.271	A
B-2110	25-mar	2.667	AB
B-2228	03-mar	1.818	BC
B-2228	27-mar	1.204	C

Tukey (0.05)

Figure 4 Effect of continuous hours and days of temperature ≥ 33 °C, recorded within two commercial bean fields, in the Yaqui Valley, Sonora, Mexico, during the spring of 2023

Porch and Jahn [22] reported that daytime temperatures exceeding 30 °C and night-time temperatures above 20°C induce abortions of flowers, flower buds, and pods, in addition to reducing pollen viability and causing damage to the pollen tube. Under prolonged high-temperature conditions, susceptible bean cultivars may experience grain yield losses of up to 100 %, while event heat-tolerant materials exhibit substantial yields reduction [23,24,25,26,27]. As with the fall sowing, pod abortion in spring beans was frequent in pods 1–20 mm long, particularly under prolonged periods of temperatures ≥ 33 °C combined with irrigation scheduling deficiencies. Soil waterlogging, resulting from excessive or poorly distributed irrigation, was associated with an increased number of plants that dried out prematurely and failed to produce pods. In contrast, fields managed with drip irrigation applied every 6–7 days, without losses due to filtration or excess moisture, showed a lower percentage of pod abortion and higher grain yield, which is related to a reduction in the number of hours of exposure to extreme temperatures.

3.2.3. Fall-winter maize

November sowings present a higher risk of damage from low temperatures (≤ 4 °C) during the first 15 days of January. At this stage, the crop is in the ear leaf development phase (leaves 9-10 and beyond), so cold-induced leaf necrosis affects the active photosynthetic surface, reducing yield proportionally to the degree of damage. Furthermore, the loss of leaf area causes a growth delay of 8 to 12 days. In contrast, with December sowings, the temperature drops coincide with the 4th to 7th leaf development stage (Figure 5), when the crop has a greater capacity for recovery. The emergence of new leaves allows it to compensate for the initial damage and maintain adequate development, resulting in better yields compared to early or late sowings.

Figure 5 Frost damage in maize plants from a commercial field, in the Yaqui Valley, Sonora, Mexico

Freezing temperatures prior to corn maturity can mean yield loss, although the severity greatly varies based on local climate conditions, crop maturity and topographical features [28]. From the February sowing onward, the main risk is associated with high temperatures (≥ 33 °C) that intensify from April. These conditions affect pollination and grain filling processes (Figure 6A), increasing the proportion of plants without ears and of small ears or ears without grain. Furthermore, the effect is exacerbated in warm seasons with high residual moisture from the last irrigations, which favors fungal growth in the grain (Figure 6B), leading to a decrease in weight and quality for consumption.

Figure 6 Effect of continuous hours and days with temperature ≥ 33 °C, recorded within commercial maize fields

Table 5 summarizes the results obtained in the 18 monitored commercial fields. It was observed that sowing dates after November 14th reduced yield by a range of 0.65 to 42.16 % (0.118 to 7.539 t ha^{-1}) compared to the average yield obtained in the two fields planted on November 14th. Likewise, the impact of frost showed that for every 1 % of foliar damage, production decreased by 30.1 kg ha^{-1}, corresponding to the severity of the event. Due to the spatial dynamics of the frost wave, some fields did not register significant damage, while partial or minor damage was concentrated in fields near the sea, where minimum temperatures were more moderate. Finally, frost tolerance was associated with the timely application of irrigation, since maintaining adequate soil moisture buffered extreme temperature fluctuations and reduced the severity of the damage.

Table 5 Impact of temperatures ≤ 4 °C on the production of 18 commercial maize fields, during the fall-winter season 2022-2023, in the Yaqui Valley, Sonora, Mexico

Sowing date	Foliar damage (%)**	Complete cobs (No.)	Medium cobs (No.)	Small cobs (No.)	Cobs without grain (No.)	Grain yield (12 % grain moisture) t ha-1
14/11/2022	48.5	9.2	0.8	0.7	0.2	14.577
14/11/2022	0.8	10.0	0.3	0.3	3.0	21.183
20/11/2022	32	9.3	1.0	0.3	1.0	17.762
20/11/2022	36	7.8	1.0	0.5	1.2	11.510
20/11/2022	14	9.7	1.7	0.2	2.0	14.999
25/11/2022	1	8.8	1.5	0.5	1.7	16.206
01/12/2022	25	9.0	0.3	1.0	0.7	11.611
01/12/2022	42	10.5	0.5	0.5	4.3	12.629
02/12/2022	4	8.5	0.8	0.2	3.8	17.189
05/12/2022	20	8.8	1.7	0.0	0.7	10.341
05/12/2022	38	9.3	1.0	0.0	0.5	14.334
06/12/2022	6	10.5	0.8	0.5	0.0	15.355
10/12/2022	76.5	9.0	2.3	0.5	1.3	12.971
13/12/2022	48.8	8.5	1.3	0.3	1.0	13.782
13/12/2022	81	7.8	2.2	0.8	1.8	12.967
22/12/2022	14	8.2	2.2	0.8	2.3	12.653
30/12/2022	76.5	8.7	1.5	0.7	1.0	15.316
06/01/2023	0	9.3	0.8	0.3	3.0	13.121
Promedio	31.3	9.1	1.2	0.5	1.6	14.4

**The period with low temperatures below <=4°C was from January 18 to 28, and on February 2, 3 and 4

3.2.4. Wheat

Wheat yield showed greater sensitivity to nighttime temperature (Table 6). The negative correlation was most pronounced in the Mayo Valley (r = -0.806) and, in general, in the southern region of Sonora (r = -0.785), indicating that an increase in nighttime temperature has a significantly adverse effect on yield. On average, it was estimated that for every 1 °C increase in mean nighttime temperature above 11.6 °C, yield decreased by 531 kg ha^{-1} (Figure 7). This result agrees with that reported by Peng *et al.* in rice (*Oryza sativa* L.) [29] and Prasad *et al.* in wheat [30], who observed that nighttime temperatures above 14 °C reduce photosynthetic efficiency and that values ≥ 20 °C affect spikelet fertility, limiting grain filling. On the other hand, daytime relative humidity also showed a negative correlation with yield, especially in the southern region of Sonora (r = -0.457), where for every 1 % increase in daytime relative humidity from 52 %, yield decreased by an average of 116 kg ha^{-1}. This behavior is associated with a higher incidence of foliar diseases and pests, which thrive under conditions of high humidity and moderate temperature, particularly in the Mayo Valley, where historically there is a higher level of disease pressure [31].

Table 6 Correlation coefficients of temperature (°C) and relative humidity (%) with wheat yield, during the agricultural seasons 2004-2005 to 2023-2024 in southern Sonora, Mexico

Region	Temperature and grain yield		Relative humidity and grain yield	
	Daytime	Nighttime	Daytime	Nighttime
Souhern Sonora	-0.024	-0.785	-0.457	0.022
Yaqui Valley	0.180	-0.599	-0.361	0.287
Mayo Valley	-0.136	-0.806	-0.377	-0.086

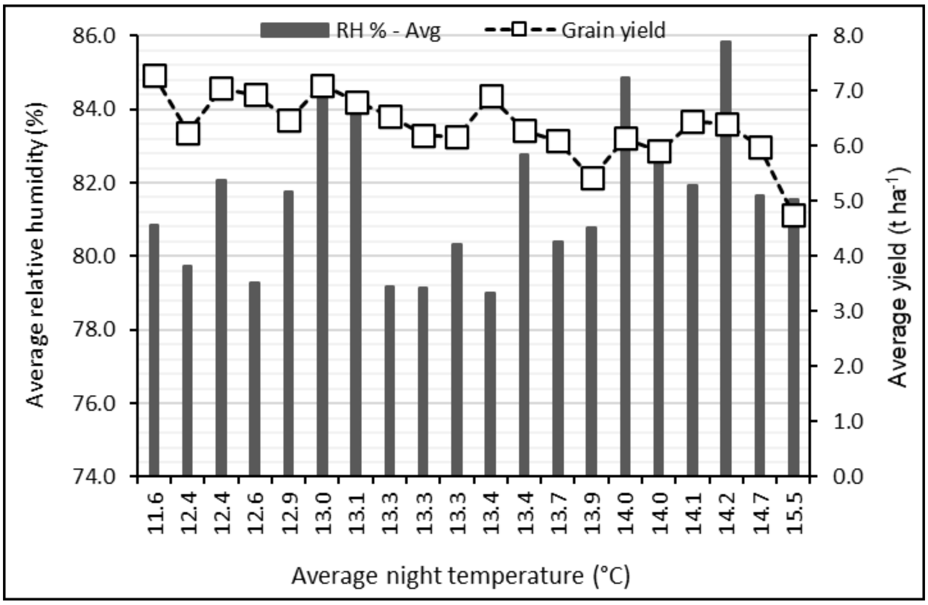

Figure 7 Relationship between temperature and mean nighttime relative humidity with wheat yield, during the agricultural seasons 2004-2005 to 2023-2024 in southern Sonora, Mexico

The most affected sowing dates in southern Sonora are those occurring before November 20 and after December 20, according to information obtained from the set of fields monitored over 20 wheat growing seasons (Figure 8). In years with warm Novembers and Decembers, early sowings tend to accelerate the first phenological stages, affecting floral differentiation and structure, primarily by reducing the number of grains per spike. On the other hand, late sowings (after December 20) face critical temperature conditions during the grain-filling phase, registering a high number of hours with values ≥ 33 °C in April [32] (Table 1). This thermal threshold is associated with decreased pollen viability, increased grain abortion in early stages, and a reduction in the weight of formed grains, directly affecting the final yield [33,34].

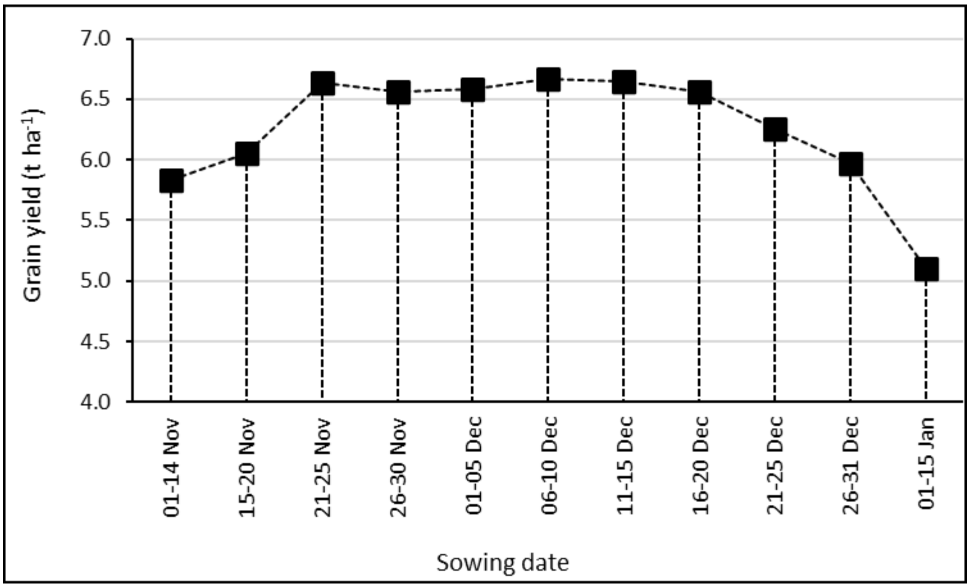

Figure 8 Average yield of commercial wheat fields, grouped by sowing date, in the last 20 wheat seasons (2004-2005 to 2023-2024)

On average, the sown area in southern Sonora over the last 24 growing seasons totals 225,496 ha [4]. Of this area, an estimated 43,700 ha are at risk of thermal damage due to sowing outside the optimal range (before November 20 or after December 20), which historically has resulted in yields below the cost of production. Regional historical data demonstrates that sowing outside the optimal period increases the economic risk for producers by reducing the probability of achieving the target profitability.

4. Conclusion

The climate changes observed in the agricultural region of southern Sonora have increased the daily temperature range and the frequency of extreme thresholds, mainly during the months of October, November, April and May.

This behavior highlights the need to adjust the technologies and production schedules for maize, beans, and wheat to mitigate the risks associated with temperatures outside the optimal range.

In beans, irrigation schedules need to be re-scheduled based on adjustments to both autumn and spring sowing dates.

In maize, it is recommended to maintain sowing in December, thus avoiding damage from early frosts and high temperatures during critical crop stages.

In wheat, adjusting the sowing date would reduce risk in approximately 19.3 % of the area currently outside the optimal range, defining the ideal sowing period between November 20 and December 20.

Compliance with ethical standards

Acknowledgments

This research was financially supported by the Mexican National Institute for Forestry, Agriculture, and Livestock Research (INIFAP).

Disclosure of conflict of interest

The authors declare that No conflict of interest.

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