



(RESEARCH ARTICLE)



DAYTIME AND NIGHTTIME THERMAL THRESHOLDS ASSOCIATED WITH WHEAT YIELD LOSS IN THE YAQUI VALLEY, SONORA, MEXICO

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ABSTRACT

Rising temperatures in southern Sonora are a major factor affecting wheat yield; however, the thermal thresholds that reduce yield and the specific growth stages during which these effects occur have not been defined. The objective was to identify the day and night temperature thresholds associated with yield loss and to determine the phenological stage most affected. During the 2025–2026 crop season, hourly temperatures were recorded in 17 commercial fields in the Yaqui Valley and at the nearest weather station from the Sonora automated weather station network. Daytime hours ≥ 30 °C and nighttime hours ≥ 14 °C were recorded for each phenological stage and related to yield using linear regression, impact analysis by 1 °C interval with bootstrap resampling, and multiple regression. Hours at ≥ 30 °C between spike emergence and physiological maturity explained 91 % of the yield variation ($-23.3 \text{ kg ha}^{-1} \text{ h}^{-1}$; $p < 0.001$), and the impact per hour increased above 33 °C and 36 °C. At night, the impact was significant starting at 18 °C, but its effect could not be separated from the daytime effect ($r = 0.90$). Digital sensors placed within each wheat field, recorded an average of 252 more daytime hours at ≥ 30 °C and 140 fewer nighttime hours at ≥ 14 °C than the weather stations; consequently, the thresholds derived from station data are not equivalent to those experienced by the crop. Daytime heat during grain filling was the thermal factor most strongly associated with wheat performance in the region.

Keywords: *Triticum* Spp., Wheat, Grain Yield, Temperature, Thermic Threshold

1 INTRODUCTION

Wheat (*Triticum* spp.) production is the most significant agricultural activity during the autumn-winter growing season in southern Sonora, Mexico, in terms of the land area cultivated each year. During the 2024–2025 crop season, 3,182.5 ha were sown, resulting in a production of 23,452.50 tons and an average yield of 6.50 t ha⁻¹ [1]. Wheat yield is the result of the interaction between a variety's genetic potential, agronomic management, and the environmental conditions that prevail throughout the crop's growth cycle [2]. Among climatic factors, temperature plays a fundamental role by regulating the plant's rate of development from emergence to physiological maturity [3].

In recent decades, rising temperatures associated with climate change have increased the frequency and intensity of heat stress events in crops. Félix *et al.* [4] reported that in southern Sonora, hourly records of climatic conditions have shown significant changes over the last two decades, with a trend toward greater temperature fluctuations. Furthermore, they have documented the impact of temperature and relative humidity on yield variance -analyzed across different sowing dates in commercial fields over 20 growing seasons- a finding consistent with observations in other wheat-producing regions [5, 6].

Wheat is particularly sensitive to high temperatures; Moreno-Dena *et al.* [7] note that high temperatures promote increased metabolic activity in the plant, as well as the acceleration of physiological processes that determine its growth and development. Temperatures ≥ 30 °C during meiosis and anthesis affect the viability of both pollen and ovules, and reduce the number of grains. During grain filling, such temperatures accelerate the senescence of the foliage and shorten the period of dry matter accumulation in the caryopsis [8]. In southern Sonora, hours with temperatures ≥ 30 °C occur more frequently from mid-March onwards, coinciding with the heading and grain-filling stages for a large portion of the crops. Furthermore, the shortening of the growth cycle alters the optimal timing for supplemental irrigation—which is crucial for nutrient assimilation and helps buffer the impact of extreme temperatures [9].

Nighttime temperature also regulates crop development. In the region, a decrease in the number of hours with a minimum temperature ≤ 10 °C has been recorded [10]. Low temperatures slow down wheat development and extend the duration of the vegetative and early reproductive phases [11]. Conversely, an increase in nighttime temperature enhances maintenance respiration and alters the source-demand relationship for photoassimilates. It also accelerates leaf senescence, which reduces the availability of carbohydrates for grain filling and, consequently, diminishes both grain yield and quality [12]. Despite this, the effect of nighttime temperature has received less attention than that of daytime heat. In southern Sonora, the daytime and nighttime temperature thresholds that reduce wheat yield -as well as the specific phenological stage during which each threshold has the greatest impact- have not yet been defined. Furthermore, regional analyses rely on weather stations located several kilometers away from the fields; the data recorded at these stations may differ from the actual thermal conditions within the crop canopy. The 2025–2026 growing season experienced higher temperatures than previous seasons from the onset of sowing, providing an opportunity to evaluate these thresholds under commercial conditions. Consequently, this study aims to identify the daytime and nighttime temperature thresholds in the Yaqui Valley associated with reduced wheat grain yield, as well as to determine the phenological stage at which each threshold has the greatest impact.

2 MATERIALS AND METHODS

The study was conducted during the 2025–2026 fall-winter crop season across 17 commercial wheat fields in the Yaqui Valley, Sonora, Mexico (27°10'–27°50' N, 109°55'–110°36' W; 25 m asl). According to the Köppen climate classification as modified by García [13], the southern Sonora region is characterized by a hot, dry climate (BW(h)) and extreme heat (BSO). Each field was georeferenced using a GPS receiver. Sowing dates ranged from November 24, 2025, to January 9, 2026; the cultivar, sowing and physiological maturity dates, and the duration of each growth stage for each field are presented in Table 1. Agronomic management was carried out by each producer according to their standard practices and based on the recommendations of Figueroa-López *et al.* [14].

Table 1: Cultivar, sowing dates, physiological maturity, and duration of developmental stages for 17 commercial wheat fields evaluated in the Yaqui Valley, Sonora, Mexico, during the crop season 2025-2026

Field	Cultivar	Sowing date	Physiol. maturity	Sowing – first node (days)	First node – spike emergence (d)	Spike emergence - maturity (d)	Sowing - maturity (d)
B-207	CIRNO C2008	24/11/2025	31/03/2026	52	34	41	127
B-511	CIRNO C2008	20/12/2025	08/04/2026	36	28	45	109
B-604	Borlaug 100 F2014	22/12/2025	14/04/2026	37	31	45	113
B-705	Borlaug 100 F2014	12/12/2025	08/04/2026	40	27	49	117
B-817	Borlaug 100 F2014	14/12/2025	08/04/2026	45	21	49	115
B-912	CIRNO C2008	28/12/2025	07/04/2026	28	26	46	100
B-1115	Borlaug 100 F2014	14/12/2025	05/04/2026	42	30	40	112
B-1201	PD Chanate C2023	11/12/2025	10/04/2026	42	23	55	120
B-1209	CIRNO C2008	05/12/2025	01/04/2026	38	30	49	117
B-1504	Noroeste C2021	10/12/2025	10/04/2026	48	22	51	121
B-1512	Noroeste C2021	25/11/2025	31/03/2026	38	41	47	126
B-1706	PD Chanate C2023	13/12/2025	10/04/2026	38	31	49	118
B-1716	Borlaug 100 F2014	01/12/2025	07/04/2026	45	24	58	127
B-1816	Noroeste C2021	31/12/2025	14/04/2026	35	24	45	109
B-2008	CIRNO C2008	04/12/2025	03/04/2026	40	29	51	120
B-2020	Noroeste C2021	20/12/2025	15/04/2026	46	26	44	116
B-2128	CIRNO C2008	09/01/2026	20/04/2026	30	22	49	101
			Mean	40	28	48	116

In each field, an OMEGA digital sensor (model OM-EL-WIN-USB)—programmed using Data Logger v7.2.1 software—was installed to record hourly air temperature and relative humidity. The sensors were positioned at canopy height and adjusted as the crop grew. To compare measurements, hourly temperature and relative humidity records were obtained from the nearest station in the Sonora Automated Weather Station Network [15] for each field. The distance between the station and the field ranged from 2 to 8 km.

Phenology was recorded according to the scale of Zadoks *et al.* [16]. Three stages were defined: stage 1 spanned from sowing to the first detectable node (Z31), corresponding to tillering; stage 2 spanned from the first node to the beginning of spike emergence (Z31–Z50), corresponding to stem elongation; and stage 3 spanned from the beginning of spike emergence to physiological maturity (Z50–Z87), corresponding to grain filling.

Daytime hours were defined as 07:00 to 18:00, and nighttime hours as 19:00 to 06:00. Based on the records from each data source (sensor and REMAS station), the number of daytime hours with temperatures ≥ 30 °C and nighttime hours with temperatures ≥ 14 °C was tallied for each stage, using a thermal threshold with 1 °C intervals.

To determine grain yield, six 1 m² samples were taken from each field, selected at random. The yield for each field was expressed as the average of the six samples, converted to kg ha⁻¹.

The accumulated hours recorded by the sensor and the station in each field were compared using a paired-sample Student's t-test. Normality of the differences was verified using the Shapiro-Wilk test. The association between the sensor and station data was evaluated using Pearson's correlation coefficient.

The relationship between grain yield and thermal hours was evaluated using simple linear regression for each data source and phenological stage, in two ways. First, using the cumulative hours above each threshold, from which the slope (kg ha⁻¹ h⁻¹) and the coefficient of determination (R^2) were obtained; these regressions were also performed including the number of days since the initial sowing as a covariate. Second, using the hours recorded within each 1 °C interval, where the slope was interpreted as the impact of that specific interval on yield; only intervals with an average of at least 1 hour per field were analyzed. The significance of each impact, as well as the differences between intervals within each phenological stage, were assessed via bootstrap resampling of the fields (5,000 iterations) with a Holm adjustment for multiple comparisons, and the results were summarized using grouping letters.

Once the thresholds at which damage began were identified, their combined effect was evaluated using multiple linear regression, with daytime hours ≥ 30 °C (from spike emergence to maturity) and nighttime hours ≥ 18 °C (over the entire cycle) as independent variables. Collinearity between the two was assessed using the variance inflation factor (VIF).

A significance level of $\alpha = 0.05$ was considered. Analyses were performed in R version 4.5.2 [17] using the packages readxl, dplyr, ggplot2, car, and multcompView.

3 RESULTS AND DISCUSSION

Temperatures during the 2025–2026 crop season were higher than those of the 2024–2025 season, starting from the time of sowing (Figure 1). From November to April, the average daytime temperature was 1.47 °C higher, and the nighttime temperature was 3.56 °C higher, than in the previous season. The duration from sowing to maturity ranged from 100 to 127 days (with a mean of 116 days) (Table 1) -an average of 28 days shorter than in the previous season- with the duration of phenological stages reduced across all cultivars. Other studies have reported this shortening of the growth cycle due to the accumulation of growing degree-days [18, 19].

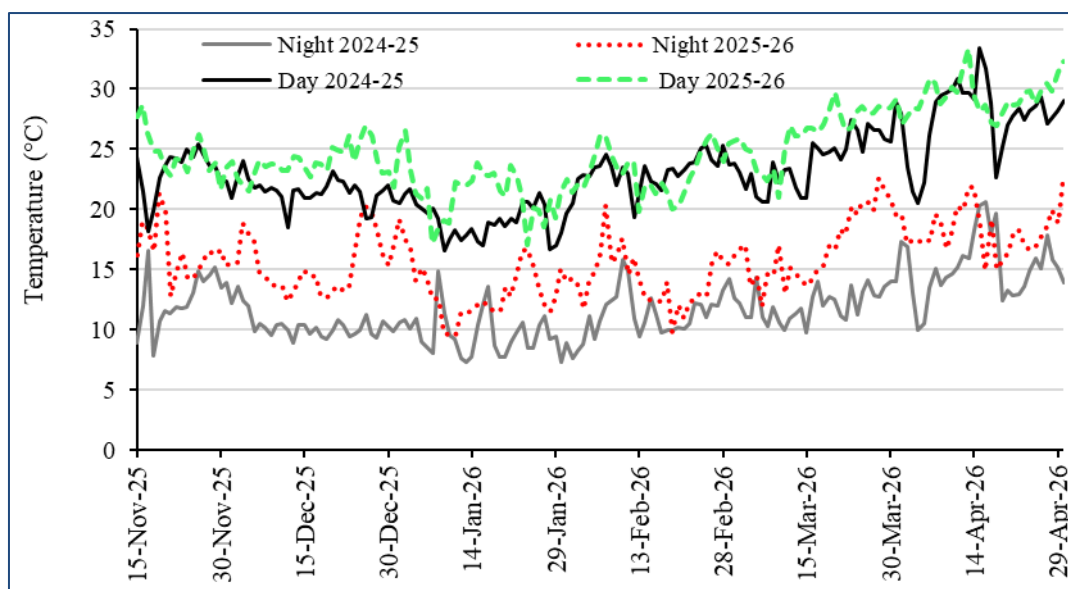


Figure 1: Average daytime and nighttime temperatures from November 15 to April 30 for the 2024–2025 and 2025–2026 fall-winter crop seasons, in the Yaqui Valley, Sonora, Mexico

From sowing to physiological maturity, the sensor recorded an average of 252 more daytime hours $\geq 30^{\circ}\text{C}$ than the REMAS station (95 % CI: 226–278 h; $t_{16} = 20.7$; $p < 0.001$). Conversely, it recorded 140 fewer nighttime hours $\geq 14^{\circ}\text{C}$ (95 % CI: 112–168 h; $t_{16} = -10.6$; $p < 0.001$) (Table 2). Despite these differences in magnitude, the accumulated hours recorded by the sensor and the station were correlated across fields ($r = 0.64$, $p = 0.006$ for daytime hours; $r = 0.73$, $p < 0.001$ for nighttime hours).

Table 2: Daytime hours $\geq 30^{\circ}\text{C}$ and nighttime hours $\geq 14^{\circ}\text{C}$ recorded by sensors and weather stations, from sowing to physiological maturity in each wheat field, during the 2025–2026 fall-winter crop season, in the Yaqui Valley, Sonora, Mexico

Field	Daytime hours 30–40 $^{\circ}\text{C}$		Nighttime hours 14–25 $^{\circ}\text{C}$	
	Sensor	Weather St.	Sensor	Weather St.
B-207	463	215	725	996
B-511	404	145	596	714
B-604	469	263	695	862
B-705	420	163	650	756
B-817	394	207	701	859
B-912	557	251	695	837
B-1115	418	187	710	864
B-1201	520	230	763	888
B-1209	411	142	686	869
B-1504	468	207	703	862
B-1512	458	145	744	803
B-1706	554	228	819	913
B-1716	544	221	784	829
B-1816	384	210	611	733
B-2008	415	168	656	867
B-2020	544	330	754	920

B-2128	363	194	587	692
Mean	458	206	699	839

The mean yield across the 17 fields was 5,386 kg ha⁻¹ (ranging from 4,192 to 6,771 kg ha⁻¹). Daytime heat during grain filling was the factor most strongly associated with yield. According to the sensor data, fields that experienced more hours at ≥30 °C between spike emergence and physiological maturity had lower yields: each additional hour reduced yield by 23.3 kg ha⁻¹ ($p < 0.001$) (Figure 2a). The number of hours at ≥30 °C accumulated during earlier stages showed a weaker relationship with yield, and the sowing date did not alter this result. Based on data from the network, the relationship was even weaker ($R^2 = 0.20$; $p = 0.07$). This aligns with wheat's sensitivity to high temperatures during the reproductive phase—conditions that accelerate senescence, shorten the grain-filling period, and reduce individual grain weight, ultimately leading to substantial declines in wheat yield [12,20].

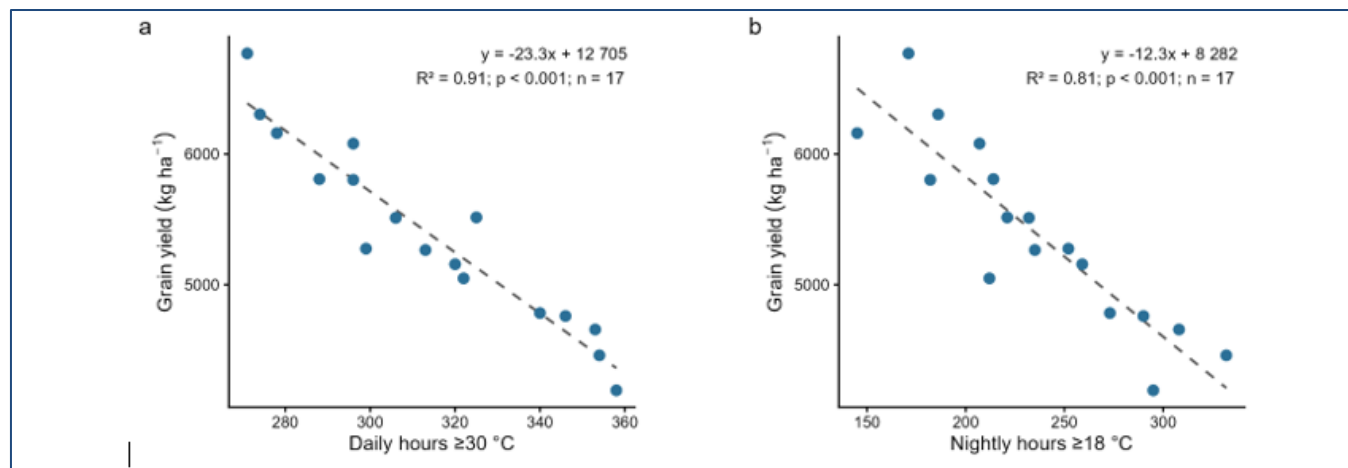


Figure 2: Relationship between grain yield and (a) daytime hours ≥30 °C from spike emergence to physiological maturity, and (b) nighttime hours ≥18 °C from sowing to physiological maturity, as recorded by the sensor

Analysis in 1 °C increments showed that damage began at 30 °C and increased with temperature. Based on sensor data, the impact was significant starting at the 30 °C threshold during the stages from sowing to the first node (Figure 3a) and from spike emergence to maturity (Figure 3c), and starting at 31 °C during the stage from the first node to spike emergence (Figure 3b). During the stage from spike emergence to maturity, three levels of damage per hour were identified: -73 to -130 kg ha⁻¹ h⁻¹ between 30 and 32 °C, -166 to -275 kg ha⁻¹ h⁻¹ between 33 and 35 °C, and -425 to -917 kg ha⁻¹ h⁻¹ at 36 °C and above (Figure 3c). With the net, no daytime interval was significant (Figure 3d–3f). This increase indicates that the damage is not proportional to temperature, but rather intensifies beyond certain thresholds.

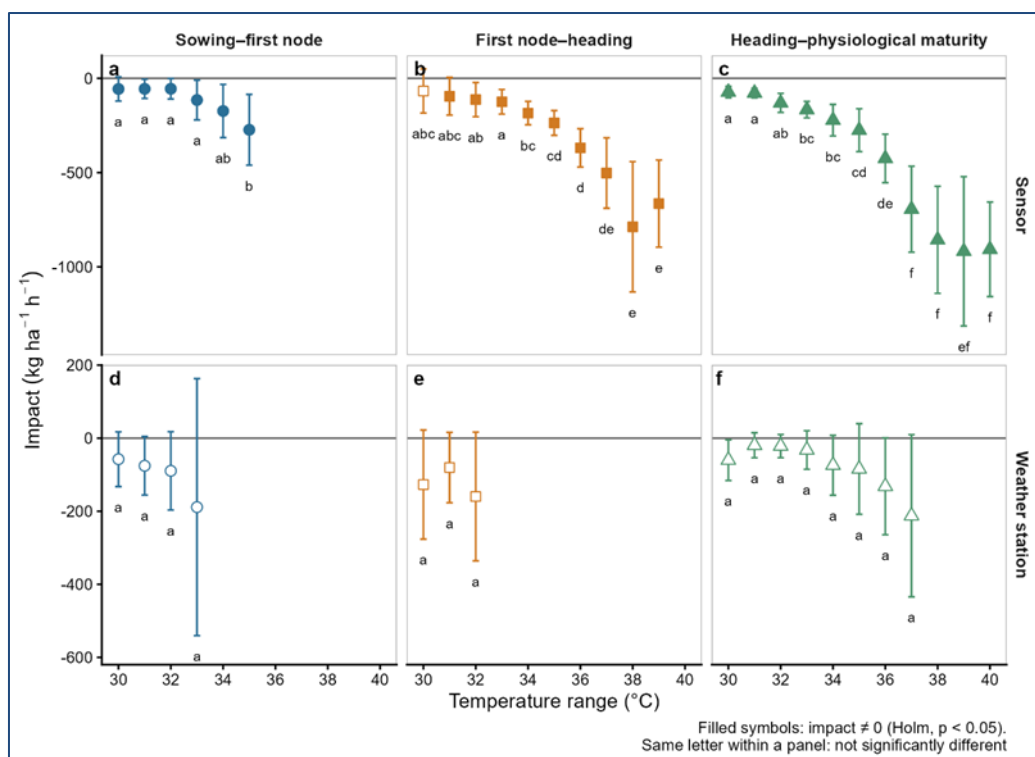


Figure 3: Impact of daytime hours, in 1 °C intervals, on grain yield (slope $\pm$ 95 % CI), by phenological stage

Nighttime hours were also associated with lower yield. According to the sensor, at temperatures of 17–18 °C and above, the cumulative hours from sowing to maturity accounted for approximately 80 % of the yield differences between fields; at ≥ 18 °C, each additional hour reduced yield by 12.3 kg ha^{-1} ($R^2 = 0.81$; $p < 0.001$) (Figure 2b). Above 19 °C, the relationship weakened, and for all three phenological stages, the best fit was obtained at around 18 °C (Figure 4a). Using data from the network, the best fit was achieved with higher thresholds—between 22 and 23 °C ($R^2 = 0.87$) (Figure 4b)—which aligns with the fact that the network records warmer nights than the sensor does. This threshold is consistent with the negative effects of warm nights on wheat [21], which are associated with increased maintenance respiration and reduced carbohydrate availability for grain filling [12]. Similarly, Han *et al.* [22] and Giménez *et al.* [23] documented that nighttime warming reduces starch accumulation and yield potential due to increased nighttime respiration, although it may enhance certain grain protein quality attributes.

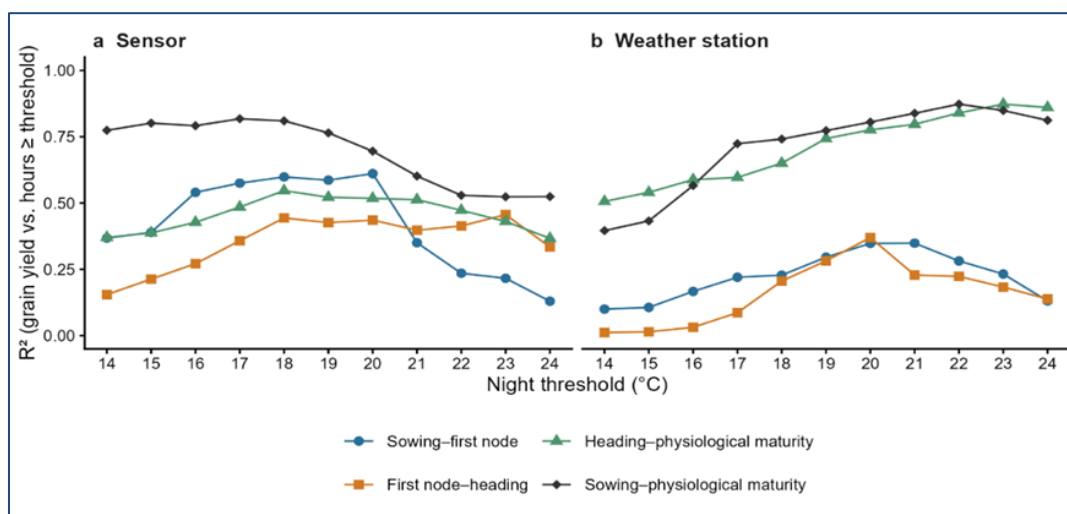


Figure 4: Coefficient of determination (R^2) of the regression of yield against accumulated nighttime hours above each threshold, by phenological stage, using data from (a) the sensor and (b) the REMAS station

Interval-based analysis confirmed that nighttime damage began at approximately 18 °C. Based on sensor data, the hours between 14 and 17 °C were not associated with yield at any stage (Figures 5a–5c). From 18 °C onwards, the impact was negative and significant during the stages from the first node to spike emergence ($-112 \text{ kg ha}^{-1} \text{ h}^{-1}$; $p = 0.036$) (Figure 5b) and from spike emergence to maturity ($-64 \text{ kg ha}^{-1} \text{ h}^{-1}$; $p = 0.029$) (Figure 5c); for the period from sowing to the first node, the impact was marginal at 18 °C ($p = 0.054$) and significant at 20 °C ($-87 \text{ kg ha}^{-1} \text{ h}^{-1}$; $p = 0.004$) (Figure 5a). Unlike during the day, the impact did not differ significantly between nighttime intervals. Based on the network data, from sowing to spike emergence, no threshold was significant (Figures 5d and e). The onset of damage occurred at 19 °C only during the stage from spike emergence to maturity (Figure 5f) which aligns with the fact that the network records warmer nighttime temperatures than the individual sensor. In northwestern Mexico, experimental nighttime warming of 2 °C in the field reduced grain yield by 1.9 % per degree [24].

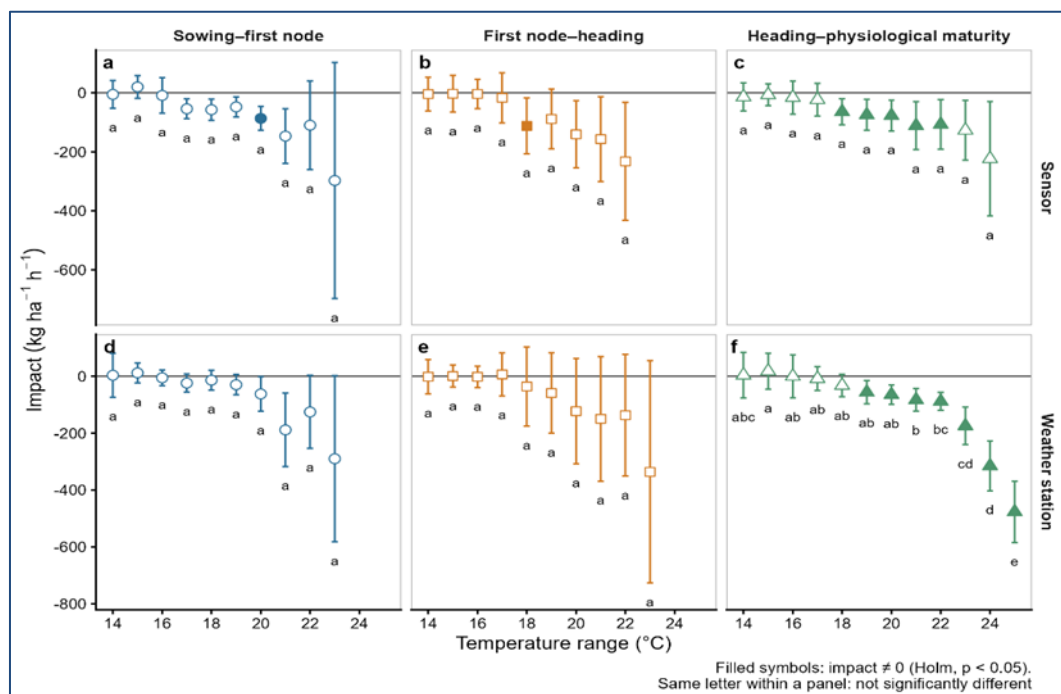


Figure 5: Impact of nighttime temperatures (in 1 °C intervals) on grain yield (slope ± 95 % CI), by phenological stage

Daytime hours ≥ 30 °C from spike emergence to maturity and nighttime hours ≥ 18 °C throughout the growth cycle were highly correlated across fields ($r = 0.90$; VIF = 5.5). In a multiple regression model including both variables ($R^2 = 0.92$), daytime hours maintained a significant effect ($-18.5 \text{ kg ha}^{-1} \text{ h}^{-1}$; $p = 0.001$), whereas nighttime hours did not ($-3.0 \text{ kg ha}^{-1} \text{ h}^{-1}$; $p = 0.26$). This indicates that daytime heat was the primary factor, although in this cycle it was not possible to determine with certainty how much of the damage was attributable to the nights, because hot days and hot nights occurred simultaneously.

4 CONCLUSION

Daytime heat during the grain-filling period was the primary thermal factor associated with wheat yield loss in the 2025–2026 growing season. Each hour at ≥ 30 °C between spike emergence and physiological maturity reduced yield by 23.3 kg ha^{-1} ; the damage per hour intensified above 33 °C and, even more significantly, above 36 °C.

Nights with temperatures ≥ 18 °C were also associated with lower performance, and 18 °C was the threshold above which the nighttime impact became non-zero. However, its effect could not be disentangled from daytime heat, with which it was highly correlated.

Weather stations underestimated hot daytime hours and overestimated warm nighttime hours compared to conditions recorded within the crop. Consequently, thresholds and relationships derived from station data are not equivalent to those measured within the canopy. These thresholds must be validated using data from multiple cycles before being used as decision-making criteria.

STATEMENTS ON 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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