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Impact of temperature and relative humidity on sowing date and commercial grain yield of wheat in southern Sonora, Mexico

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Abstract

This work aimed to analyze the variation in temperature (T) and relative humidity (RH) in wheat seasons 2004-05 to 2023-24, and its impact with sowing dates on grain yield in southern Sonora, Mexico. The T and HR were recorded in hourly format from the meteorological stations in the region during November to April. Commercial fields were selected based on territorial distribution in the Yaqui (YV) and Mayo (MV) Valleys, covering sowing dates from November 1 to January 15, and grain yield was determined based on a 1 m^2 sample with six replications in each field. The daytime T in both valleys had a positive trend, in the YV it increased between 1.4 and 2.9 °C, while in the MV between 1.8 and 3.5 °C. The night T had mostly a negative trend in both valleys, the MV had a tendency with 1.6 °C less and the YV with 1 °C. RH during the day showed a decrease tendency throughout most of the season in both valleys, in the YV the decrease ranged from -2.6 to 0.9 %, and from -4.9 to -2.5 % in the MV. Nighttime humidity had an increase tendency in the YV with a range of 1.1 to 8.0 %, whereas in the MV, it showed a tendency to decrease in November, January, February, and March. The night temperature was negatively correlated with grain yield in both valleys, while relative humidity was not. The highest grain yields (above 9.5 t ha^{-1}) were obtained in wheat seasons characterized with more than 670 cold units, and grain yield over 6.5 t ha-1 was obtained in sowing dates from November 21 to December 20.

Keywords: Wheat; *Triticum* sp.; Climate change; Sowing date; Risk

1. Introduction

Climate change is a natural process, but trends related to climate change are alarming mainly due to anthropogenic reasons [1]. Climate change has increasingly been recognized as a major threat to agriculture [2] due to its great magnitude and sensitivity to meteorological parameters, which cause important negative economic impacts [3]; furthermore, the climate directly influences food production worldwide, because the climate of a region/country determines the nature and characteristics of vegetation and crops [4]. Climate change scenarios include higher temperatures, changes in rainfall and increased atmospheric CO_2 concentrations, which may affect yield (both quality and quantity), growth rates, photosynthesis and transpiration rates, moisture availability, through changes in water use (irrigation) and agricultural inputs such as herbicides, insecticides and fertilizers [1,4]. Studies conducted since the 1990s on the effects of climate change in Mexico, concluded that the country will experience higher temperatures and hence, higher evaporation rates with a doubling of CO_2. Precipitation will be heterogeneous depending on the

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geographic area evaluated; summer rainfall could decrease in most of the country and increase during the winter in the northern region. Models used to test the sensitivity of different regions of Mexico to climate change, project that coastal areas and the northern and central regions could be the most vulnerable to climate change [5, 6, 7, 8, 9, 10, 11,12]. Wheat (*Triticum* spp.) is one of the crops most cultivated around the world for human consumption, but the main cereal worldwide is maize (*Zea mays* L.) followed by wheat and rice (*Oryza sativa* L.) [13]. In Mexico, it is among the five main crops produced. Wheat is sown in the fall-winter crop seasons in the northern and northwestern regions, as well as spring-summer sowing in the central region. The largest wheat production is concentrated in five states (Sonora, Baja California, Sinaloa, Guanajuato, and Chihuahua), which together represent around 92 % of the total national production [14]. Sonora has been the main producer of wheat in Mexico; in 2024, 248,000 ha were allocated for wheat cultivation, obtaining a production of over 1,571 million t, equivalent to 56.6 and 61.9 % of the national wheat area and production, respectively. Most of the wheat production in Sonora takes place in the southern part of the state in the Yaqui Valley (YV) and to a lesser extent in the Mayo Valley (MV); both valleys have an arid climate and poor humidity for most of the year, and they are considered a world reference in wheat production [15]. However, since Southern Sonora is prone to limitations in water availability [16], the agricultural area is irrigated with water from dams [17]. The YV is one of the main agricultural production regions in northwestern Mexico, covering the area between the Sierra Madre to the east and the Gulf of California to the west. The climate is semiarid, with variable precipitation rates with an annual average of 317 mm and an average temperature of 21 °C during the fall-winter crop season, and 30 °C for the spring-summer season [18]. Similarly, the MV is located in the extreme south of Sonora; the climate of the region is defined as a hot and desert climate with an average annual temperature of 23 to 27 °C, with a maximum range of 43 to 48 °C during June, July, and August, and a minimum range of 3.5 to 4 °C in December and January. The average annual precipitation range is 200 to 400 mm, concentrated during July to September with 70 % [19]. Temperature is considered the most important factor inducing wheat plant development from emergence to flowering and maturity [20], and it affects growth processes [21]. Relative humidity is essential in all active stages of phytopathogens, and the temperature-humidity interaction establishes the methodology for the forecast of important diseases [22]. Historical analysis of wheat yield showed a global decline of 5.5% in aggregate wheat production since 1980, as a result of rising global average temperatures [23]. Lobell *et al*. [24] reported that wheat yields in northwestern Mexico have increased by 25 % from 1980 to 2001, mainly due to cooling trends in minimum nighttime temperatures that probably cause reduced plant respiration. Selection of the sowing date is one of the most important management decisions, where various factors that directly and indirectly affect the yield potential of the cultivar to be used must be considered [25]. Solís *et al*. [26] reported that in early sowing dates (November 16) the crop season was lengthened because there were climatic conditions that favored the crop, which led to a greater production of grains per unit of area and greater grain yield, while in late dates (January 15), the biological cycle up to physiological maturity was reduced, which indicates that this date accelerates the development of the wheat plant. Therefore, the productivity and quality of wheat is controlled by the genetic characteristics of the cultivar being grown, which can be modified by the weather conditions that prevail during the crop season and the agronomic management [27]; therefore, the present work aimed to analyze the variation in temperature and relative humidity in the last 20 agricultural fall-winter wheat seasons, and its impact on the sowing date and wheat grain yield in southern Sonora.

2. Material and methods

Temperature and relative humidity data were downloaded in hourly format from meteorological stations in southern Sonora, from the last 20 wheat agricultural crop seasons. From 2004 to 2015, 14 stations were considered in the YV and 9 in the MV (Figure 1A), and from 2016-2024, there were 21 stations in the YV and 12 in the MV (Figure 1B), belonging to the Network of Automated Meteorological Stations of the state of Sonora (REMAS) [28], during the months of November to April. The data was arranged in daytime and nighttime, considering daytime data from 7:00 to 18:00, and nighttime data from 19:00 to 06:00. The increase or decrease of the temperature and relative humidity was determined through trend analysis.

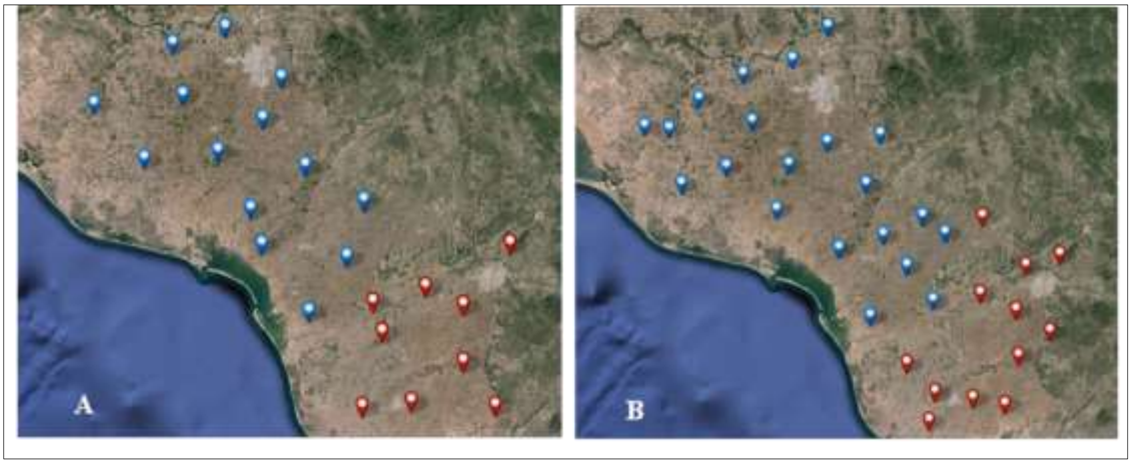

Figure 1 Geographic location of the meteorological stations in the Yaqui Valley (blue dots) and Mayo Valley (red dots), A) from 2004-2015, and B) from 2016 to 2024

Regarding field data, commercial fields were chosen based on the distribution of the meteorological stations; field tours were carried out in both valleys from November 1 to January 15. An average of 70 fields were selected each agricultural crop season. Table 1 lists the cultivars with the largest area sown in each agricultural crop season. The crop was monitored several times and the phenological phases and irrigations applied were recorded. The grain yield was obtained based on a 1 m^2 sample from six random replications in each field. Through correlation and linear regression analysis, the yield was related to the temperature and relative humidity at night for each crop season, in addition to the interaction of the different sowing dates with grain yield.

Table 1 Wheat cultivars with the largest area sown, in the last 20 wheat agricultural crop seasons (2004-05 to 2023-24), in southern Sonora, Mexico

Crop season	Commercial cultivars used by farmers
2004-05	Átil C2000 [29], Júpare C2001 [30], Rayón F89 [31], Altar C84 [32]
2005-06	Átil, Júpare, Rayón
2006-07	Átil, Júpare
2007-08	Átil, Júpare
2008-09	Átil, Júpare, Samayoa C2004 [33]
2009-10	Átil, Júpare, Tacupeto F2001 [34]
2010-11	Átil, Júpare, Tacupeto
2011-12	Átil, Tacupeto, CIRNO C2008 [35]
2012-13	Átil, Tacupeto, CIRNO
2013-14	Átil, Tacupeto, CIRNO
2014-15	Tacupeto, CIRNO
2015-16	Tacupeto, CIRNO
2016-17	CIRNO
2017-18	CIRNO
2018-19	CIRNO
2019-20	CIRNO
2020-21	CIRNO
2021-22	CIRNO

2022-23	CIRNO
2023-24	CIRNO, CENEB C2017 Oro [36]

3. Results and discussion

3.1. Tendency of temperature and relative humidity during the last 20 wheat seasons in southern Sonora.

The trend towards increasing the temperature during the day has been positive in both valleys; in the YV it has increased between 1.4 and 2.9 °C, while in the MV the trend has fluctuated between 1.8 and 3.5 °C (Table 2). The months with the greatest increase in both valleys were December and April, and the month with the lowest increase was February. The night temperature in most of the agricultural wheat season has shown a negative trend in both valleys; only the months of November and December had a positive trend in the YV, and in the MV, it was only November. The months with the greatest tendency to cool were January and March in both valleys; however, the MV had the greatest negative tendency with 1.6 °C less, while the YV was 1 °C less.

Table 2 Trend towards increasing and/or decreasing the temperature in the last 20 wheat seasons (2004-05 to 2023-24), in southern Sonora, Mexico

Month	Day			Night		
	YV*	**MV**	**SS**	**YV**	**MV**	**SS**
November	2.3	2.8	2.5	0.3	0.1	0.3
December	2.9	3.5	3.1	0.2	-0.2	0.0
January	1.9	2.1	2.0	-1.0	-1.6	-1.3
February	1.4	1.8	1.5	-0.3	-0.9	-0.6
March	2.0	2.1	2.1	-0.5	-1.3	-0.8
April	2.6	3.2	2.8	-0.2	-0.8	-0.4

*YV= Yaqui Valley; MV= Mayo Valley; SS= Southern Sonora

Regarding relative humidity, both valleys showed a tendency to decrease during the day throughout the agricultural crop season, except for the months of November and April in the YV (Table 3). The percentage of decrease in humidity during the day was from -2.6 to 0.9 % in the YV, and from -4.9 to -2.5 % in the MV; the months with the greatest tendency to decrease were March in the YV and December in the MV. Nighttime humidity in the YV had a tendency to increase, with a range between 1.1 and 8.0 %, the month of April had the highest tendency (8 %), whereas in the MV, it showed a tendency to decrease in November, January, February, and March.

Table 3 Trend towards increasing and/or decreasing the relative humidity in the last 20 wheat seasons (2004-05 to 2023-24), in southern Sonora, Mexico

Month	Day			Night		
	YV*	**MV**	**SS**	**YV**	**MV**	**SS**
November	0.9	-2.5	-0.4	3.3	-2.2	1.2
December	-0.2	-4.9	-2.2	4.6	1.0	3.2
January	-0.2	-3.9	-1.8	5.4	-0.3	3.1
February	-1.5	-4.6	-2.7	1.1	-3.5	-0.6
March	-2.6	-4.0	-3.1	3.4	-0.4	2.0
April	0.6	-4.1	-1.2	8.0	0.2	5.0

*YV= Yaqui Valley; MV= Mayo Valley; SS= Southern Sonora

Analysis of the two climatic factors in southern Sonora shows that temperature and relative humidity have changed their oscillation in recent agricultural crop seasons; the region is becoming more extreme during the day, as humidity is lost and the temperature increases, causing extreme periods of heat units, mainly in November, December, March, and April, in addition to the increase of frost risks in January and February. Moreno *et al*. [37] indicate that high temperatures favor greater metabolic activity of the plant, as well as an acceleration of physiological processes that determine its growth and development. Prasad *et al*. [38] reported that night temperature > 14 °C decreases photosynthesis and ≥ 20 °C is associated with decreased fertility of wheat spikelets. On the other hand, in regard to relative humidity, this cereal requires between 40 and 70 %; from the time of heading to harvest is the period with the greatest demand in this regard, since the relative humidity needed lies between 50 and 60 % and a dry climate for its maturation [39].

3.2. Relationship with grain yield

The analysis of the night temperature of each wheat season with the average yield obtained from commercial fields indicated that they were negatively correlated in both valleys (Figure 2); in the YV, the value was r = - 0.5992, which means that it is a negative-medium strong correlation, on the other hand, in the MV, the correlation value was r = - 0.8061, being a negative-strong relationship; both correlations indicate that in a cold agricultural season, wheat yield is expected to be high.

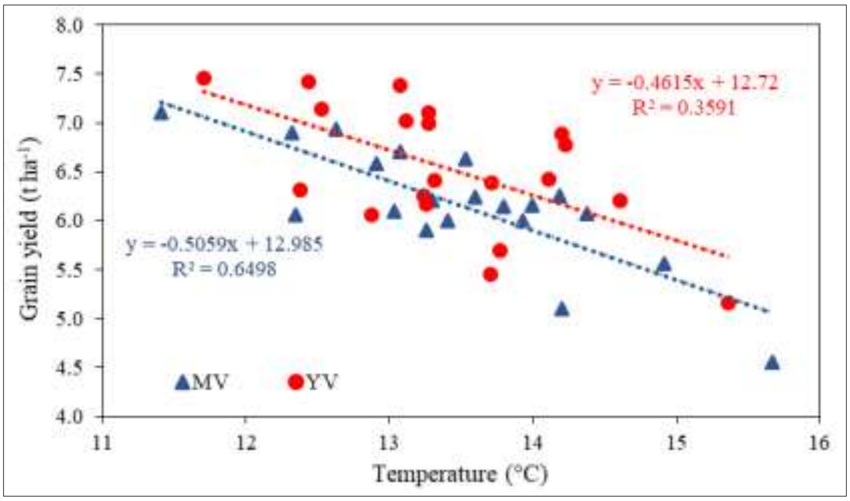

Figure 2 Response of wheat grain yield to average night temperature, in 20 fall-winter agricultural crop seasons (2004-05 to 2023-24), in southern Sonora, Mexico

Low values were obtained in relation to nocturnal relative humidity with grain yield; in the YV, the value obtained was r = 0.2868, being a weak-positive correlation, while in the MV it was a weak- negative correlation (r = 0.0866); therefore, in both valleys the effect of relative humidity was small in relation to grain yield (Figure 3).

In general, each agricultural crop season is different. In some, temperature and relative humidity are favorable for the crop, but a low grain yield is obtained; on the other hand, in some seasons, high relative humidity and a high thermal level may occur, and even so, yields above the historical average are obtained. In this regard, and according to each of the wheat seasons analyzed, those in which the crop had a good performance did not present continuous extreme levels of temperature and humidity, which could brought periods of stress, an increase in pests or presence of diseases with a negative effect on production. Monitoring of the commercial fields in each of the crop seasons in southern Sonora, indicated that grain yield had an average range from 4.749 to 7.293 t ha^{-1} (Table 3). Wheat seasons 2020-21, 2021-22, and 2022-23 showed the highest average grain yield over 7 t ha^{-1}, while seasons 2004-05 and 2014-2015 had the lowest average grain yield (Table 4). However, the highest grain yields were obtained in crop seasons 2011-12, 2012-13, 2020-21, and 2022-23 with 10.584, 10.226, 9.802, and 9.587 t ha^{-1}, respectively. These crop seasons were characterized for cool conditions and accumulation of 876, 672, 794, and 901 cold units, respectively. Wheat seasons with the lowest grain yield were 2004-05, 2014-15, 2013-14, and 2016-17 with 2.761, 2.812, 3.179, and 3.460 t ha^{-1}, respectively. The accumulated cold units in those seasons were 456, 249, 404, and 352, respectively; wheat season 2014-15 was characterized as warm and humid as the monthly average temperature for November to April was 20.9, 16.8, 16.0, 18.2, 19.6, and 21.7 °C, with a relative humidity of 63.8, 66.9, 73.1, 80, 74.7, and 62.7 %, and precipitation of 31.6, 0.0, 22.8, 26.4, 39.3, and 24.2 mm, which induced an outbreak of spot blotch caused by the fungus *Bipolaris sorokiniana* (Sacc.)

Shoemaker [40], that caused an important grain yield reduction. The performance disparity between farmers´ wheat fields reflects the differences they have in providing timely management of the irrigation water [41], availability of machinery and inputs to the productive potential of the soil [42], and the use of genetically improved wheat cultivars adapted to the regional environment [35], that the farmer chooses primarily for their yield potential.

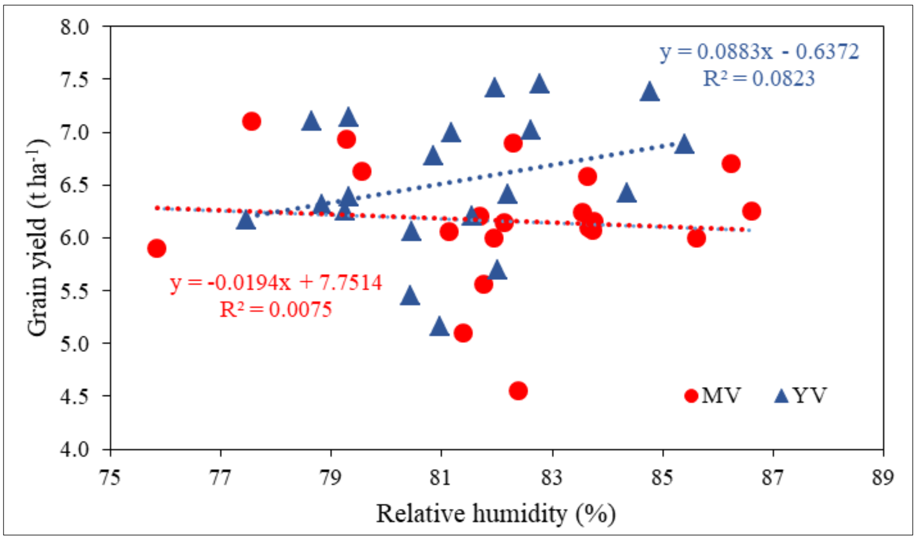

Figure 3 Response of wheat grain yield to average night relative humidity, in 20 fall-winter agricultural crop seasons (2004-05 to 2023-24), in southern Sonora, Mexico

Table 4 Average, maximum and minimum grain yield of commercial wheat fields monitored in 20 fall-winter agricultural crop seasons (2004-05 to 2023-24) in southern Sonora, Mexico

Agricultural crop season	Grain yield (t ha^{-1})		
	Sample average	Sample maximum	Sample minimum
2004-05	5.420	7.255	2.761
2005-06	6.199	8.217	4.057
2006-07	6.166	7.750	4.799
2007-08	6.473	7.851	3.859
2008-09	5.910	6.744	4.978
2009-10	6.278	8.325	4.902
2010-11	6.249	9.362	3.806
2011-12	6.929	10.584	3.680
2012-13	6.907	10.226	4.277
2013-14	5.989	8.652	3.179
2014-15	4.749	7.285	2.812
2015-16	6.090	9.107	3.796
2016-17	6.142	8.508	3.460
2017-18	6.444	8.913	3.625
2018-19	6.801	9.424	4.171
2019-20	6.406	9.158	3.650
2020-21	7.044	9.802	4.090

2021-22	7.111	8.970	4.753
2022-23	7.293	9.587	5.733
2023-24	6.551	8.549	5.417

3.3. Relationship with the sowing date

The average grain yield of the sampled fields on the different sowing dates is shown in Figure 4. Early sowing from November 1 to 14 showed an average grain yield of 5.829 t ha^{-1} and 6.052 from November 15 to 20; from November 21 to December 20 yields above 6.5 t were obtained, and sowings from December 21 onwards showed lower yields with a minimum of 5.103 t ha^{-1} in sowings from January 1 to 15. Based on the temperature trend described in Table 2, it is projected that wheat seasons will have a greater probability of warmer initiation and a greater number of hours with extreme temperatures, which may mainly affect early sowing dates before November 20; this in turn will cause a decrease in production, due to the acceleration of the early stages of development, and thus, unbalancing the efficiency of the first complementary irrigation. This trend will also affect sowings after December 20, since the risk of heat stress would increase as temperatures may reach $\geq$ 31 °C, which are harmful to the formation of the floral structure and the initial stage of grain development, and shorten the grain-filling period, conditions that occur most frequently in March and April. The risk of high thermal levels is greater in warm seasons, which represent 62 % of those analyzed, the rest (38%) were cold seasons with optimal conditions for wheat growth and production, and where the farmer could start sowing on November 21 and close on December 20.

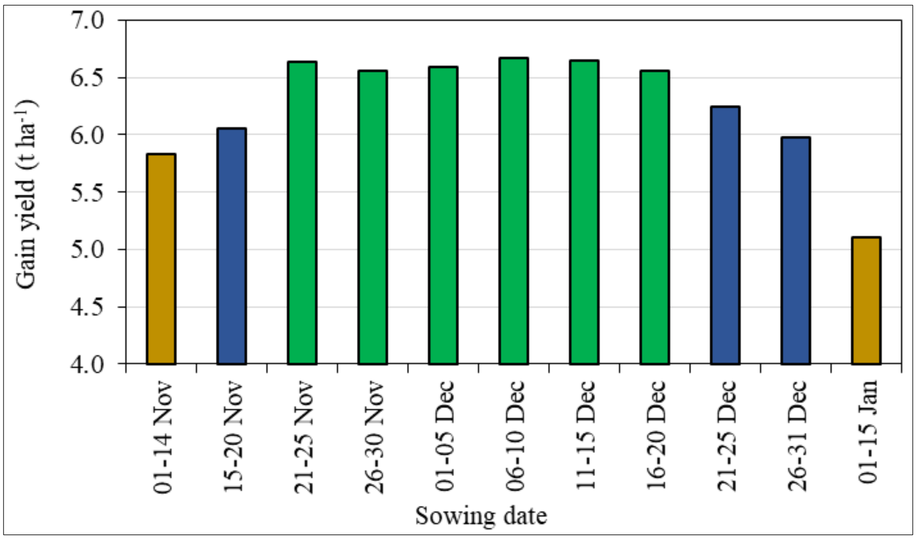

Figure 4 Average wheat grain yield of the sampled fields by sowing date in the last 20 fall-winter agricultural crop seasons (2004-05 to 2023-24) in southern Sonora, Mexico

Based on the 20 agricultural fall-winter wheat seasons analyzed, 43,700 ha which represent 19 % of the area grown with wheat in southern Sonora were affected by the climatic impact (Table 5). A grain yield reduction of 0.58 t ha^{-1} was calculated for the sowing date period between November 15 to 20 in comparison with the average grain yield obtained in the sowing period of November 21-25; the affected area represents about 11,500 ha. Similarly, the sowing date period between December 21 to 31 showed a grain yield reduction between 0.31 and 0.59 t ha^{-1}, in comparison with the average grain yield obtained in the sowing period between December 16-20; in this case, the area affected represents 20,700 ha. Therefore, based on the temperature increase detected in southern Sonora from season 2004-05 to 2023-24, in order to obtain the maximum grain yields, sowing should be carried out between November 20 to December 20. These results comprise an additional complement to the report by Félix-Valencia *et al.* [43], who indicated November 15 to December 15 as the optimal sowing date in the region, based on an analysis from wheat seasons 2004-05 to 2008-09.

Table 5 Wheat sown area affected by the climate impact based on sowing dates, in southern Sonora, Mexico

Sowing date	%	Affected area (ha)**
01-14-November	1.0	2,300
15-20-November	5.0	11,500
21-31-December	9.0	20,700
01-15-January	4.0	9,200
Total	19.0	43,700

** Area calculated based on the area harvested during 20 wheat seasons (2004-05 to 2023-24)

4. Conclusion

The trend towards increasing daytime temperatures in wheat seasons 2004-05 to 2023-24 was positive in the Yaqui and Mayo Valleys, Sonora, Mexico; in the former it increased between 1.4 and 2.9 °C, while in the latter between 1.8 and 3.5 °C. Months with the greatest increase were December and April. The night temperature showed a negative trend from January to April in the Yaqui Valley and from December to April in the Mayo Valley.

Relative humidity showed a tendency to decrease in both valleys during the day throughout most of the wheat season, ranging from -2.6 to 0.9 % in the Yaqui Valley, and from -4.9 to -2.5 % in the Mayo Valley. Nighttime humidity in the Yaqui Valley had a tendency to increase, with a range between 1.1 and 8.0 %, whereas in the Mayo Valley, it showed a tendency to decrease in November, January, February, and March.

The night temperature was negatively correlated with grain yield in both valleys, while relative humidity was not. The highest grain yields (above 9.5 t ha^{-1}) were obtained in wheat seasons characterized with more than 670 cold units, and average grain yield over 6.5 t ha^{-1} was obtained in sowing dates from November 21 to December 20.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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