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Cold units and their relationship with wheat grain yield in the Yaqui Valley, Sonora, Mexico

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Abstract

Global warming has the potential to cause the reduction of the cold period available during the winter, which may affect the production of wheat and deciduous fruit trees. Wheat requires accumulated cold units (CU) to switch from a vegetative period to a productive one, making the phenological cycle slower and promoting greater productive yield. The objective was to analyze the accumulation of CU and wheat yield during the last five fall-winter agricultural seasons (2018-2019 to 2022-2023) in the Yaqui Valley, Sonora, Mexico. Data of air temperature were obtained from 21 meteorological stations from the network of automatic meteorological stations of the state of Sonora, located in the Yaqui Valley. The number of CU (≤ 10 °C) was calculated for the wheat season (November 15 to April 30) from the years 2018 to 2023, and the grain yield was obtained from the reports by the Agri-Food and Fisheries Information Service. Descriptive statistics of central tendency, dispersion and the Shapiro-Wilk test were performed to determine the normality of the data; also, correlation analysis and the simple linear regression model by least squares were performed. The 2022-23 crop season showed the highest average grain yield (7.79 t ha^{-1}) and the highest average number of CU (882) among the five seasons analyzed. Wheat seasons 2018-2019 and 2019-2020 had an average number of CU lower than 500. The Pearson correlation analysis showed a highly positive correspondence between CU and grain yield. The linear regression model showed that starting from a base of 434 CU, wheat production per hectare would be 5.90 t, and it will increase 214.3 kg for every additional 100 CU.

Keywords: Wheat; *Triticum* spp.; Cold units; Grain yield; Yaqui Valley

1. Introduction

Climate change represents one of the main problems facing agriculture and is a threat to global food security, due to the alterations it causes in weather patterns and the increase in the atmospheric concentration of greenhouse gases [1,2]. The increase in temperatures ends up reducing crop production, while causing the proliferation of weeds and pests, changes in rainfall regimes increase the probabilities of crop failure in the short term and reduction in productivity in the long term production [3]. The temperature of agricultural areas in Mexico has been increasing perceptibly since the 1990s [4], this increase in temperature brings with it modifications in agroclimatic variables such as the accumulation of cold in the winter period [5, 6]. In northwest Mexico, climate change forecast of 2.5°C for the next ten years have already been exceeded [7]; In Sonora, average temperatures have increased by 3.59 °C during the summer and 3.3 °C in the winter [8], constituting a region under thermal stress. Sonora has been the main producer of wheat in Mexico; in 2023, 268,000 ha were allocated for wheat cultivation, obtaining a production over 1,994 million t, equivalent to 55.02 and 59.96% of the national area sown with wheat and production, respectively [9]. The Yaqui and Mayo Valleys, located in southern Sonora, have an arid climate and low precipitation for most of the year; however, they are considered a world reference in wheat production [10]; but, it also must be taking into consideration the availability of irrigation water from dams [11]. Wheat yield is influenced by various factors, such as agronomic management (planting date,

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irrigation, fertilization, pest and weed control) and meteorological factors (air temperature, humidity, duration of daylight) [12]. Temperature is considered the most important factor that induces the development of the wheat plant from emergence to flowering and maturity [13] and affects growth processes [14]. High temperature favors greater metabolic activity of the plant, as well as an acceleration of the physiological processes determining its growth and development [15], contrary to low temperatures, where wheat requires accumulated hours of cold to switch from a vegetative period to a productive one, making phenological cycles slower and promoting greater productive yield [16]. Cold hours or units (CU) are defined as the number of hours that the plant species spends in a certain time range where temperatures are lower than a certain amount of degrees. In the case of wheat, it is the temperature equal to or less than 10° Celsius that records the meteorological station for one hour [12]. Global warming has the potential to reduce the cold available in winter and affect the production of wheat and deciduous fruit trees [17]. Various studies have been carried out that have used different models or methodologies and have predicted the decrease in the accumulation of CU in various regions of the world [5,18,19,20,21]. Therefore, knowing the effect of variations in temperature helps producers make adaptation and mitigation decisions, including the use of specific technologies to increase productivity and obtain maximum use of the weather conditions in a specific season [12]. The objective of this work was to analyze the accumulation of CU and wheat yield during the last five fall-winter agricultural seasons in the Yaqui Valley, Sonora, Mexico.

2. Material and methods

Data of air temperature were obtained from 21 meteorological stations located in the Yaqui Valley (Figure 1) which form part of the automated meteorological station network [22] of the state of Sonora; the digital memory of each station records readings every 10 min and provide integrated hourly and daily data. The data set consisted of information from November 15 to April 30, from the year 2018 to 2023. The average number and accumulation of cold units (CU) from each meteorological station were calculated, considering a CU as one hour recorded with a temperature below 10 °C [12].

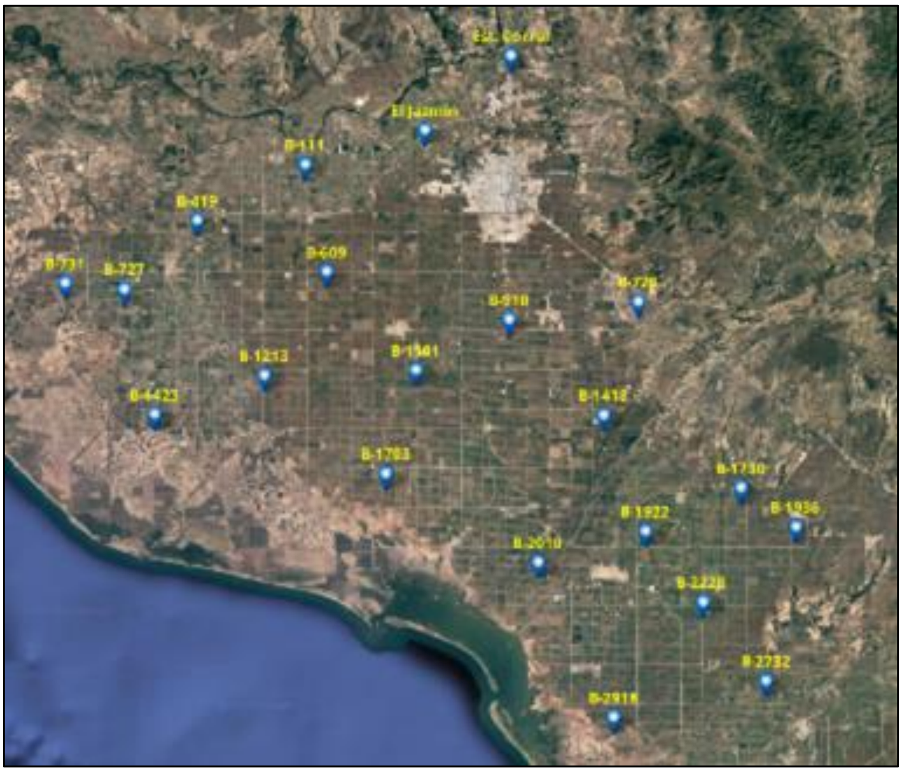

Figure 1 Geographic location of the 21 automated meteorological stations in the Yaqui Valley, Sonora, Mexico

Cold units were determined for each month of the wheat season and for the period of seasons that comprised the study (2018-2019 to 2022-2023). Also, the average grain yield produced during the fall-winter wheat seasons in the Yaqui Valley was obtained from the reports by the Agri-Food and Fisheries Information Service [9]. After generating the temperature information, the description of each of the agricultural season was made; In addition, descriptive statistics of central tendency and dispersion were calculated, as well as the Shapiro-Wilk test to determine normality in CU and grain yield. Subsequently, the correlation analysis and the simple linear regression model by least squares were carried out between the number of CU and the productive yields identified in the agricultural seasons, to estimate parameters of CU as a dependent variable, as well as their impact on productive yields.

3. Results and discussion

The temperature during the last five years ranged between 0.95 and 36.02 °C with an average of 16.44 °C. During the 2018-2019 wheat season the avg temperature was 17.11 °C with a range of 0.95 and 34.15 °C; the avg of accumulated cold units (CU) was 513 (Figure 2) and the grain yield was 6.91 t ha^{-1}. During the wheat season 2019-2020, the temperature ranged between 1.41 and 35.49 °C with an avg of 17.87 °C; this season had the lowest number of CU with a total avg of 434. Despite the fact that the number of CU was lower than the previous season, the avg grain yield was 6.83 t ha^{-1}. The temperature range during the 2020-2021 wheat season was 2.51 to 36.02 °C with an avg of 16.81 °C; there were 784 CU recorded which were favorable for grain yield with an avg of 7.41 t ha^{-1}. During the wheat season 2021-2022, the avg temperature was 17.43 °C with a range of 2.37 °C to 35.54 °C; the accumulated CU was 633, 151 less than in the previous season, but the avg grain yield was higher by 170 kg. The highest avg number of CU for the period of the study was recorded during the 2022-2023 wheat season with 882 (Figure 2); also, the highest avg grain yield was obtained during this season with 7.79 t ha^{-1}. The avg temperature was 16.16 °C, ranging from 2.75 to 32.88 °C. The difference between seasons with the lowest and highest number of CU was 448 and 960 kg in grain yield per ha. The avg grain yield during the five seasons in the Yaqui Valley (7.304 t ha^{-1}) ranks the region as one of the best wheat grain-producing areas after New Zealand, The Netherland, The United Kingdom, and Denmark [1]. Grain yield is determined by several factors, mainly the sowing date, timely and sufficient irrigation, nutritional deficiencies, salinity, soil types, timely control of pests and weeds [12], as well as the cultivars used. In the case of the Yaqui Valley, durum wheat cultivar CIRNO C2008 [23] during the period of the study, occupied an average of 93.32 % of the area sown with durum wheat and 78.17 % of the area sown with wheat (Table 1). Bread wheat cultivar Borlaug 100 [24]), occupied an average of 91.64 % of the area sown with bread wheat and 14.86 % of the area sown with wheat [25,26,27,28].

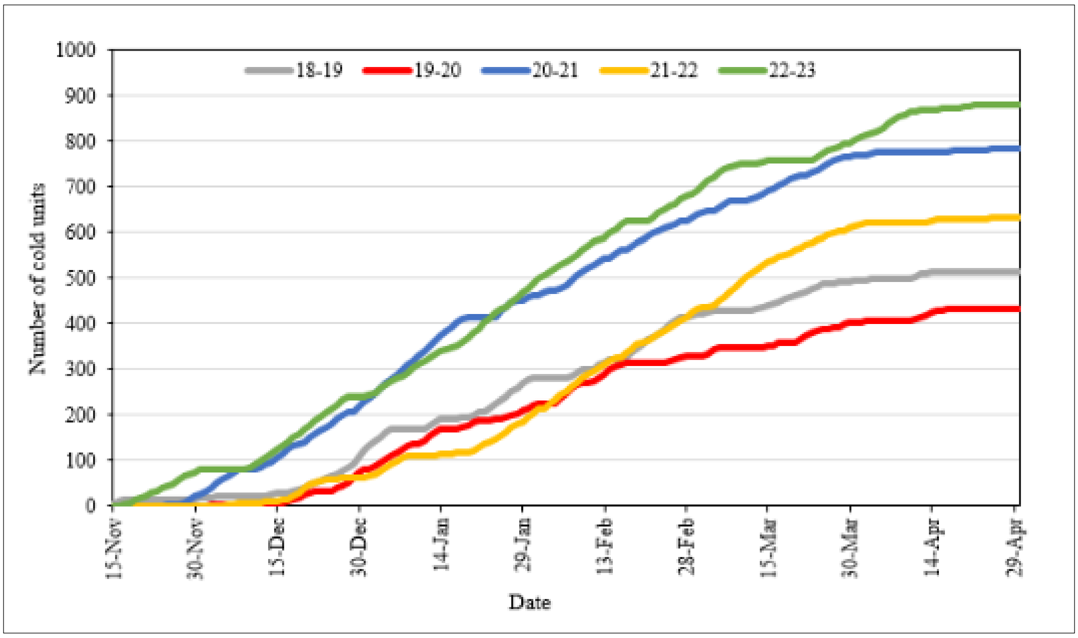

Figure 2 Average cold units accumulated from November 15 to April 30, during the fall-winter wheat seasons 2018-2019 to 2022-2023 in the Yaqui Valley, Sonora, Mexico, recorded by 21 meteorological stations

These two cultivars have had an important positive impact in the region and the country due to their high grain yield potential, which have contributed to the yields already indicated [29,30]. Despite that CIRNO C2008 has lost its resistance to leaf rust race BBG/BP_CIRNO, caused by the fungus *Puccinia triticina* E. [31], farmers have preference for this cultivar for commercial export.

Table 1 Total area sown with durum and bread wheat during five consecutive seasons in the Yaqui Valley, Sonora, Mexico, and the area and percentage occupied by the most popular durum and bread wheat cultivars during that period

Wheat season	Total durum wheat (ha)	CIRNO C2008 (ha)	%	Total bread wheat (ha)	Borlaug 100 (ha)	%	Total Yaqui Valley (ha)	CIRNO C2008 (%)	Borlaug 100 (%)
2018-2019	108,116.07	101,356.75	93.75	24,568.76	20,119.18	81.89	132,684.83	76.39	15.16
2019-2020	85,737.57	80,795.35	94.24	45,852.84	44,381.68	96.79	131,590.42	61.39	33.73
2020-2021	110,786.62	104,740.44	94.54	11,686.60	10,887.35	93.16	122,473.22	85.52	8.89
2021-2022	159,072.56	146,948.50	92.38	9,309.78	8,983.03	96.49	168,382.34	87.27	5.33
2022-2023	125,623.67	115,206.27	91.71	17,896.90	16,080.56	89.85	143,520.57	80.27	11.20

The wheat agricultural season initiates in the second half of November in the Yaqui Valley, and during the five seasons, the accumulated CU during the first 15 days were less than 25 with the exception of the 2022-2023 season, in which 70 CU were recorded (Figure 3). The total number of CU recorded was 107.

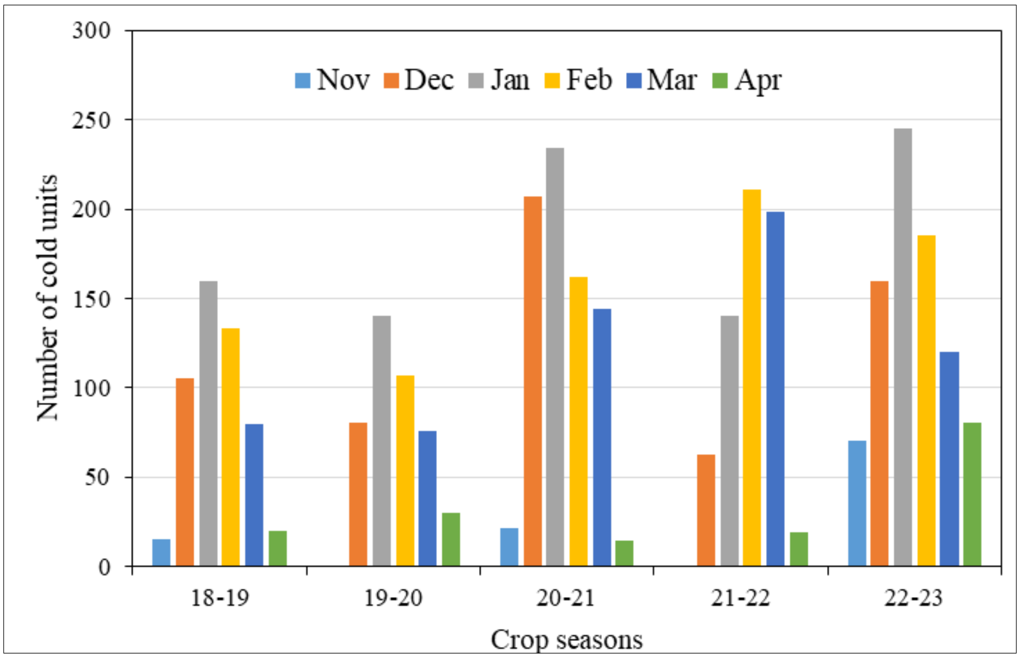

Figure 3 Average number of cold units by month recorded by 21 meteorological stations, in the Yaqui Valley, Sonora, Mexico, during five fall-winter crop seasons (2018-2019 to 2022-2023)

The average number of CU accumulated in December was 123 with a range of 63 to 207. The seasons 2022-2023 and 2020-2021 accumulated the highest number with 160 and 207, respectively. The total number of CU accumulated in this month was 616. The month of January recorded the highest number of accumulated CU with 920, an avg of 184 and a range of 160 to 245. With the exception of wheat season 2021-2022, January showed a higher number of accumulated CU than the rest of the months. The month of February recorded the second highest number of accumulated CU with 799, an avg of 160 and a range of 107 to 211. During the last three wheat seasons, more than 150 CU were recorded in February. The month of March recorded the third highest number of accumulated CU with 619, very similar to December which accumulated 616, it had an avg of 124 and a range of 76 to 198. The accumulation of CU during March of 2021-2022 was the highest with 198, but below February which accumulated 211. The accumulation of CU in April reduced greatly, and had an avg of 33, a range of 15 to 81, and the total number was 164. The performance of the CU and grain yield were analyzed through the use of descriptive statistics of central tendency and dispersion (Table 2); the avg number of CU during the five wheat seasons was 649 and the grain yield 7.30 t ha^{-1}. Similarly, the Shapiro-Wilk test was applied to determine the normal distribution of the variables, by presenting an associated probability greater than 5 % (Table 3).

Table 2 Descriptive statistics of the variables to be analyzed and normality

	Cold units	Grain yield
Mean	649	7.30
Standard Error	82.87	0.19
Median	633	7
Standard deviation	185.30	0.42
Sample variance	34336.35	0.18
Kurtosis	-1.90	-2.49
Skewness	0.17	-0.17
Range	447.97	0.96
Maximum	882	7.79
Minimum	434	6.83

Table 3 Shapiro-Wilk normality test

	Cold units	Grain yield
W-stat	0.9596	0.9093
p-value	0.8051	0.4634
alpha	0.05	0.05
normal	yes	yes

Since the CU and the grain yield showed a normal distribution, an analysis by Pearson´s correlation was carried out which indicated a coefficient $r= 0.90$ ($p < 0.05$); this reflects a high positive correspondence between the variables analyzed (CU and grain yield per hectare) (Figure 4).

These results agree with those reported by Félix-Valencia *et al*. [12] who indicate that CU extend the phenological stages of the wheat plant by reducing the speed of the physiological processes, consequently retarding growth, and in general induce greater grain yield. They indicate that by the end of February to beginning of March, the wheat plants are heading if sown by the middle of December, and the accumulated CU would be around 500 hundred if the season is cool. Taking this into consideration, out of the five seasons of this study, seasons 2018-2019 and 2019-2020 had not completed 500 CU, but still grain yield per hectare was 6.91 and 6.83 t ha^{-1}, respectively, while the other three seasons had more than 500 and grain yields were greater than 7.4 t ha^{-1}. Despite that during wheat seasons 2004-2005 to 2008-2009 the total avg of accumulated CU in the Yaqui Valley was 766 with a range of 619 to 916, avg grain yield was 5.75 t ha^{-1} with a range of 4.9 to 6.25 t ha^{-1} [12]; those low grain yields in comparison to wheat seasons 2018-2019 to 2022-2023 could be explained by the wheat cultivars used during both periods. Félix-Valencia *et al*. [12] and Cortés Jiménez *et al*. [32] found a positive correlation between accumulated CU and grain yield. By the simple linear regression model for the least squares, the estimated grain yield per hectare based on the accumulated CU during seasons 2018-2019 to 2022-2023, and from a base of 434 CU, it would be 5.9 t ha^{-1}, and for 100 additional CU there would be an increase of 214.3 kg of grain yield (Table 4). Félix-Valencia *et al*. [12] estimated a correlation between CU and grain yield with 89% confidence, that a base of 340 CU would generate 4.63 t ha^{-1}, and for each 100 CU there would be 330 kg increase in grain yield.

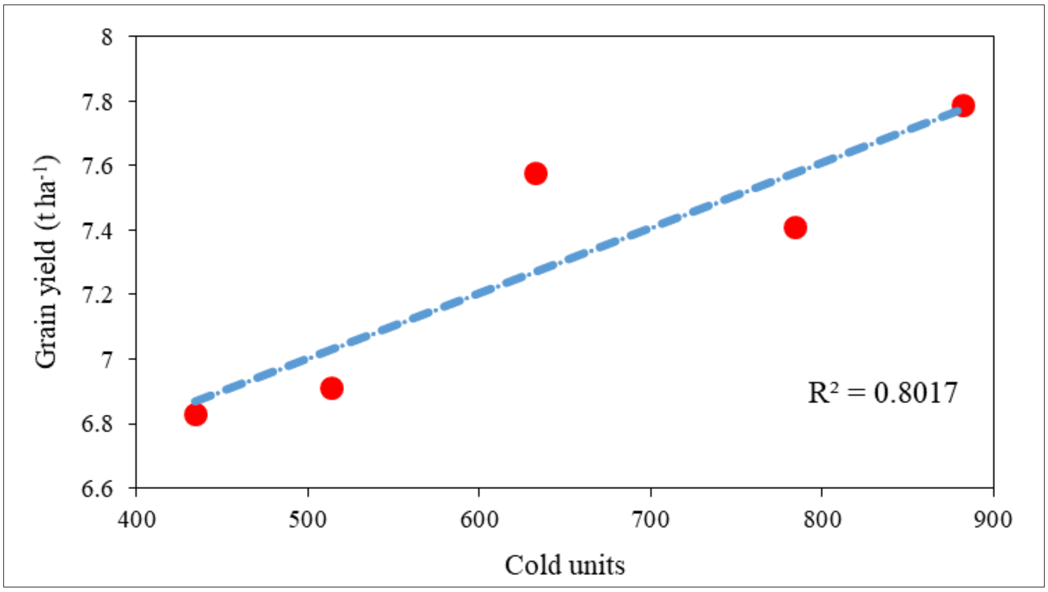

Figure 4 Relationship between wheat grain yield and recorded cold units by 21 meteorological stations, in the Yaqui Valley, Sonora, Mexico, during five fall-winter crop seasons (2018-2019 to 2022-2023)

Table 4 Simple linear regression model for the least squares

	coeff	**std err**	**t stat**	**p-value**	**Lower**	**Upper**
Constant	5.8999	0.6804	8.6711	0.0010	4.0108	7.7891
Cold units	0.002143	0.0010	2.0563	0.1089	-0.0008	0.0050

4. Conclusion

The 2022-2023 wheat season showed the highest average grain yield and number of cold units among the five seasons analyzed; the accumulated avg of cold units in that season was 882 and the avg grain yield obtained was 7.79 t ha^{-1}. The Pearson correlation analysis determined a highly positive correspondence between cold units and grain yield. The linear regression model showed that starting from a base of 434 cold units, wheat avg production per hectare would be 5.90 t, and it would increase 214.3 kg for every additional 100 cold units.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

No conflict of interest.

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