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Analysis of the effect of temperature and relative humidity on spring wheat as recorded by dataloggers installed within the crop in southern Sonora, Mexico

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Abstract

The objective of this work was to analyze the effect of temperature and relative humidity on spring durum wheat cultivar CIRNO C2008 as recorded by dataloggers (DL) installed within the crop in five commercial fields in southern, Sonora, Mexico, during the crop season fall-winter 2021-2022. The minimum (MINTT) (≤ 4 °C) and maximum thermal threshold (MAXTT) levels (≥ 33 °C), relative humidity (RH) (≥ 90%), and cold units (CU) (≤ 10 °C), were compared between DL and weather stations (WS) closest to the sensors. DL recorded greater number of MINTT periods from February 03 and MAXTT from March 14, and the MINTT periods were longer than those recorded by WS. With regard to the MAXTT, DL recorded 5 periods in fields located in block (B) 703 and Mocorua, two in B-2036, and one in B-2324. The main period of MINTT detected by WS was March 09 to 10. These WS did not record any continuous periods of MAXTT. The total accumulation of CU quantified in the fields with DL and with WS were: B-2036/B-1936 = 846 and 566, B-2324/B-2328 = 851 and 718, B-2814/B-2918 = 870 and 773, Mocorua/Sahuaral = 885 and 696, and B-703/B-609 = 955 and 743, respectively. DL recorded an average of 182 (21.6%) more CU than WS. DL began the recording of cold units from December 7 while WS from December 18. The daily accumulation of continuous hours with > 90% RH, had a significant difference between WS and DL. The WS in B-2918 recorded 277 more hours than the DL in B-2814, and the WS located in Sahuaral recorded 138 more hours than the DL in Morocua. However, DL in B-2036, B-703, and B-2324, recorded 539, 375, and 73 more hours with > 90% than their respective WS.

Keywords: Durum wheat; *Triticum durum*; Thermal threshold; Cold units; Relative humidity; Microclimate

1. Introduction

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.) [1]. In Mexico in the year 2021 around 3.1 million t of wheat were produced, 56.66% was durum wheat (*Triticum durum* Desf.) and 43.34% bread wheat (*Triticum aestivum* L.). The state of Sonora in northwestern Mexico contributed with 54.77% of the wheat production, while 36% was produced in the states of Baja California, Guanajuato, Michoacán, and Sinaloa [2]. Every crop season, variable grain yields are produced in southern Sonora, Mexico, influenced by the technological activities, but also, due to the interaction among the main climatic factors such as temperature and relative humidity, which exert great influence during plant growth and affect yield production [3,4,5]. The temperature may promote or limit biomass development; extremes of this abiotic factor might lead the plant to a latent state or to a lethal limit, including death [6,7,8]. Damage may be gradual in relation to the length of exposure, and plant deterioration magnifies as oscillation of temperature becomes greater during the day or night. Also, the plant requires optimal thermal continuity for

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development, that is, an accumulation of heat (thermal units) and cold (cold units), which determine, according to the developmental stage, germination, accumulation of plant material, flowering, reproduction, and fruit development.

With the resurgence of the global positioning system technology and the development of more sophisticated devices, the idea of a different strategy for a given environment has oriented towards the technology variation in reduced spaces (microenvironments) based on information generated from yield maps. This type of agriculture intends to improve the efficiency on the use of inputs, improve the economic outcome, and reduce the impact of using incorrect technology [9].

Micrometeorology has to do with interaction phenomena between the soil surface and the first meters or kilometers of the atmosphere, such as gas emissions, evapotranspiration to improve irrigation, dispersion of micro-drops of products by the atmospheric turbulence, transportation of phytopathogens like rusts, and the vertical and horizontal concentration of maize pollen during flowering [10]. There are challenges in having data available and precise information as well as adequate temporal-space within the productive plots for the study of extreme variables like frosts, behavior and development of pests and diseases, variability in the distribution of available water, and at the same time certain management practices for a proper care of the environment (Pablo Mercuri, cited by Guerra, 2021).

The use of simulation models for predicting crop yield as function of weather and climate has been studied extensively [11]. Bannayan *et al*. [12] indicated that reliable yield forecasting within the growing season would enable improved planning and more efficient management of grain production, handling, and marketing; so, they showed that using only stochastically generated weather data to substitute measured data could provide a reliable forecast for wheat grain yield in the United Kindom.

Productivity and quality of wheat is controlled by genetic characteristics of cultivars, and they can be modified to certain extent by the agronomic management (availability of nutrients in the soil, nitrogenous fertilization, sowing date, control of pests and diseases), and by the climatic conditions that prevail during the crop season [13]. In the state of Sonora, Mexico, anomalies in the climate behaviour in its historical series have been related in regard to precipitation and temperature [14]. High temperatures in combination with relative humidity have affected significantly wheat production [15].

The availability and transfer of information in relation to the climatic analysis, in the short or medium term will be necessary for the wheat-producing regions, according to the climatic changes in the 2030`s [16]. The knowledge about temperature variation help farmers in the adaptation and mitigation decisions, among them, the use of specific technologies in order to increase productivity and to obtain the maximum use of environmental factors in a given crop season [3]. In the case of wheat, all phenological stages are sensitive to the oscillation of air temperature; high temperatures favor a greater metabolic activity of the plant, as well as an acceleration of the physiologic processes that determine its growth and development [17]. On the contrary, wheat requires the accumulation of cold units (CU) to prolong its biological cycle, and generally renders greater grain yield [3]. Since it is evident to move foreward to adaption to the new climatic conditions by the possible impact of global climate change, it is necessary the re-adjustment and establishment of new management strategies within the different agricultural production systems. To maintain the grain quality under climate change is highly important for human nutrition, end-use functional properties and the commodity value [18]. The technological development will be based on the institutional financial strengthening [19], which will allow the development of greater productive efficiency between the balance of the ambient impact and the technological development.

The objective of this work was to analyze the effect of temperature and relative humidity on spring durum wheat cultivar CIRNO C2008 as recorded by dataloggers installed within the crop in five commercial fields in southern, Sonora, Mexico, as compared to stations closest to the sensors which form part of the automated weather station network in the state of Sonora.

2. Materials and methods

This work was carried out during the crop season fall-winter 2021-2022 in five commercial wheat fields with durum wheat cultivar CIRNO C2008 [20], located in Blocks 2324, 2814, in Mocorua Etchojoa county, B-2036, and 703, in southern Sonora, Mexico (Figure 1).

Figure 1 Location of the wheat fields with dataloggers installed within the crop, and their correspondent weather stations in southern Sonora, Mexico, during the crop season fall-winter 2021-2022

Sowing was carried out on November 22, December 6, 7, 8, and 17, 2021, respectively. Bed separation was 0.80 m with four rows separated by 17.5 cm. The study of microclimates was performed with the information obtained from dataloggers (DL) (Omega, serie OM-EL-WIN-USB, Data Logger Software v7.2.1) located within the fields at the crop canopy level and from the automated weather station (WS) network of the state of Sonora [21], chosen for their closeness to the wheat fields, and located in Blocks 2328 (distance 3.4 km), 2918 (6.8), the station located in Sahuaral, Etchojoa county (7.3), 1936 (2.2), and 609 (6.8), respectively (Figure 1). The minimum (MINTT) (≤ 4 °C) and maximum thermal threshold (MAXTT) (≥ 33 °C), relative humidity (RH) (≥ 90 %), and number of CU (≤ 10 °C) were calculated. DL were programmed to record hourly data from plant emergence to physiological maturity when samples were collected. Grain yield (t ha^{-1}) was determined as well as number of spikes (m^{-2}), leaf area index (LAI) and grains per spike; other parameters evaluated were a thousand grain weight, grain protein content (%), and yellow berry (%). Grain yield, number of spikes, and LAI were taken from 1 m^{2} of six random replications from each field, and analyzed in a randomized complete block design with the statistical package InfoStat [22] and mean comparison with Tukey´s test (P = 0.05). The impact of thermal threshold was analyzed with the methodology applied by Félix *et al*. [23].

3. Results and discussion

The analysis of variance of grain yield, the number of spikes, and the LAI and their interactions were highly significant (Table 1).

Table 1 Multivariate analysis of variance for grain yield, number of spikes, and leaf area index in five commercial fields with durum wheat cultivar CIRNO C2008 in southern Sonora, Mexico, during the crop season fall-winter 2021-2022

S.V.	Sum sq	df	Mean sq	F val	Pr (>F)
Grain yield (GY)	25.55	4	6.387	8.198	0.000681
Number of spikes (NS)	28056	4	7014	11.56	0.000174
Leaf area index (LAI)	24.191	4	6.048	12.06	0.000139
GY*LAI	2663.7	8	665.9	24.08	0.000002
GY*NS	8005089	8	2001272	12.7	0.000104
LAI*NS	5619106	8	1404776	10.27	0.00033
GY*LAI*NS	637707277	12	159426819	17.49	0.000016

The field with the highest grain yield was B-703 with 8.45 t ha^{-1}, statistically similar to B-2036 and Mocorua, although this last field had 6.875 (Table 2); field B-2814 had the lowest yield with 5.55 t ha^{-1}. The highest number of spikes m^{-2} was obtained from field B-2036 with 438, statistically similar to fields B-2324 and B-703; Mocorua had the lowest number with 341. The highest LAI was recorded in field B-2036, statistically similar to B-2814 and B-703, while the lowest LAI was recorded in Mocorua. B-2036 showed consistency being second in grain yield and first in number of spikes and LAI. Similarly B-703 showed the highest grain yield and although it was third in number of spikes and LAI, it was statistically similar to the first and second ones. Mocorua was third in grain yield but the lowest in number of spikes and LAI. B-2814 showed the lowest grain yield, fifth in spike number and second in LAI.

Table 2 Mean comparison of grain yield, number of spikes, and leaf area index in five commercial fields with durum wheat cultivar CIRNO C2008 in southern Sonora, Mexico, during the crop season fall-winter 2021-2022

Grain yield (t ha^{-1})			**Number of spikes (m^{-2})**			**Leaf area index**		
Field	**Mean**	**LSD=1.85**	**Field**	**Mean**	**LSD=53.8**	**Field**	**Mean**	**LSD=1.3**
B-703	8.45	A	B-2036	438	A	B-2036	6.4225	A
B-2036	8.225	A	B-2324	410	A	B-2814	6.1025	A
Mocorua	6.875	A B	B-703	395	A B	B-703	5.6575	A
B-2324	6.175	B	B-2814	345	BC	B-2324	3.9725	B
B-2814	5.55	B	Mocorua	341	C	Mocorua	3.7775	B

C.V. = 19.6Error = 0.716 C.V. = 23.6, Error = 606.5 C.V. = 11.5, Error = 0.39.
Fields for each variable with the same letter are not significantly different (Tukey, 0.05).

The highest grain protein content was obtained in field B-2324 (Table 3) which was fourth in grain yield followed by Mocorua which was third in grain yield. Fields B-703 and B-2036 which were first and second in grain yield had moderate protein content, while B-2814 with the lowest protein content was also the lowest in grain yield. In the case of B-2324, the low grain yield correlates with the high protein content, but in the case of B-2814 it does not, however, the percentage of yellow berry was the highest in this last field. The a thousand grain weight in the five fields had a range of 51.2 to 57.6 g and the range of grains per spike was 31.2 to 35.1.

Table 3 Grain protein, yellow berry, a thousand grain weight and number of grains per spike in five commercial fields with durum wheat cultivar CIRNO C2008 in southern Sonora, Mexico, during the crop season fall-winter 2021-2022

Field	**Grain protein (%)**	**Yellow berry (%)**	**A thousand grain weight (g)**	**Grains per spike***
B-703	9.76	79.5	54.9	35.1
B-2036	9.90	58.4	57.6	34.8
Mocorua	12.47	2.0	51.2	34.0
B-2324	12.48	0.7	57.4	31.2
B-2814	7.75	98.1	52.0	31.3

*Average of sample

The microclimate within fields through thermal threshold indicates that continuous days with temperatures below or equal to 4 °C, and maximum temperatures greater or equal to 33 °C, are conducive to cause physical or metabolic damage during the structural development of the wheat plant [24]. Comparison of these thermal thresholds between data from the WS did not reflect an equivalent of hours in both temperature threshold levels, as those recorded by DL within the crop, probably due to the influence by water management and plant canopy as the crop season progressed. The only exception was the period between March 09 and 10 within the MINTT.

DL within the wheat fields recorded greater number of MINTT periods from February 03 and MAXTT from March 14, and the MINTT periods were longer than those recorded by WS. The most severe minimum temperatures were recorded in B-703 with -1.5 °C, 2036, Mocorua, and 2324 with 0.5 °C, and 2814 with 1.5 °C. With regard to the MAXTT (≥ 33 °C), DL recorded 5 periods in B-703 and Mocorua, two in B-2036, and one in B-23-24 (Table 4). The main period detected by WS was March 09 to 10 with minimum temperatures of 1.05 °C in B-2918, 1.06 °C in B-609, 1.71 °C in B-2328, 3.07

°C in B-1936, and 2.07 °C in Sahuaral. These WS did not record any continuous periods of temperatures with MAXTT (Table 5).

Table 4 Periods of continuous days with three or more hours with minimum and maximum threshold damaging temperatures recorded by dataloggers, in five commercial fields with durum wheat cultivar CIRNO C2008 in southern Sonora, Mexico, during the crop season fall-winter 2021-2022

Thermal threshold	B-2814	B-703	B-2324	B-2036	Mocorua
Minimum	09-12 Mar	03-05 Feb	06-12 Mar	06-13 Mar	17-19 Feb
≤ 4 °C		07-09 Feb			09-15 Mar
		06-12 Mar			
Maximum		14-20 Mar	24-27 Mar	25-27 Mar	16-20 Mar
≥ 33 °C		22-27 Mar		05-09 Apr	23-28 Mar
		30 Mar-03 Apr			31 Mar-3 Apr
		05-09 Apr			5-11 Apr
		13-17 Apr			13-20 Apr

Table 5 Periods of continuous days with three or more hours with minimum threshold damaging temperatures recorded by weather stations in five commercial fields* with durum wheat cultivar CIRNO C2008 in southern Sonora, Mexico, during the crop season fall-winter 2021-2022

Thermal threshold	B-2918	B-609	B-2328	B-1936	Sahuaral
Minimum	09-11 Mar	9 and 10 Mar	9 and 10 Mar	9 and 10 Mar	9 and 10 Mar
≤ 4 °C					

*Weather stations located closest to the fields shown in Table 4 in the same order.

The five fields were at different phenological stages during March 9-12, period in which the temperature descended and oscillated between 1.5 and 3.0 °C in B-2814 which was in the first stage of grain filling (Zadoks stage 70 [25]); 1 and 3 °C in B-2324 at the last phase of grain filling; 0.5 and 3.0 °C in Mocorua at the first stage of grain development; 0.0 and 1.5 °C in B-703 at boot stage (Zadoks stage 49); and 0.5 and 2.0 °C in B-2036 at the beginning of grain development. Research on abiotic stresses, such as deficient or excessive water, high or low temperature, high salinity, heavy metals, and ultraviolet radiation, cause damage to the plant at the cellular level during growth and development which lead to affecting crop yield [26]. Zhao *et al.* [27] reported that the duration of grain filling was longer under low temperature stress and shorter under high temperature stress, and that grain yield was most sensitive to temperature stress during 15 to 17 days post-anthesis. Koga *et al.* [28] found that aside from the longer duration of grain filling under low temperature, grain weight also increased in experiments with two spring wheat cultivars under controlled climate chambers with a temperature range of 13-10 °C, 18-15 °C, and 23-20 °C (day/night) during the whole grain filling period. Nasehzadeh and Ellis [29] reported that wheat cultivar Tybalt showed temporal sensitivity to extreme temperatures (29-20 °C, 34-20 °C, 15-10 °C, and 34-20 °C (day/night) during short exposures from 7 days after anthesis onwards; seed longevity was poorest in response to low temperature later in development and maturation. Despite the periods of extreme low temperature, durum wheat cultivar CIRNO C2008 was not affected since grain yield was quite high in B-703 and B-2036 (8.45 and 8.22 t ha^{-1}, respectively) and the rest of the fields had a range of 5.55 to 6.87 t ha^{-1} (Table 2). B-2814 did not experience periods of MAXTT as recorded by DL; B-2324 had one period of continuous four days at physiological maturity; B-2036 had two periods of MAXTT between March 25-27 at dough grain and between April 5-9 at the end of grain filling and beginning of physiological maturity of the grain; while Morocua and B-703 had five periods of MAXTT at the stage of grain filling. Post-anthesis treatment with continuous high temperature (35 °C) during 4 to 12 days caused a significant reduction in mature grain weight due to a decrease of the cell wall pericarp expansion [30]. In the case of the five fields in southern Sonora, there were no continuity of high temperature for days, and therefore, plants escaped the effect of such extreme intermittent high temperature periods. Although it is not conclusive, it is possible that the 4th complementary irrigation applied to B-703 mitigated the heat effect, since there was no visible damage and contributed to produce the highest grain yield (Tables 2 and 6). Research studies on the impact of heat during grain development have been discussed by Mohammadi [31] and Wang *et al.* [32]. The field located in B-2814 was at the agricultural perimeter close to the ocean; sowing date was December 6 and MAXTT did not occur during the crop season. The number of CU (870) and the leaf area index (6.1) were the third and second highest among the five fields (Tables 2 and 6). The low yield in this field could be associated to the salinity condition of the soil in that area which affect growth, grain yield and quality [33,34]; the plant expressed a premature drying of lowest leaves, and its grain protein content was the lowest with 7.5%; it had the highest percentage of yellow berry (98.1%) and the second lowest a thousand grain weight (52 g) (Table 3); these data also reflect a nitrogen deficiency.

Table 6 Relationship between the dates of complementary irrigations (CI) with the phenological stage (PhS) and the accumulated cold units (CU), in five commercial fields with durum wheat cultivar CIRNO C2008 in southern Sonora, Mexico, during the crop season fall-winter 2021-2022

Sowing date	Fields	1st CI	2nd CI	3th CI	4th CI	Harvest Sample	Total CU
22/11/2021	B-2324	10-Jan	05-Feb	25-Feb		07-Apr	
	Days	49	75	95		136	
	PhS	3th node	Flowering	4/4 Grain f		Physiol. mat	
	CU	132	154	208		357	851
06/12/2021	B-2814	27-Jan	19-Feb	27-Mar		11-Apr	
	Days	52	75	111		126	
	PhS	2nd node	Boot	Milky grain		Physiol. mat	
	CU	230	231	364		45	870
07/12/2021	Mocorua	01-Feb	23-Feb	26-Mar		15-Apr	
	Days	56	78	109		129	
	PhS	2nd node	Flowering	Milky grain		Physiol. mat	
	CU	247	211	337		90	885
12/12/2021	B-2036	26-Jan	21-Feb	14-Mar		14-Apr	
	Days	45	71	92		123	
	PhS	2nd node	Flowering	4/4 Grain f		Physiol. mat	
	CU	151	255	241		199	846
17/12/2021	B-703	27-Jan	20-Feb	16-Mar	02-Apr	18-Apr	
	Days	41	65	89	106	122	
	PhS	1st node	Boot	1/2 Grain f	Milky grain	Physiol. mat	
	CU	196	255	265	165	74	955

Grain f = grain formed; Physiol. mat = physiological maturity.

The region of Mayojusalit, B-609, and the regions of Capetamaya and Tesia, which form part of the central Eastern area of the Yaqui and Mayo Valleys (Figure 1), were the coldest zones during the crop season 2021-2022. The average number of accumulated CU between November 15 and April 30 was 662, with a range of 938 and 418. The cold weather initiated with breaks from December 15 to 23, re-initiated on December 31 to January 7, and then re-initiated on January 20 up to April 20 as recorded in some of the WS. The accumulation of CU quantified in the fields with DL and with WS, from sowing to the collection of spikes were: B-2036/B-1936 obtained 846 and 566; B-2324/B-2328 obtained 851 and 718; B-2814/B-2918 obtained 870 and 773; Mocorua/Sahuaral obtained 885 and 696; and B-703/B-609 recorded 955 and 743, respectively. DL recorded an average of 182 (21.6%) more CU than WS. DL began recording CU from December 7 while WS from December 18. Both devices in general, recorded greater number of CU from January 20 up to April 3. Fields in B-2814 and Mocorua accumulated lower number of CU from the boot stage to flowering, but similarly to field in B-2324, there were greater number of CU during the milky stage of the grain than the rest of the fields. The field in B-2036 accumulated greater number of CU at the beginning of flowering and then it gradually decreased in the following stages of grain filling. The field in B-703 recorded greater number of CU from the boot stage to a half grain development, and gradually decreased during the milky and dough stage of the grain.

RH was recorded from January 26 to April 21 (date when the last field was harvested), so, it covered the five fields from stem elongation to physiological maturity. The daily accumulation of continuous hours with ≥ 90% RH, had a significant difference among the five WS and DL installed within the crop (Figure 2). The WS in B-2918 located in the agricultural perimeter and the closest to the ocean, recorded 277 more hours with ≥ 90% RH than DL in field B-2814. A similar situation occurred with the station located in Sahuaral -with similar characteristics to B-2918 regarding their georeferenciation-, which recorded 138 more hours than the DL located within the crop in Morocua. However, DL in B-2036, B-703, and B-2324, recorded 539, 375, and 73 more hours with ≥90% RH than their respective WS.

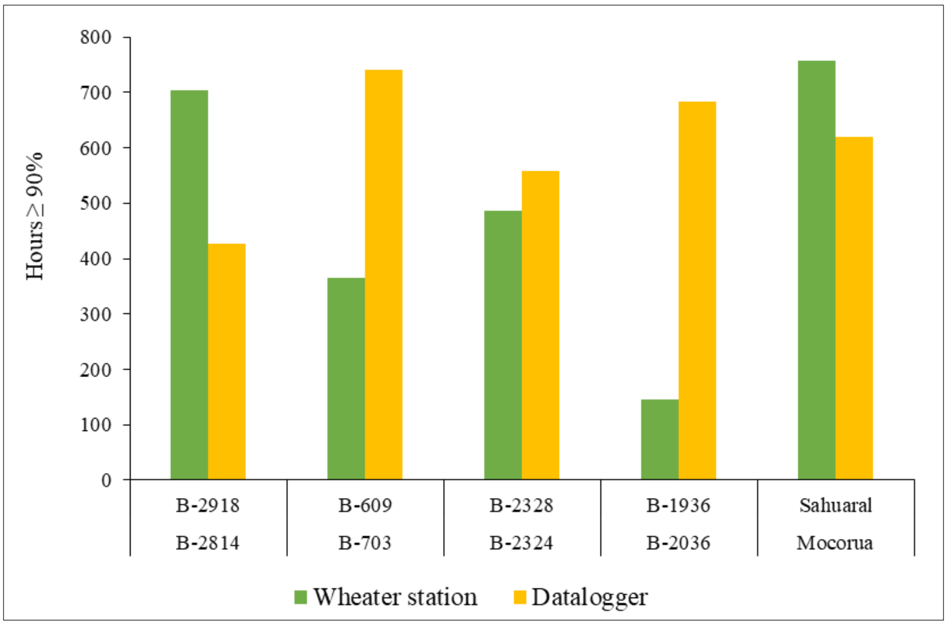

Figure 2 Periods of continuous hours with relative humidity equal or greater than 90% recorded by weather stations and dataloggers, in five commercial fields with durum wheat cultivar CIRNO C2008 in southern Sonora, Mexico, during the crop season fall-winter 2021-2022

Noteworthy was the fact the field with the highest grain yield (B-703) had the highest number of continuous hours with ≥ 90% RH. It seems that as indicated by Torres-Cruz *et al.* [35], location of the instruments is of primary importance for the difference in measurements, since DL are close to the canopy and also to the irrigation water and dew; they reported that comparison of air temperature data obtained from the WS and the DL located within the wheat plot, showed significant differences between the mean of both devices. The minimum temperature recorded by DL was 1.2°C and 0.76°C below the range shown by the WS, while the maximum temperature recorded by DL was 1.42°C and 5.39°C above the range shown by the WS. The overall average temperature recorded by the DL was 0.44°C higher than the WS, and also it recorded 122 more CU than the WS. This could be relevant for crop management since models that assume that temperature recorded by WS is similar to that recorded by sensors installed in the vineyard canopy, could have greater uncertainty than models that consider the temperature within the canopy [36]. Similar relevance may have the sensors with different technologies [37], such as those that also monitor soil humidity and other variables throughout the crop season [38]. Results from other studies indicate the usefulness of sensor technology for economizing fertilizer, diminish the impact on the environment, and contribute to the cost effectiveness of wheat production [39].

4. Conclusion

The analysis of temperature and relative humidity showed significant differences between data collected from the dataloggers (DL) and weather stations (WS) in the temperature thresholds ≤ 4°C and ≥ 33°C, in the accumulation of cold units (CU), and in the number of hours with relative humidity (RH) ≥ 90%, which indicates that different climatic conditions prevail within the crop, being influenced by the geographic location, crop development and its management, that is, a specific microclimate develops within each wheat field.

During the cold period from March 9 to 11, DL recorded twice the number of hours within the threshold ≤ 4 °C, and the temperature oscillated from 0.0 to 3.0 °C, while WS recorded minimum temperatures between 1.05 y 3.9 °C. Similarly, DL recorded maximum temperature threshold ≥ 33 °C while WS did not record this threshold level; therefore, DL recorded a longer and more severe temperature period than the recorded data by WS.

DL recorded an average of 182 (21.6%) more CU than WS. DL began the recording of CU from December 7 while WS from the 18. The daily accumulation of continuous hours with ≥ 90% RH, had a significant difference between WS and DL. The WS in B-2918 recorded 277 more hours than the DL in B-2814, and the WS located in Sahuaral recorded 138 more hours than the DL in Morocua. However, DL in B-2036, B-703, and B-2324, recorded 539, 375, and 73 more hours with ≥90% RH than their respective WS.

The analysis of variance of grain yield, the number of spikes, and the LAI and their interactions were highly significant. The field with the highest grain yield was B-703 with 8.45 t ha^{-1}, and the field in B-2814 had the lowest with 5.55.

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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