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Thermal risk analysis for winter-spring maize (*Zea mays* L.) in the Yaqui Valley Sonora, Mexico

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Abstract

The state of Sonora in Mexico contributed with 2.8 % of the maize national production (788,885.77 t) in 2021; however, its production has been affected by low temperatures. The objective was to analyze the effect of minimum (MINTT ≤ 3 °C) and maximum temperature threshold levels (MAXTT ≥ 33 °C) on maize production. Five commercial fields sown with hybrid Hipotótamo and five with DK-4050 were selected in the Yaqui Valley. Temperature data were obtained from the automated weather station network in the state from December 2021 to June 2022. The minimum temperatures recorded between March 8 and 10, 2022, covered about 35 % of the total area sown with maize in southern Sonora. Foliar damage as shown by necrosis between the 5th and 10th leaf oscillated from 3 to 12 %, and it was associated with a temperature range of 1.05 and 4.30 ºC. Frost severity was not significant, so the crop recovered by the production of new leaves. From April, different periods of days with different continuous hours with MAXTT were recorded by weather stations; the highest number of periods occurred in fields B-419 and B-1101 with six. The highest number of hours with MAXTT was recorded in B-1922 with 374, followed by B-419 with 288. Hipopótamo showed the highest grain yield in field B-1101 (16.62 t ha^{-1}). Damage by MAXTT to maize production during 2021-2022 winter-spring season, caused a reduction of 1.53 t ha^{-1} in relation to the regional average in the previous season.

Keywords: Maize, *Zea mays*, Thermal stress, Grain yield

1. Introduction

Maize (*Zea mays* L.) production worldwide was 1210,235,135.14 tons from a harvested area of 205,870,016 ha with an average grain yield of 5.87 t ha^{-1} [1]. In Mexico, the production of maize grain under irrigation and rainfed condition in the year 2021 was 27,503,477.82 t with an average yield of 3.85 t ha^{-1}. The state of Sonora is ranked as the 11th producer in the country and contributed with 2.8 % of the national production with 788,885.77 t with an average of 11.3 t ha^{-1} [2]. Maize is the most important agricultural crop in Mexico from the food, industrial, political, and social points of view [3]; white and yellow maize are the main varieties cultivated in the country. White maize is exclusively cultivated for human consumption due to its high nutrient content (annual consumption per capita 196.4 kg) [4] and yellow maize for animal feed and industrial processing. Both varieties may be used in any of two crop seasons: spring-summer or fall-winter, under a diverse agroclimatic conditions, under irrigated or rainfed conditions, and subjected to different technologies [3]. In the year 2021, national production of white maize was 24,235,821.46 t and 3,147,058.83 of yellow maize, while in Sonora 788,867.77 and 18 t, respectively [2]. Production of yellow maize in Mexico satisfies only 23.9 % of the domestic consumption, therefore, 12.95 million t were imported from The United States, Argentina, Brazil, and Canada, and although the domestic production of white maize covers the internal need, about 1 million t were imported from the United States in 2017 [4], and 164,000 t during the months of January-February 2021 [5]. In southern Sonora, maize cultivation has been technologically recommended in various sowing dates: for spring from March 1 to 31, for

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the summer during the second fortnight of August [6]; Ortega *et al*. [7] also recommend sowing during June. For the fall-winter season, Cota Agramont *et al*. [8] recommend sowing from the second week of August to September 10 in order to evade frost damage, and sowing of sweet maize for canning from October to February. More recently, Valenzuela Borbón *et al*. [9] recommend sowing maize in December, since yield potential is high and with a low risk of frost damage for the current hybrids used in the region; they have also reported that sowing in October-November, hybrids show the highest grain yield, but the risk of frost is greater. The temperature for the last 10 years in southern Sonora, Mexico, has maintained a 0.2 °C increase tendency in the spring season, mainly during the months of April and May [10]. There is unequival evidence that earth is warming at an unprecedented rate and that human activity is the principal cause [11]. The extreme minimum temperature has a tendency to increase and the relative humidity has been unstable. Generally, the southern region of the state of Sonora, is characterized by extreme minimum temperatures of -1.8 °C mainly in January, and extreme maximum temperatures of 32.5 to 44.2 °C during June, July, and August; although in certain years like 2020, temperatures above 32 °C during the day might occur in May and September [11,12]. The influence of climate in a crop is highly relevant, since it does not only depend on the climatic characteristics of the locality, but also to a great extent upon the conditions over which production takes place [13]. In Southern Sonora, maize is an asset for the economy of the region, and it is highly relevant for the fall-winter crop pattern. In this state, maize is the second most important crop after wheat (*Triticum aestivum* L. and *T. durum* Desf.) [14]; however, the current production system requires changes or adjustments in order to mitigate the effect of climate change, and be adapted to the current needs in order to assure the integrity and profitability of the crop [15]. 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 [16,17,18]. 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 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. Southern Sonora has experienced climatic abnormal temperature events, like the frosts during the 2003-2004 and 2010-2011 crop seasons [19], where even the wheat producers were affected by the magnitude of the damage, and for the limitations of the crop insurance coverage, and an unsually warm and humid one during 2014-2015 which caused losses in various crops [20,21]. The frequency of frosts and the increase of heat waves, will be more frequent phenomena according to Smith *et al*. [22]. Therefore, the temperature is an important factor for the sowing date during the fall-winter and winter-spring crop seasons. If sowing is carried out too early, seedlings might be exposed to low temperatures which will slow down their growth and development. If it is carried out too late, plants will be exposed to high daily and nightly temperatures during grain filling, which will increase their respiration rate and reduce grain yield [23,24]. Considering the technological proposals which intend to adjust the sowing date in December with new maize genotypes with greater productivity potential, the objective of this work was to analyze the minimum and maximum thermal levels that represent a damage risk to the phenological development of maize and their impact on grain yield.

2. Materials and methods

Ten commercial maize fields were selected within the irrigation district 041 in Cajeme County where the Yaqui Valley is located (Figure 1). Distance between fields was based on the location of their closest weather stations that belong to the automated weather station network in the state of Sonora [10]. Temperature data were taken in an hourly basis from December 2021 to June 2022, period that covered the winter-spring crop season.

A follow up was given to the crop which included the two hybrids Hipopótamo [25] and DK-4050 [26], and data were recorded on dates of complementary irrigations, and damage to the crop by extreme climatic events. In order to estimate the damage to the crop by the cold-high temperature, the local methodology generated by Félix Valencia *et al*. [19] was used as well as the methodology utilized by Fernández *et al*. [27] and Fraschina *et al*. [28]. The minimum (MINTT) (≤ 3 °C) and maximum thermal threshold level (MAXTT) (≥ 33 °C) were calculated. Grain yield from each field was obtained by taking six 1 m^2 random samples which were analyzed in a randomized complete block design with the statistical package InfoStat [29] and mean comparison with Tukey´s test ($P = 0.05$). The impact of thermal threshold was analyzed with the methodology applied by Félix Valencia *et al*. [19].

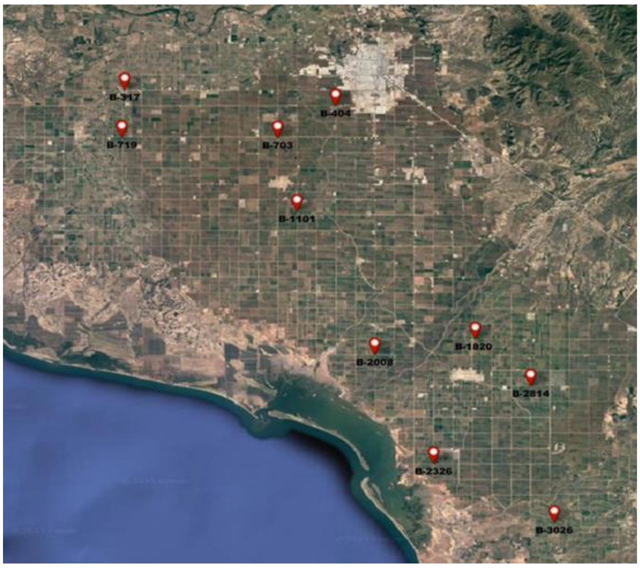

Figure 1 Maize fields evaluated in the Yaqui Valley, Sonora, Mexico, during the winter-spring crop season 2021-2022.

3. Results and discussion

3.1. Impact by the minimum thermal threshold level (MINTT)

The minimum temperatures recorded between March 8 and 10, 2022, covered about 35 % of the total area sown with maize in southern Sonora. The phenological maize stages damaged were between the 5th and 10th leaf exposed (Table 1).

Table 1 Vegetative and reproductive stages sensitive to periods of low and high temperature, in ten commercial maize fields sown with Hipopótamo and DK-4050 hybrids, in the Yaqui Valley, Sonora, Mexico, during the winter-spring crop season 2021-2022|.

Field	Cultivar	Sowing date	Vegetative stage with risk to low temperature		Reproductive stage with risk to high temperature	
			Germination date	Period of exposure between 5th and 10th leaf	Boot-heading	Milky grain
1	Hipopótamo	05/11/2021	11/11/2021	Dec 28 - Feb 03	Feb 23	Mar 21
2	DK-4050	24/11/2021	30/11/2021	Jan 14 – Feb 17	Apr 05	Apr 19
3	DK-4050	04/12/2021	11/12/2021	Feb 03 – Mar 04	Apr 05	Apr 29
4	DK-4050	08/12/2021	15/12/2021	Feb 07 - Mar 01	Apr 05	May 13
5	DK-4050	10/12/2021	17/12/2021	Jan 22 – Feb 25	Apr 11	Apr 29
6	DK-4050	16/12/2021	22/12/2021	Jan 27 – Mar 03	Mar 21	Apr 19
7	Hipopótamo	16/12/2021	23/12/2021	Feb 04 - Mar 03	Mar 28	Apr 29
8	Hipopótamo	20/12/2021	26/12/2021	Feb 10 - Mar 07	Apr 29	May 16
9	Hipopótamo	26/12/2021	03/01/2022	Feb 07 - Mar 03	Apr 17	May 02
10	Hipopótamo	27/12/2021	03/01/2022	Feb 09 - Mar 05	Apr 18	May 10

The highest damaged recorded occurred in the central-eastern region with varying degrees of damage to the commercial fields. Foliar damage (Figure 2) as shown by necrosis between the 5th and 10th leaf oscillated from 5 to 12 %, and it was associated with temperatures recorded in the range of 1.05 and 2.97 ºC (Table 2).

Figure 2 Frost damage in maize plants from commercial fields, in the Yaqui Valley, Sonora, Mexico, during the 2021-2022 crop season.

Table 2 Continuous hours with temperature ≤ 3 °C during March 8 to 10, 2022, recorded by weather stations closest to the evaluated maize fields, in the Yaqui Valley, Sonora, Mexico, during the winter-spring crop season 2021-2022.

Fields evaluated	Location of weather station*	Temperature recorded (°C)	Mar 08	Mar 09	Mar 10	Damage (%)**
1	B-1101	1.51-2.43	0	3	0	0
2	Sahuaral	2.07-2.56	0	2	3	0
3	B-2328	1.71 - 2.97	0	4	4	7
4	B-1922	1.95 - 2.89	0	5	2	3
5	B-2918	1.05-2.8	0	3	5	5
6	B-419	3.96-4.3	0	0	0	0
7	B-2010	1.33 - 2.84	0	4	4	10
8	B-419	3.96-4.3	0	0	0	0
9	B-910	2.36-2.95	0	2	0	0
10	B-609	1.06 - 2.79	0	5	5	12

*B= indicates the area of a 2 x 2 km square within the Yaqui Valley, which are commonly referred to as blocks; **calculated based on the percentage of the field area affected multiplied by the percentage of foliar damage.

Quantified damage by the local plant health council on the total area sown with maize coincides with this work, which indicated a moderate severity and recovery of many of the affected fields. The exposure of the fields evaluated to the MINTT (≤ 3 °C) did not complete three consecutive days, and only four fields were exposed to two days with more than 3 continuous hours with minimum temperature between 1.05 to 2.97 °C; foliar damage was recorded in fields 3 (B-2328), 5 (B-2918), 7 (B-2010), and 10 (B-609), ranging from the phenological stages between the 5th and 10th leaf (Table 2). Frost severity was not significant, and therefore, the crop recovered by the production of new leaves. The effect of frost on young corn when it is accompanied by temperatures no lower than about -1.11 °C is primarily damage and death of the exposed above ground leaf tissue. As long as the growing point of the young plant (the apical meristem) is still protected below the soil surface, the injured plant usually recovers from the effects of the superficial leaf damage [30]. No foliar damage was recorded in fields 1 (B-1101 Hipopótamo), 2 (Sahuaral DK-4050), 6 (B-419 DK-4050), 8 (B-419 Hipopótamo), and 9 (B-910 Hipopótamo); however, the Local Plant Health Council found important damage ranging between 5 and 35 % in the following localities: El Chucarit, Tesia, Capetamaya, and B-1730 (Mayojusalit region) (Table 3).

Table 3 Continuous hours with temperature ≤ 3 °C during March 8 to 10, 2022, recorded by weather stations closest to the evaluated maize fields evaluated by the Local Plant Health Council, during the winter-spring crop season 2021-2022 in the Yaqui Valley, Sonora, Mexico.

Fields evaluated	Location of weather station	Temperature recorded (°C)	Mar 08	Mar 09	Mar 10	Damage (%)*
1	B-1730	0.31 - 2.96	5	9	7	35
2	Capetamaya	0.71 - 2.69	4	6	5	21
3	Tesia	1.1 2.87	2	6	4	23
4	Chucarit	1.45 - 2.95	0	5	3	5

*Calculated based on the percentage of the field area affected multiplied by the percentage of foliar damage.

Freezing temperatures prior to corn maturity can mean yield loss, although the severity varies greatly based on local climate conditions, crop maturity and topographical features [31]. A corn killing freeze occurs when temperatures dip to 0 °C for four hours or -2.2 °C for minutes. A killing freeze can still happen with temperatures above 0 °C, in low and unprotected areas when there is no wind. Corn leaves are more easily damaged than stalks, and leaves above the ears are more susceptible to injury than those below. Freeze-damaged leaves initially appear water-soaked, they are light green to gray after drying and later turn brown (Figure 3). If the freeze injury is not severe enough to cause the kernel black layer to prematurely form, kernels will continue to accumulate dry matter by translocating sugars from the stalk and remaining green leaf area. Due to the variable nature of a natural freeze, yield losses are difficult to estimate, yield and quality reductions depend on the crop stage when the freeze occurs and its severity. Severely frost-damaged corn often has kernels more susceptible to cracking, grain that is less digestible and silage with less energy (starch) and contains more fiber than normal

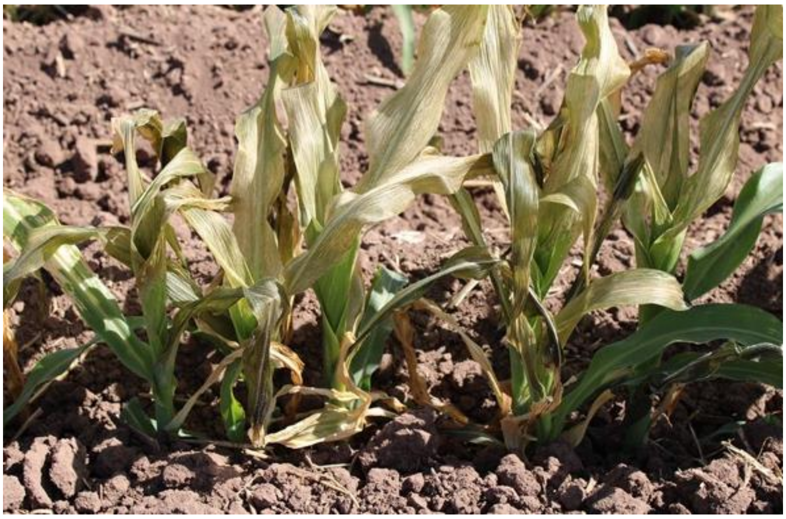

Figure 3 Freeze-damaged leaves in young maize plants with a water-soaked light green to gray appearance, in a commercial field in the Yaqui Valley, Sonora, Mexico, during the 2021-2022 crop season.

3.2. Impact by the maximum thermal threshold level (MAXTT)

In general, continuous periods of temperature ≥ 33 °C did not present a risk to the pollination of corn sown from December 1 to 15, given that pollination of these sowings occurred between March 10-20. Temperatures from April 16 onwards posed a higher risk, since that was the period where the beginning of flowering and the first stage of grain development occurred for sowings from the end of December to February. Thus, from the month of April, periods of MAXTT started and were recorded by two weather stations (Table 4). Different periods of days with different continuous hours with MAXTT were recorded by the weather stations; B-609 recorded two extreme periods, B-1922, B-2328, B-2010, Sahuaral, and B-2918 recorded four extreme periods, B-910 recorded five, and B-419 and B-1101 recorded six. Detection of MAXTT by any of the ten weather stations comprised from April 16 to June 30, with the exception of the periods April 29 and 30, May 1 to 4, and May 19 to 25. The highest number of hours with MAXTT was recorded by B-1922 with 374, followed by B-419 with 288, B-910 with 276, and B-1101 with 275, while the lowest number of hours with MAXTT was recorded by B-2918 with 114. Although B-609 had only two periods of MAXTT, the number of hours added up to 164.

Table 4 Continuous hours and days with temperature $\geq$ 33 °C during April 15 to June 30, 2022, recorded by weather stations closest to the ten evaluated maize fields, during the winter-spring crop season 2021-2022 in the Yaqui Valley, Sonora, Mexico.

Weather station	Period 1	Hours	Period 2	Hours	Period 3	Hours	Period 4	Hours	Period 5	Hours	Period 6	Hours
B-1922	16-20 Apr	20	5-18 May	84	26 May-24 Jun	231	26-30 Jun	39				
B-419	26-28 Apr	9	9-12 May	19	14-18 May	24	26-29 May	33	31 may-2 Jun	9	5-30 Jun	194
B-1101	5-7 May	14	9-18 May	58	26-28 May	26	5-7 Jun	14	10-24 Jun	126	27-30 Jun	37
B-910	9-17 May	54	26-29 May	33	5-7 Jun	15	10-25 Jun	136	27-30 Jun	38		
B-2328	9-18 May	50	26-29 May	29	5-7 Jun	12	9-24 Jun	129				
B-2010	10-14 May	31	27-29 May	24	10-24 Jun	106	27-30 Jun	34				
Sahuaral	14-17 May	15	26-29 May	25	10-25 Jun	109	27-30 Jun	31				
B-2918	27-29 May	20	12-17 Jun	31	20-24 Jun	39	27-30 Jun	24				
B-609	10-25 Jun	126	27-30 Jun	38								

The month of June was intense in terms of the periods and number of hours with MAXTT, particularly from June 10 to 24 and from 27 to 30. In some periods of MAXTT during May and June, temperatures above 40 °C were also recorded.

3.3. Analysis of commercial production

The highest grain yield was shown by the hybrid Hipopótamo in field 1 (B-1101) with 16.62 t ha^{-1} (Table 5); this field had the earliest sowing date and escaped the MAXTT during the sensitive phenological stages.

Table 5 Grain yield of two maize hybrids from ten commercial fields, evaluated during the winter-spring crop season 2021-2022 in the Yaqui Valley, Sonora, Mexico.

Fields	Cultivar	Mean	LSD= 3.364
1	Hipopótamo	16.62	A
8	Hipopótamo	15.45	A
5	DK-4050	14.18	A
6	DK-4050	13.52	A B
7	Hipopótamo	10.63	B C
9	Hipopótamo	10.49	B C
3	DK-4050	9.95	C
4	DK-4050	9.98	C

10	Hipopótamo	9.76	C
2	DK-4050	8.71	C
Tukey (α= 0.05).			

Agronomic management by the farmers and climatic factors must have influenced the rate of growth and development of the crop (Figure 4); Wang and Xing [32] found that a positive relationship between nitrogen fertilizer level and growth rate.

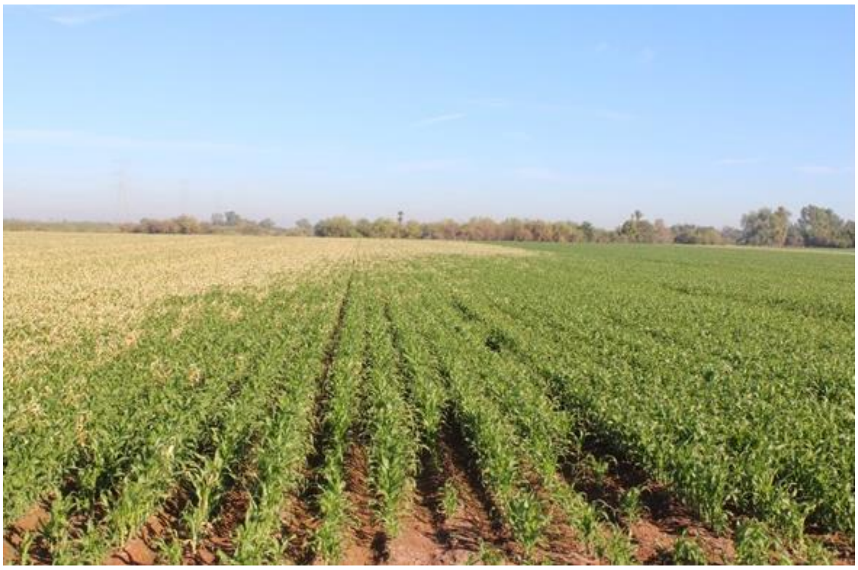

Figure 4 Protective effect in a section of a commercial field in Block 305, by irrigating just before a frost occurred, in the Yaqui Valley, Sonora, Mexico, during the 2021-2022 crop season.

Hipopótamo also in field 8 (B-419) showed the second the highest grain yield with 15.45 t ha^{-1}, followed by the hybrid DK-4050 in fields 5 (B-2918) and 6 (B-419) with grain yields of 14.18 and 13.52 t ha^{-1}, respectively. Although there were continuous days with temperatures higher than 33 °C during the grain filling stage in field 8, the timely application of irrigation helped to avoid the negative effect of the high temperature on the weight of the grain. The lowest yields occurred in fields 3 (B-2328, DK-4050), 4 (B-1922, DK-4050), 10 (B-609, Hipopótamo), and 2 (Sahuaral, DK-4050); only field 4 (B-1922) coincided with high temperatures that occurred during the end of flowering and the development of grain filling. Dates after December 20 were more exposed to heat damage. The damage by the MAXTT to maize production during the 2021-2022 winter-spring season caused a reduction of 1.53 t ha^{-1} in relation to the average regional grain yield as compared to the previous season [5]; in addition, there was greater presence of pests such as stigma fly (*Euxesta stigmatias* Loew) and common leaf rust (*Puccinia sorghi* Schwein). High night-time temperatures can cause corn plants to respire more to cool down, which uses up sugars (energy) that could otherwise be provided to the developing kernels. Reduced kernel size lowers potential grain yield [33]. Previous research has shown little impact to yield when soil moisture is sufficient and corn plants experience temperatures between 35 to 36.6 °C. However, four or more consecutive daytime temperatures in this range can begin to reduce yield potential. One attribute that has allowed corn plants to deal with excessively high temperatures is that they typically shed most of their pollen in the morning hours before temperatures rise to their afternoon. Badu-apraku *et al.* [34] reported that grain yield per plant was lower under higher temperatures, and the decrease in grain yield was almost entirely determined by a shorter duration of grain-filling, while no temperature effect was observed on kernel growth rates or on kernel number per ear. Maize hybrids showed a significant statistical difference in grain yield (Table 5); Hipopótamo produced an average of 1.33 t ha^{-1} higher than DK-4050, and although its maximum yield was 16.62 t ha^{-1} in field 1 (B-1101), it also had the second lowest yield with 9.76 in field 10 (B-609).

4. Conclusion

Foliar damage to maize caused by the minimum thermal threshold level was associated to a temperature range of 1.05 to 2.97 °C in four fields (3 B-2328, 5 B-2918, 7 B-2010, and 10 B-609), exposed for two days with more than 3 continuous hours. The damage occurred during the phenological stage of the 5th to the 10th leaf with a damage of 5 to 12 %. Frost severity was not highly significant, and therefore, the crop recovered by the production of new leaves.

Two periods of days with the maximum thermal threshold level (MAXTT) occurred in the field in B-609, four in B-1922, B-2328, B-2010, Sahuaral, and B-2918, five in B-910, and six in B-419 and B-1101. The highest number of hours with MAXTT was recorded by B-1922 with 374, followed by B-419 with 288, B-910 with 276, and B-1101 with 275.

In general, continuous periods of MAXTT did not present a risk to the pollination of corn sown in November and first half of December since pollination occurred early during the season. MAXTT from the end of April onwards posed a higher risk, since that was the period where the beginning of flowering and the first stage of grain development occurred for sowings from the end of December to February.

The highest grain yields were produced by the hybrid Hipopótamo in fields 1 (B-1101) with 16.62 t ha^{-1}, and 8 (B-419) with 15.45 t ha^{-1}, followed by the hybrid DK-4050 in fields 5 (B-2918) and 6 (B-419) with grain yields of 14.18 and 13.52 t ha^{-1}, respectively.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

The authors declare that No conflict of interest.

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