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EVALUATION OF THE IMPACT OF HIGH TEMPERATURES ON RAINFED CORN IN JALISCO, MEXICO

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Abstract: Maize (Zea mays L.) produced under rainfed conditions is the main crop in Mexico and Jalisco has the highest grain yield, with wide variation at the municipal level. This yield variability is attributed to the level of intensification of production systems, local environmental conditions, establishment of the crop on unsuitable land, with consequent soil degradation and loss of productivity, profitability and yield. Climate is a source of yield variation, particularly due to high ambient temperatures. This characteristic needs to be evaluated as a limiting factor for corn in Jalisco. The objective of the present study was to evaluate the impact of environmental temperature on rainfed maize in Jalisco, Mexico. Monthly normal data for the period June to November of maximum and minimum temperature from 130 climatological stations in Jalisco were used. The concept of meteorological equivalents was applied to calculate the Thermal Efficiency (TE). The TE was obtained by rating the maximum and minimum temperatures in the growing season (EC) of Jalisco. With this rating a Thermal Index was obtained, with which the ET of corn in the EC was determined, which was mapped with ArcView GIS and Idrisi selva. The effect of ET on corn yield was evaluated with corn data from 2009 and 2010. The results showed the in the period with a value of 91.8%, which identifies it with high category. The in the period was 96.7%, identified with high category. These results indicate that corn in Jalisco has high thermal efficiency, only the coastal region has medium TE. It was found that ET currently has minimal influence on grain yield, but probably in the long term the increase in temperature due to climate change will evolve into a limiting factor for corn
Keywords: Thermal efficiency, Thermal Index, Corn.

INTRODUCTION

In agricultural environments of Jalisco, Mexico, the largest area planted is with rainfed maize, with average yields of 6.94 ton/ha, but within the state there is a wide variation at the municipal scale, with values ranging from 9.78 ton/ha in Atotonilco el Alto to 0.88 ton/ha in Mezquitic (SIAP-SADER, 2023). This yield variability is attributed to the level of intensification of agricultural production systems (APS), to local environmental conditions, to the establishment of the crop on unsuitable land with the consequent soil degradation and loss of productivity, profitability and yield. In this context, climate is an uncontrollable factor of the PPS, especially temperature and precipitation, which have high variability in time and space, a condition that confers them a high risk of agricultural production (Turrent 1985), to the extent of considering them the main limiting factors of the crop (Monteith, 1977). According to the IPCC (2021), temperature is a key indicator in the functioning of the local, regional or global climate, during the crop cycle and throughout the years, so its characterization is essential to understand the functioning of the SPA, with the current high temperatures or even expected extreme values.

The IPCC (2023) indicated that the earth's global temperature is unequivocally increasing due to human activity. It indicated that in the period 2001 to 2020, the temperature rose 0.99°C above the temperature in the period 1850 to 1900. The effects of these thermal changes are complex, but reflected in the geographic distribution of many plant species, including the maize crop, which is experiencing changes in the size of suitable agroclimatic zones with increasing thermal growing season length and changes in its phenology (Gulev et al., 2021; Hatfield, 2016; Robertson, 1983). With the increase in global temperature, many agricultural areas are having suboptimal conditions due to excessive heat, with consequent decrease in productivity and SPA yield (IPCC, 2023), in crop development (Teng et al., 2022; Sanchez et al., 2014), with magnitude dependent on thermal intensity, duration of exposure to high temperatures and rate of temperature increase (Porch and Hall, 2013).

The negative impact of high temperatures is associated with critical phenological stages such as flowering or grain filling in maize (Teng et al., 2022; Xin Dong et al., 2021; Wang et al., 2019; Lou, 2011). This situation has directed much research to evaluate the impact of temperature extremes on heat events and changes in the characteristics of extreme events, extreme heat on crop yield (Zhang et al., 2021). To this end, various tools have been used alone or in combination such as crop simulation models (Adeyemi et al., 2024; Gabaldón-Leal et al., 2016; Flores-López et al., 2014), statistical models (Kamkar et al., 2023; Tandzi and Mutengwa, 2020), geographic information systems with agroclimatic indices and satellite imagery (Zhou et al., 2024; Zhang et al., 2021; Zhang et al., 2020). While these tools have produced important results for understanding the influence of high temperatures on crops, their application requires little available information, software, and equipment. Another research approach to assess extreme maximum temperature conditions for maize is the concept of weather equivalents, understood as the degrees of temperature or thermal efficiency (TE) that separate the normal thermal situation from the abnormal one due to excess or insufficiency (Azzi, 1956).

The evaluation of ET using the weather equivalent approach requires rating the maximum and minimum temperatures by assigning a score according to the degree to which the optimum thermal requirement of the crop is met. The thermal requirement of maize is reported with wide variation during its development cycle. Sanchez et al. (2014) report that the period from planting to the beginning of male flowering, the minimum, optimum and maximum temperatures are 9.3, 28.3 and 39.2°C, respectively; for in the grain filling period they are 8.0, 26.4 and 36.0°C, respectively and in the development of the flowering structure they are 7.7, 30.5 and 37.3. Ruíz-Corral et al. (2002) determined the base temperature, optimum temperature and maximum threshold temperature for the developmental stages of maize from planting to flowering of maize hybrid H-311 with values of 9.4, 24.3 and 28.8° C, respectively, while from flowering to physiological maturity the values were 10.2, 25.7 and 30.2° C, respectively. Optimal maximum maize temperature is reported to range from 29 to 32°C and minimum from 17 to 23°C, with threshold values from 10 to 38°C (Schlenker and Roberts, 2009; Lisaso et al., 2018), and photosynthetic dormancy at 45°C (Tao et al., 2016). Maize can survive brief adverse temperature exposures ranging from 0°C to 45°C, with growth limit from temperatures of 5°C to about 35°C, germination and slow growth near 10°C (Muchow, 1990). Optimum daytime temperatures for growth range from 25 to 32/33°C, while the optimum night temperature ranges from 17 to 23°C, but in rainfed corn begins to become stressed when air temperature exceeds 32°C during the stigma formation and pollen dehiscence stages and in the grain filling period (Neild and Newman, 1986). High temperatures have an impact on yield reduction, number of grains and 1000-grain weight when the temperature is above 35°C during this critical period (Dong et al., 2021). In the grain filling and flowering period, optimum temperatures of 24 to 26° C are reported, but reduction in grain weight when above 33°C (Tao et al., 2016). According to Porch and Hall (2013), it is important to identify the locations of high temperatures and understand their influence on maize performance. The objective of the present study was to evaluate the Thermal Efficiency of rainfed corn in Jalisco, Mexico, to identify the risk conferred by this factor to the crop.

MATERIALS AND METHODS

The growing season (GC) for rainfed agricultural production in Jalisco, Mexico, runs from June to November (Flores and Gonzalez, 2024). To evaluate the effect of high temperatures on CD in Jalisco, Mexico, the monthly normal data for the period June to November of the maximum and minimum temperature of 130 climatological stations in Jalisco were used, with historical series updated to 2020, and distribution shown in Figure 1.

Distribution of the climatological stations of the National Water Commission used in this study.

The evaluation of Thermal Efficiency (TE) with the approach of Azzi (1956) required rating the maximum and minimum monthly temperatures, assigning a score according to the degree to which the thermal needs of corn are satisfied (Arteaga, 1992). The values with which they rated the maximum and minimum temperatures are shown in Table 1. These temperature values were obtained by literature review.

Maximum Temperature Range (°C)	Rating Thermal Index Score	Minimum Temperature Range (°C)	Rating Thermal Index Score
> 38	0	> 26	0
36 - 38	1	25 - 26	1
34 - 36	2	24 - 25	2
33 - 34	3	23 - 24	3
32 - 33	4	21 - 23	4
< 32	5	< 21	5

Table 1. Ratings applied to the normal monthly maximum and minimum temperatures evaluated for climatological stations in Jalisco, to obtain the Thermal Index of the temperature and determine its Thermal Efficiency.

With the scores for the maximum temperature (P_{TMAX}) and for the minimum temperature (P_{TMIN}) of the monthly normal values from June to November, a Thermal Index (TI) was obtained. With the monthly Thermal Index of the maximum temperature (IT_{TMAX}) and the minimum temperature (IT_{TMIN}), according to the following expressions:

$$IT_{TMAX} = \sum_{i=1}^{n}(P_{TMAX})_i \ ;$$

$$IT_{TMIN} = \sum_{i=1}^{n}(P_{TMIN})_i$$

The Total Thermal Index (IT_{TOTAL}) was obtained with the average of the Thermal Index of the maximum temperature (ITmax) and Thermal Index of the minimum temperature (ITmin) for the period from June to November. According to the monthly value of 5 assigned to the optimum thermal condition, the maximum IT_{TOTAL} was 30. The ET in the period with the maximum temperature (ET_{TMAX}) was calculated with the expression:

$$ET_{TMAX} = \frac{IT_{TMAX}}{30} x100$$

The ET in the period for the minimum temperature () was calculated with the formula:

$$ET_{TMIN} = \frac{IT_{TMIN}}{30} x100$$

The Average Thermal Efficiency (ET_{MED}) was obtained with the sum of the average of ET_{TMAX} and ET_{TMIN}, according to the expression:

$$ET_{MED} = \frac{ET_{TMAX} + ET_{TMIN}}{2}$$

The interpretation of ET for maximum temperature (ET_{MAX}) and minimum temperature (ET_{MIN}) have four categories, which are presented in Table 2.

Interpretation of Thermal Efficiency (Arteaga, 1992).

Thermal efficiency in the period (%)	Category
0 - 25	Marginal
25 - 50	Download
50 - 75	Media
75 - 100	High

The mapping of the ET_{MAX} and ET_{MED}, obtained for the state of Jalisco was carried out with an ArcView and Idrisi Selva GIS. The statistical analysis used descriptive statistics, correlation analysis and regression analysis in the EXCEL program.

RESULTS AND DISCUSSION

Figures 2 a,b show the thermal efficiency with the maximum temperature and minimum temperature for the corn crop in the period from June to November, corresponding to the growing season by humidity and temperature in Jalisco.

The ET_{TMAX} was 91.8%, which identifies it as a high ET_{TMAX} category. The ET_{MED} in the period was 96.7%, identified as high ET category. The was 93.8%, which qualifies it as a high ET category. These results show that corn has high thermal efficiency with maximum and minimum temperature. Given that the coastal region has high temperatures during the analyzed period, the ET_{TMAX} expected during the day are medium values and in some areas low ET, as shown in Figure 2a. This figure shows that the ET_{TMAX} has a high value in almost the entire state.

The ET_{TMIN} shown in Figure 2b is high in most of the state, except in coastal areas. This implies that minimum temperatures are not currently a problem for corn productivity. However, the most important trends in climate are related to the increase in minimum temperature in the short term (IPCC, 2023), which implies that for corn yields it represents a limiting factor in the medium and long term.

The mean thermal efficiency for corn for the period from June to November in the state of Jalisco, Mexico, is shown in Figure 3. The mean value of this indicator is 93.8%, which represents a high ET category.

The state of Jalisco has a surface area of 78,595.9 km^2 (INEGI, 2025). The percentage of this surface area occupied by the ET categories in Jalisco is shown in Table 2, according to Figures 2 a,b and Figure 3. With maximum temperature, 86.4% of the surface area of Jalisco shows high thermal efficiency for corn, 12.6% with medium ET and 1.0% low ET. At minimum temperature, the percentage of area with high ET was 98.3%, with medium ET of 1.7%. With respect to average thermal efficiency (ETmedl), 93.3% of the area has high ET category, 6.6% medium ET and 0.1% of ET with low category.

CATEGORY	ET MAXIMUM TEMPERATURE	AND MINIMUM TEMPERATURE	TOTAL THERMAL EFFICIENCY
MARGINAL	0.0	0.0	0.0
UNDER	1.0	0.0	0.1
MEDIO	12.6	1.7	6.6
ALTO	86.4	98.3	93.3

Table 2. Percentage of area occupied by thermal efficiency categories with maximum, minimum and average temperature, shown in Figures 1,a, b and 2, for the state of Jalisco, Mexico.

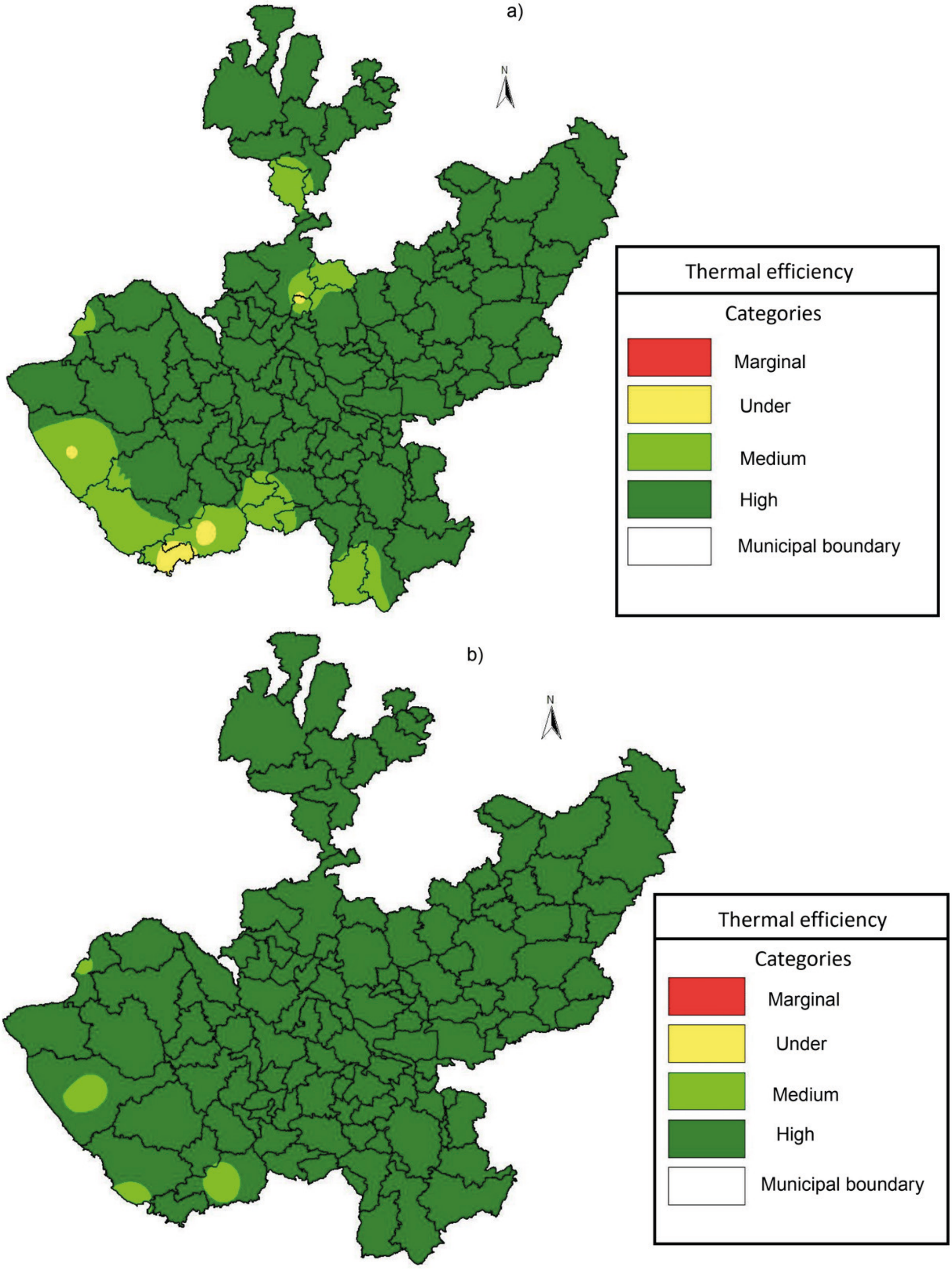


Figure 2. Thermal Efficiency (TE) for corn for: a) the maximum temperature and b) the minimum temperature, during the period from June to November in Jalisco, Mexico

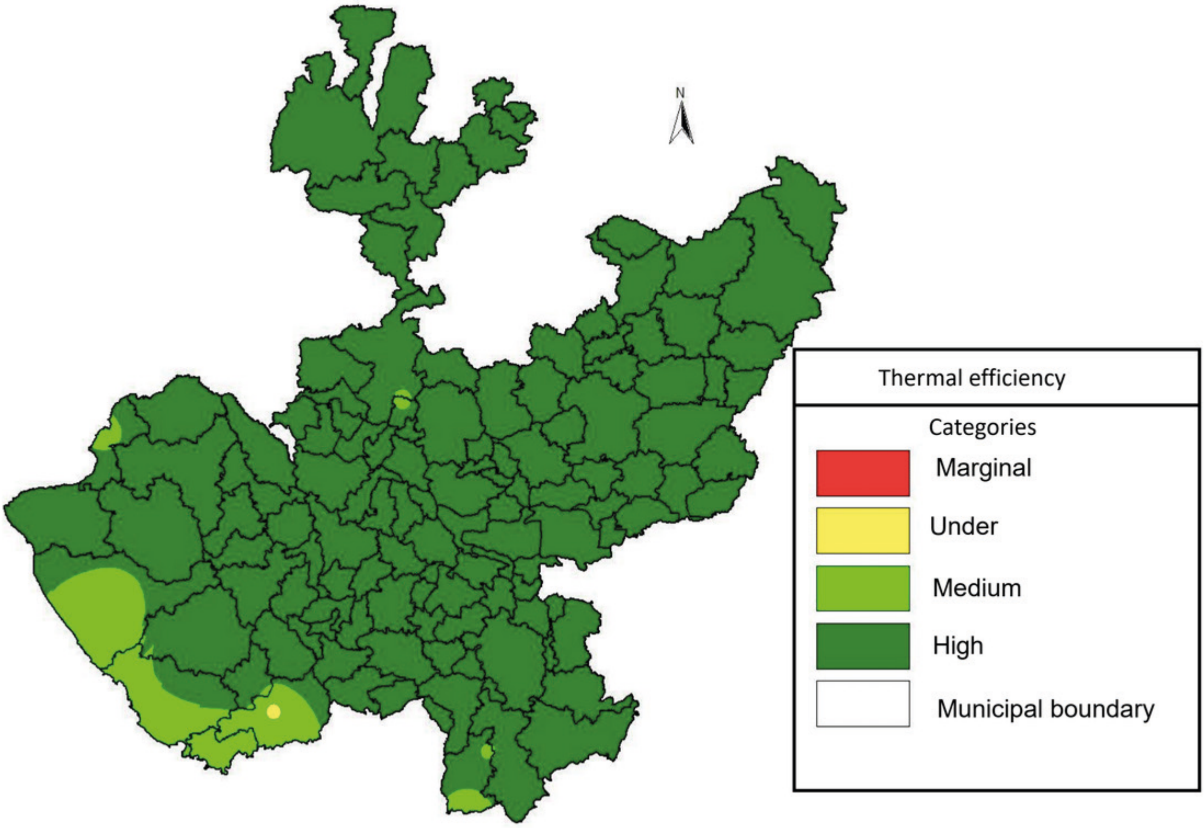


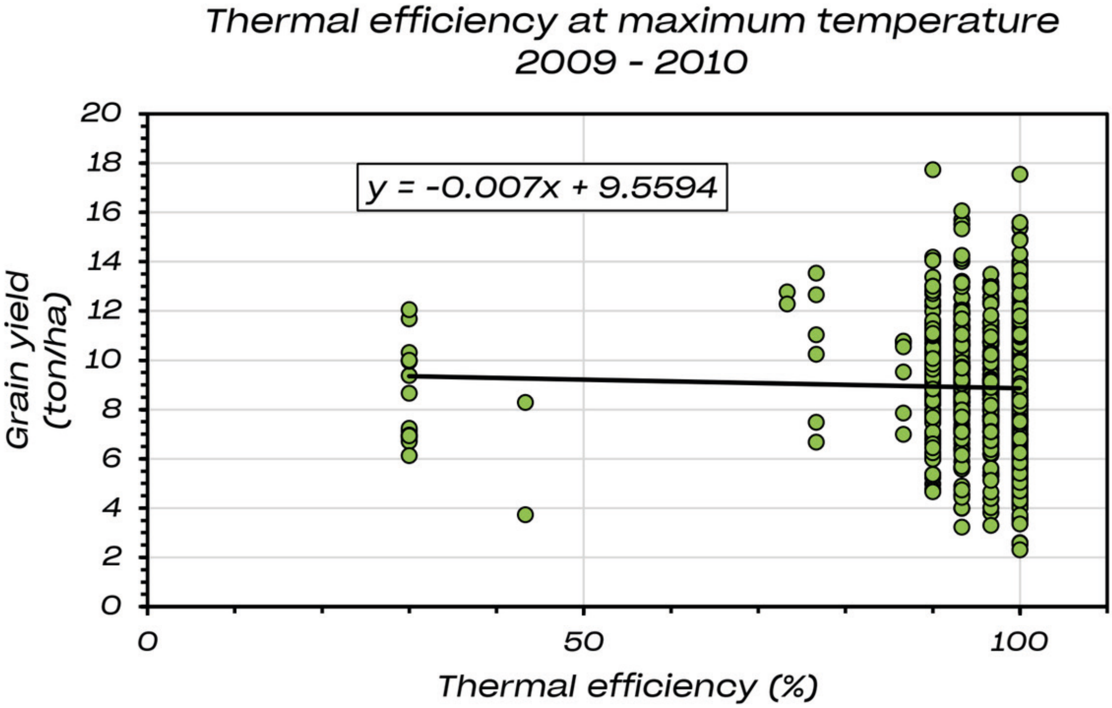
Figure 3 Average thermal efficiency during the period from June to November in Jalisco, Mexico.

The percentage of area occupied by ET with the maximum and minimum temperature in Jalisco indicates that the effect of maximum and minimum temperatures are adequate for corn in most of the state. It is the coastal zone where the maximum temperature is identified as medium and even, in small areas, as low. It has been reported that the minimum temperature is undergoing a greater increase than the maximum temperature (Vose, 2005), with negative influence on maize (Chen et al., 2024), rice (Peng et al., 200) and wheat (Fischer et al., 2022) yields. However, the temperature increase in the last 15 years has been greater than 1.5°C (UNAM-DGCS, 2025) and the thermal effect on maize yield is predicted to be a limiting factor in rainfed agriculture (Ureta et al., 2020).

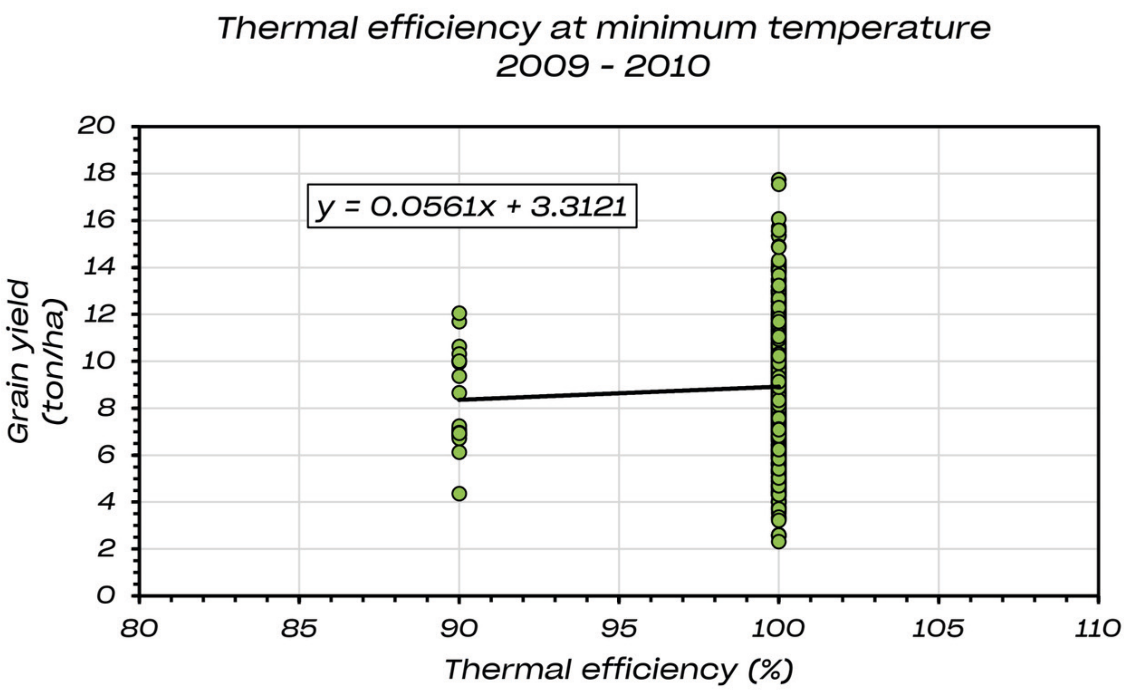
To evaluate the influence of ET with maximum and minimum temperatures on corn yield, the results of high yielding rainfed corn yields obtained during 2009 and 2010 were used (Flores et al., 2011), with the relationship shown in Figures 4 a,b. Notwithstanding the natural complexity of the components of the maize cropping system, Figures 4 a,b show a practically null effect of thermal efficiency with maximum and minimum temperatures on grain yield in the two years in which this program was developed. However, an increase in temperature of 1.5°C is currently reported (UNAM-DGCS, 2025) and it is predicted that in the long term temperature will increase due to climate change (IPCC, 2023) to levels that will become a limiting factor in rainfed agriculture (Ureta et al., 2020).

Relationship of the percentage of thermal efficiency with: a) maximum temperature and b) minimum temperature, for rainfed corn grain yield during 2009-2010, in Jalisco, Mexico.

a)


Thermal efficiency at maximum temperature
2009 - 2010
y = -0.007x + 9.5594
Grain yield (ton/ha)
0
2
4
6
8
10
12
14
16
18
20
0
50
100
Thermal efficiency (%)

b)


Thermal efficiency at minimum temperature
2009 - 2010
y = 0.0561x + 3.3121
Grain yield (ton/ha)
0
2
4
6
8
10
12
14
16
18
20
80
85
90
95
100
105
110
Thermal efficiency (%)

CONCLUSIONS

Maximum temperatures show 86.4 and 12.6% of Jalisco's surface with high and medium thermal efficiency levels, respectively. Minimum temperatures show 98.3 and 1.7% of the surface area, with high and medium thermal efficiency levels, respectively.

The results of this study indicate that the high temperatures in Jalisco, expressed by normal maximum and minimum temperatures, do not yet represent a limiting factor in corn production, but it is likely that in the coming years the increase in temperature due to climate change will become a limiting factor for rainfed agriculture.

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