Colegio de Postgraduados

Effect of thermal and water stress on growth, biomass and yield of native corn in the Yucatan Peninsula, Mexico

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ABSTRACT
Objective: The effect of thermal and water stress on growth, biomass production and yield in native corn (*Zea mays* L.) was evaluated.
Design/methodology/approach: The study grouped 17 native corn cultivars. Heat unit accumulation, leaf area growth, yield, total biomass dry weight, and other dry matter characteristics were evaluated. Individual analyses of variance and correlation were performed using SAS® statistical software. Means were compared using the Tukey test (P≤0.05).
Results: The effect of thermal and water stress allowed to observe a significant variation in the growth of the leaf area and production of dry matter and yield of native corn; on average, better expression was obtained through the genotypes Saak dzit baakal and Kằn Kằn xnuc naal that presented greater growth, biomass and yield based on thermal and water stress.
Limitations on study/implications: The study was limited to the application of water stress during the vegetative stage; it is suggested to cause stress during the reproductive stage.
Findings/conclusions: The native corns Saak dzit baakal and Kằn Kằn xnuc naal showed greater tolerance to thermal and water stress by presenting greater acclimatization that allowed them to present greater growth, biomass production and grain yield.

Keywords: temperature, genotype, physiology.

INTRODUCTION
Climate conditions affect the growth, development and yield of corn (*Zea mays* L.), including drought, heat stress, solar radiation, and the distribution of heat unit accumulation in the cultivation cycle (Ortez *et al.*, 2023). Thermal and water stress are abiotic stress

factors that affect the yield and quality of crops (Wang *et al.*, 2023). It has been reported that variation in climate had adverse effects on corn productivity in several agricultural regions throughout the world (Eck *et al.*, 2020). It has been shown that extreme climatic events, such as drought and thermal stress, are factors that affect the life cycle of corn (Sato *et al.*, 2024; Nawaz *et al.*, 2023), reducing light interception and increasing respiration (Zahra *et al.*, 2023). Therefore, thermal and water stress severely limit agricultural productivity, including corn yield (Kompas *et al.*, 2024).

Yang *et al.* (2023) indicate that both temperature and soil moisture are important covariables in corn yield; therefore, soil moisture could carry out a more important role than temperature, and the apparent adverse effect of temperature on yield variability could be the result of stress from concurrent drought instead of heat stress (Proctor *et al.*, 2022). Because of this, it is important to determine the range of temperatures and thus be able to measure growth through the daily integration of thermal energy or growing degree (D°) within the range, known as growing degree days (GDD) (Arista-Cortes *et al.*, 2018). Growing degree days (GDD) constitute the most extensive thermal indicator in use to predict plant development, obtained through daily maximum and minimum temperatures. This tool is essential to estimate the development rate and growth stage of plants, which are relevant for decision making (Arista-Paredes *et al.*, 2025). In corn, a deficient precipitation and heat can decrease the yield; likewise, it has been observed that for each additional growing degree day above 30 °C the yield decreases by 0.5% under irrigation and 2% in rainfed areas (Dhaliwal and Williams, 2022). The effects of temperature are increased by the water deficit, which demonstrates that understanding the interaction between temperature and water will be necessary to develop more effective adaptation strategies that compensate the impacts of extreme events of higher temperature associated with climate change (Hatfield and Prueger, 2015). Therefore, although this combination of natural variability and climate change is influencing corn productivity, it is important to direct studies about thermal and water stress to the physiological stages of corn. In addition to heat and drought, they are regularly linked to the corn production cycle in the Peninsula of Yucatan, where solar radiation and the distribution of heat unit accumulation during crop stages affect corn growth, biomass and yield. The objective of this study was to assess the effect of thermal and water stress on growth, biomass production and yield in native corns.

MATERIALS AND METHODS

Experimental site and genetic material

The experiment was carried out in plots in the locality of Uayamon, Campeche, Mexico, during the S-S 2024 cycle. Seeds from 17 native corn genotypes were used (Saak tux, Eh hu, Piix cristo, Chaac xmejen naal, Kȁn Kán teel, Kȁn Kȁn xnuc naal, Saak Chan Teel, Eju, Chaak Choob, Tuxpeño, Chaak teel, Saak dzit baakal, San Pableño Blanco, Kȁn Kȁn dzit baakal, San Pableño Amarillo, Rosa San Juan and Morado MX).

Establishment and conditions of the experiment

A completely randomized block design with five repetitions was used. The experimental unit consisted of five rows, 6.0 m long, with 1.0 m separation between rows and 20 cm between plants. The experiment was established manually in April 2024, when seed was deposited at 10 cm depth. For the agronomic management of the crop, the technological package from the National Institute of Forestry, Agriculture and Livestock Research (*Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias*, INIFAP) for corn production was used, under rainfed conditions, in Campeche. During emergence at 24 days after sowing (das), the application of drip irrigation was done for a period of three hours. Likewise, water stress was applied based on suspending irrigation to all genotypes starting from 25 to 45 das (Figure 1B).

Variables statistical analysis

To calculate the growing degree days (GDD), the residual method was used, whose model is the following:

$$GDD = (T\max + T\min) / 2 - Tbase$$

where: Tmax=maximum daily temperature (°C); Tmin=minimum daily temperature (°C); Tbase=base temperature, 10 °C. The maximum and minimum temperature (°C) of the air were registered with an electronic thermometer, and the precipitation with a pluviometer in cm. To determine the variables, eight plants were used per repetition and reported based on the average.

The leaf growth area per plant (LAG) was determined by measuring the length (L) and width (W) of each leaf with a graduated ruler in cm and multiplied by 0.75 (CAFP=L*A*0.75, cm^2). The dry weight of the stem (SW, g), the leaf blade (LBW, g), the leaf sheath (LSW, g), the root (RW, g), the bracts (BW, g) and total biomass (TB, g), was obtained by separating each structure and drying it in a stove (Nieto REB 450) at 70 °C for 72 h, and then weighed on an analytical scale (METLER®). The grain yield (GY, g) was determined by de-kernelling and weighing the corncobs at physiological maturity. With the data obtained, individual analyses of variance and Pearson's correlation were conducted, as well as Tukey's means comparison ($P \leq 0.05$) using the statistical software SAS®, v. 9.1 for Windows.

RESULTS AND DISCUSSION

Heat unit accumulation

Significant differences ($P \leq 0.05$) were observed in GDD between genotypes for all the stages of corn growth and development (Table 1).

According to Beegum *et al.* (2023) corn EME needs between 120 and 125 GDD with maximum (32 °C) and minimum (28 °C) air temperature. However, the sowing depth (Villalobos *et al.*, 2023), soil-air temperature, and moisture can decrease or increase the number of GDD necessary for EME in corn such as Piix cristo which presented 242 GDD compared to Saak tux, Saak Chan Teel, Tuxpeño, Saak dzit baakal and Kàn Kàn dzit baakal, and San Pableño Amarillo which on average obtained 157 GDD at EME (Table 2).

Table 1. Analysis of variance based on the accumulation of GDD in the phenological stages of native corn, S-S 2024 cycle.

SV	DF	Phenological states				
		EME	HE	MF	FF	PM
G	16	6669.3**	81651.8**	79297.9**	60273.7**	32839.1**
R	4	1848.7**	3117.8*	795.2^{ns}	830.9^{ns}	19830.3**
Error	64	227.9	1134.6	353.0	418.4	2092.4
Total	84					
C.V. %		7.6	2.2	1.1	1.2	1.6

*=P≤0.05; **=P≤0.01; ^{ns}=non-significant; VF=variation factor; G=genotype; R=repetition; EME=emergence; SP=spiking; MF=masculine flowering; FF=feminine flowering, and PM=physiological maturity.

Table 2. Means comparison based on GDD accumulation for the different phenological stages of native corn, S-S 2024 cycle.

Genotype	GDD phenological states				
	EME	HE	MF	FF	PM
Saak tux	156 c	1373 f	1523 h	1562 g	2704 e
Eh hu	232 ab	1649 b	1795 b	1816 b	2910 a
Piix cristo	242 a	1880 a	2027 a	2027 a	2909 a
Chaac xmejen naal	213 ab	1373 f	1523 h	1605 fg	2717 e
Kằn Kằn teel	156 c	1393 ef	1543 gh	1605 fg	2737 de
Kằn Kằn xnuc naal	204 b	1397 ef	1543 gh	1627 ef	2749 b-e
Saak Chan Teel	156 c	1411 ef	1562 gh	1627 ef	2724 e
Eju	232 ab	1563 c	1708 c	1729 c	2906 a
Chaak Choob	237 ab	1541 c	1687 cd	1708 cd	2848 abc
Tuxpeño	156 c	1458 de	1605 ef	1669 de	2752 b-e
Chaak teel	227 ab	1441 def	1585 fg	1627 ef	2736 e
Saak dzit baakal	156 c	1501 cd	1647 de	1669 de	2841 a-d
San Pableño Blanco	161 c	1560 c	1647 de	1708 cd	2873 a
Kằn Kằn dzit baakal	218 ab	1458 de	1605 ef	1669 de	2749 b-e
San Pableño Amarillo	161 c	1458 de	1605 ef	1647 ef	2745 cde
Rosa San Juan	237 ab	1415 ef	1562 gh	1647 ef	2852 ab
Morado MX	232 ab	1397 ef	1543 gh	1562 g	2661 e

Mean values per column with different letters are statistically different (P≤0.05). GDD=growing degree days; EME=emergence; HE=heading; MF=male flowering; FF=female flowering; and PM=physiological maturity.

A different requirement of GDD between genotypes could be due to genotype-environment actions (Xu *et al.*, 2021).

Regarding the GDD at SP and MF, Saak tux and Chaac xmejen naal, were statistically more precocious, with 1373 and 1523 GDD. When FF happens, quite marked differences were observed in GDD, due to the lower precociousness of Piix cristo (2027 GDD). However, floral asynchronism in GDD of Piix cristo allows them to ensure the receptivity of the stigmas at the time of anthesis and not with the differences of asynchronism in Chaac xmejen naal (82 GDD), Kǎn Kǎn xnuc naal (84 GDD), and Rosa San Juan (85 GDD) which risk fertilization, corncob development, and yield (Chen *et al.*, 2023). Eh hu, Piix cristo, Eju and San Pableño Blanco presented higher GDD at MF with an average of 2899 GDD. The data reported here agree with what was reported by Arista-Cortes *et al.* (2018), when differences were reported in the GDD requirements of 10 corn accessions.

In corn, an important effect of water stress is the delay in feminine flowering, which results in an increase of the anthesis-feminine flowering interval, an important cause of losses in yield (Abdoul-Raouf *et al.*, 2016).

Growth of leaf area, biomass and yield

The analysis of variance detected differences (P≤0.05) between genotypes for LAG, SW, LBW, LSW, RW, BW, TB and GY (Table 3). Heat exposure at 40 °C and water deficit during the vegetative stage (25 to 45 das), allowed observing a variation of the LAG (Figure 1), since Eh hu presents a difference of 42% (3757 cm^2/plant) and 48% (4256 cm^2/plant) compared to Chaak teel and Morado MX in LAG. However, a longer exposure

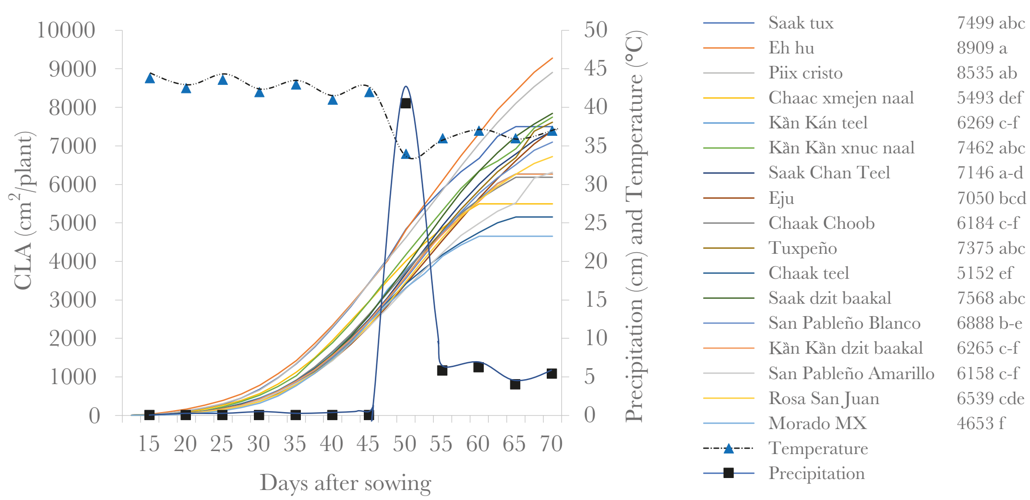

Figure 1. Leaf area growth accumulated by plant (LAG) based on tempera-ture (A) and precipitation (B), S-S 2024 cycle. *=P≤0.05. Mean values per column with different letter are statistically different (P≤0.05).

Table 3. Analysis of variance for leaf area growth per plant, dry weight of the blade and sheath of the leaf, dry weight of the root, bracts, total biomass and grain yield of the native corn, S-S 2024 cycle.

SV	DF	LA	DWS	DWBL	DWSH	DWR	DWBR	TB	YL
G	16	5794103*	4856*	359*	338*	5215*	355*	31104*	7943*
R	4	978357^{ns}	421^{ns}	29^{ns}	13^{ns}	640^{ns}	19^{ns}	4135^{ns}	584^{ns}
Error	64	549106	614.7	51.9	35.0	1467	26.1	4831	530
Total	84								
C.V.%		10.7	31.1	54.4	28.3	70.7	21.4	25.6	29.0

SV=source of variation; CV=coefficient of variation; DF=degrees of freedom; R=repetition; G=genotype; LA=leaf área growth per plant; DWBL=leaf blade dry weight; DWSH=sheath dry weight; DWS=stem dry weight; DWR=root dry weight; DWBR=bracts dry weight; TB=total biomass; YL=grain yield. *=P≤0.05; ^{ns}=no significative.

(28 days) to heat (38 °C) causes even more serious effects on the LAG, with a reduction of 72% in net photosynthetic rate (Aziz *et al.*, 2023). Hatfield and Prueger (2015), found that the greater impact of high temperatures was produced during the reproductive stage of corn development and, in every case, the grain yield was significantly reduced, up to 90% compared to normal temperature.

The amounts estimated, recorded in Table 4, indicate that the highest proportions of dry matter were found in the SW with 30%, grain weight (GY) with 29%, and RW with 19%, and the lowest % in LBW with 5%, LSW with 8%, and BW with 9%. Likewise, significant changes were seen, since Piix cristo and Chaak Choob presented higher SW with 132 g; meanwhile, Kằn Kằn xnuc naal obtained the highest BW with 35 g. A high allotment to the plant stem would be the result of the plant maximizing photosynthesis, which produces more photosynthates than necessary to meet the growth demands of the roots and leaves (Walne and Reddy, 2022).

When comparing the LBW, LSW, RW and TB of the genotypes, it was observed that Piix cristo was superior (P≤0.05) with the exception of GY. However, the impact of the thermal and water stress was higher in Morado MX; since it had lower SW, LBW, LSW, RW, BW, TB and GY, because during the vegetative stage and floral initiation (Figure 1 and 2), the high temperatures and water deficit affected the growth (Zhu *et al.*, 2021), fertilization, development of the corncob and yield (Chen *et al.*, 2023). Brief and prolonged episodes from high temperatures during the corn growth cycle (especially in the most

Table 4. Means comparison based on dry weight of native corn, S-S 2024 cycle.

Genotype	DWS	DWBL	DWSH	DWR	DWBR	TB
	g					
Saak tux	62 cd	6 c	16 def	39 bc	17 de	237 b
Eh hu	119 ab	27 ab	30 abc	100 ab	13 e	320 ab
Piix cristo	132 a	39 a	39 a	146 a	22 b-e	412 a
Chaac xmejen naal	68 bcd	13 bc	19 c-f	52 bc	24 a-e	234 b
Kằn Kằn teel	61 cd	7 c	15 ef	75 abc	31 abc	280 ab
Kằn Kằn xnuc naal	73 bcd	16 bc	29 a-d	66 abc	35 a	356 ab
Saak Chan Teel	72 bcd	9 c	19 c-f	66 abc	24 a-e	242 b
Eju	121 ab	14 bc	33 ab	60 abc	21 cde	293 ab
Chaak Choob	133 a	19 bc	25 b-e	65 abc	20 cde	319 ab
Tuxpeño	70 bcd	12 bc	20 b-e	34 bc	33 ab	294 ab
Chaak teel	60 cd	10 c	18 c-f	28 bc	27 a-d	243 b
Saak dzit baakal	106 abc	11 bc	24 b-e	44 bc	31abc	347 ab
San Pableño Blanco	74 bcd	8 c	19 c-f	37 bc	28 a-d	285 ab
Kằn Kằn dzit baakal	69 bcd	7 c	15 ef	31 bc	24 a-e	221 b
San Pableño Amarillo	53 cd	11 bc	13 ef	26 bc	25 a-d	211 b
Rosa San Juan	56 cd	7 c	15 ef	44 bc	30 abc	262 ab
Morado MX	23 d	9 c	6f	8 c	0 f	46 c

Mean values per column with different letters are statistically different (P≤0.05). DWBL=leaf blade dry weight; DWSH=sheath dry weight; DWS=stem dry weight; DWR=root dry weight; DWBR=bracts dry weight; and TB=total biomass.

critical stage of flowering) cause metabolic and/or morphological alterations, which lead to irreversible reductions of the yield (Wagas *et al.*, 2021). Water stress inhibits corn growth, stem and root length, antioxidant activity, relative water content (RWA) and germination of the seeds. In addition, it causes the loss of turgidity and a decrease in the hormonal content (Rasheed *et al.*, 2023).

In this context, Saak dzit baakal and Kȁn Kȁn xnuc naal were the ones that presented highest GY with 131 and 137 g (Figure 2), and this could be because these genotypes presented higher tolerance to thermal and water stress during the physiological stages (MF, FF, PM), since they also presented higher LAG, BW and TB compared to Morado MX which presented more sensitivity to both stresses. Therefore, the effects of the thermal and water stress on growth, dry matter and GY (Figure 2) depend on the genotype (Shao *et al.*, 2023). In addition, the sensitivity to drought (Sah *et al.*, 2020) and high temperatures (Zhu *et al.*, 2021) could reduce the GY in different degrees based on the seriousness of stress and the development stage of the plant.

The results presented here agree with those reported by Rincón-Tuexi *et al.* (2006), since they found that temperatures higher than 35 °C caused a significant reduction of aerial biomass and grain yield in corn populations, and all the organs of the plant are affected except for the bracts; the reduction in grain yield caused by the high temperature was mainly a result of the reduction in number of grains per corncob (73%). All the variables were correlated between one another in a positive way, except for the GY with SW, LBW, LSW, RW (Figure 3).

The highest correlations were between the LSW with SW (0.88) and TB (0.85); LBW-RW (0.85), GY-BW (0.84), LSW-RW (0.81), LBW-LSW (0.80), TB-SW (0.78) and LAG-TB (0.75) (Figure 3). That is, higher LAG contributed positively to a higher TB; for this study, this association was negative for Morado MX and positive for Saak dzit baakal and Kȁn Kȁn xnuc naal (Figure 1 and 2, Table 4). Other similar studies (Umer *et al.*, 2020) show that LAG is positively correlated with GY. The negative correlations observed between GY and SW, LBW, LSW, RW can happen because of limiting factors such as water stress and high

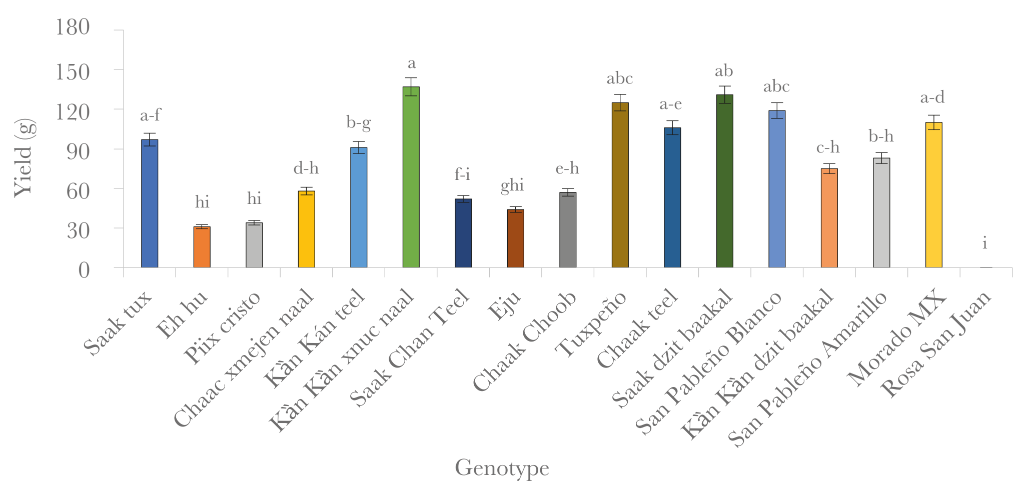

Figure 2. Means comparison of the grain yield, S-S 2024 cycle. Mean values per column with different letter are statistically different (P≤0.05).

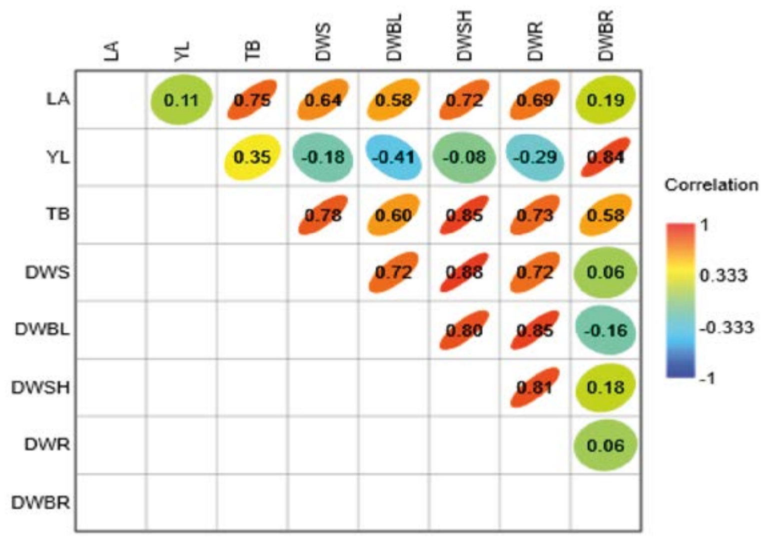

Figure 3. Pearson's correlation coefficient from agronomic characteristics of native corn, S-S 2024 cycle. LAG=leaf area growth accumulated per plant; LBW and LSW=dry weight of the leaf blade and leaf sheath; SW, RW, BW=dry weight of stem, root, bracts, and TB=total biomass.

temperatures that affect yield significantly, that is, the distribution of plant assimilates is diverted from the main objective (grains) and directed to the growth of its vegetative parts (Quintero and Escalante *et al.*, 2025).

CONCLUSION

The 17 genotypes studied show different thresholds in the requirements of Tb and GDD, which expresses their versatility and broad climatic adaptation; likewise, a significant variation was found for the growth, biomass and yield between native corn genotypes. The best expression, on average, was obtained with the genotype Saak dzit baakal and Kǎn Kǎn xnuc naal, and this genetic variability based on thermal and water stress can be integrated into programs of genetic improvement that seek the adaptation of crops to climate change, thus contributing to food security.

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