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Effects of different temperatures and water stress in germination and initial growth of creole genotypes of maize from three different agroclimatic regions of San Luis Potosí (México)

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Abstract

Most of the studies on the effects of climate change on maize have been carried out on grain yield; few have been centred on germination and growth. In this investigation, experiments were carried out at different temperatures and water stress to evaluate the germination and initial growth of 12 creole maize genotypes from different agroclimatics regions of San Luis Potosí. The temperatures were 20, 25, 30 and 35 °C, proposed for having relation with the scenarios of temperature increase due to climate change in San Luis Potosí. The simulation of the water stress was carried out by the use of PEG-8000 (-0.5, -1 and -1.5 MPa), a control (0 MPa) was used. Four repetitions of 25 seeds for each creole genotype were carried out under a design at random with factorial arrangement. Germination and initial growth of the genotypes were negatively affected by the increase of temperature and decrease of water stress. Also these results were depended by the genetics materials origins and the climatic characteristics of each agroclimatic region of the state. In addition, the genotypes from less conditions of stress (*Huasteca*) were the most affected in comparison to materials from unfavorable conditions for the growth of maize plants (regions *Altiplano* and *Media*). Results suggest that the particular conditions of each region has influenced in the dynamic of germination and growth. We concluded, the related effects of climate change have affected differently and negatively the germination and initial growth of early maize from different agroclimatic regions.

Introduction

In Mexico, climate change can cause an increment of the average annual temperature from 1 to 4 °C and changes in the average yearly precipitation from 0.4 to 1.4 times during the present century, in function of the scenario of the population growth (IPCC, 2007). Climate change is a modification in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity (IPCC, 2013).

Temperature and water supply are critical drivers for seed (initiation, break) and germination. Hence, global climate change is altering these environmental cues and will preclude, delay, or enhance regeneration from seeds, as already documented in some cases. Along with compromised seedling emergence and vigour, shifts in germination phenology will influence population dynamics, and thus, species composition and diversity of communities (Walck *et al.*, 2011a). A scenario of rising temperatures, declining rainfall, increase in extreme weather conditions, and shifting pest and disease patterns will lead to more short-term crop failures and long-term production declines (Kang and Banga 2013; Chauhan *et al.* 2014). The increase in temperature and the intensification of droughts due to the consequence of climate change have brought negative effects in ecophysiological processes such as germination and establishment of seedlings (Walck *et al.*, 2011b; Aragon-Gastelumet *et al.*, 2017). Recent evidence shows that maize (*Zea mays* L.) is relatively more sensitive to high temperature and drought stress during sensitive stages of gametogenesis, flowering, and early grain filling stages of crop development (Prasad *et al.*, 2020).

Maize is the most important cereal cultivated in Mexico (FAO, 2018; García-Lara and Serna-Saldivar, 2019), and Mexico is considered the center of origin and domestication of maize and one of the most important centers in its diversity (Matsuoka *et al.*, 2002). The genetic variability of the maize constitutes a wealth for the population and it can be the base to achieve the domestic alimentary sovereignty, especially in the face of the changes in climate (Preciado Ortiz and Montes Hernandez, 2011). According to Cabrera *et al.* (2002), 76.5% of the Mexican farmers use creole seeds for its cultivation and that use depends mainly on the type of agriculture; however, in the regions with typical rural agriculture 80 to 100% of the farmers use creole seed fundamentally for its production. However, their production is generally limited for a series of factors like drought, plagues and diseases among others that represent economic losses particularly for smallholder farmers (Bergvinson, 2004).

The state of San Luis Potosi (S.L.P.) has been considered as a potential source of genetic variation in maize. Fourteen variants of maize have been documented in a study (Ávila-Perches *et al.*, 2010a). The high abundanceof the maize variants in the state can be due to wide diversity of the surroundings, in way similar to what happens in the Mexican territory. This way, it is possible to recognize different agroecological regions, from the warm and humid climatic conditions to the dry and hot or temperate ones (INEGI, 2012). Nevertheless, it is probable that the abundance of the maize variants in the state are much bigger that consigned by Ávila-Perches *et al.* (2010b) because just in three towns of the *Huasteca*, a region that represent a fraction of the whole territory of S.L.P., 11 different variants were registered (Heindorf*et al.*, 2019).

It is proposed that the temperature values in S.L.P. will increase for a short-term scenario (2010-2040) and long term (2070-2100) (Medellín-Milan *et al.*, 2006; Ávalos Lozano *et al.*, 2017a). Also, the variation in the quantity of rain received in a month through the successive years is very big. Algara Siller *et al.* (2009) and Espinoza Jiménez & Gómez Mendoza (2019a) have also indicated the presence of drought in the state of S.L.P. It is probable that such an increase in temperature promotes, or associate with a decrease in the quantity of rain, will impact in the availability of water in soil and it will generate modifications like changes in the agricultural calendar, phenological alterations, and decrease of yields, like it has been documented in Sinaloa in crop production of maize, bean (*Phaseolus vulgaris*), potato (*Solanum tuberosum*), red tomato (*Solanum lycopersicum*) among others (Ojeda-Bustamante *et al.*, 2011). In the state of S.L.P. nearly 14,000 ha of maize are cultivated annually, of which a high proportion, around 80%, is cultivated under dry conditions (SIAP, 2017). Hence, the production of maize depends in great measure of the tolerance from the adapted genotypes of maize to conditions variables and many extreme times from the climate. This fact can mean the existence of highly adaptable creole genotypes of maize to adverse environmental conditions, what means an opportunity of use of such phylogenetic resources.

The study of the results of creole genotypes of maize coming from different conditions can help to determine and understand how the species of maize adapt to environmental conditions they face during their development and establishment, which is necessary to predict some of the effects related to climate change in the abundance and distribution of species (Dávila *et al.*, 2013). Also, the abundance of the breed and/or creole genotypes of maize and their adaptations to diverse environmental conditions could represent alternatives to cultivate in scenarios that are poised to occur due to effects of climate change. The objective of this work was to evaluate the germination and initial growth of creole genotypes of maize coming from different agroclimaticregions at different temperatures and water stress (drought) under laboratory conditions. The above-mentioned, with the hypothesis that germination and initial growth of creole genotypes adapted to specific local conditions respond differently and in dependence of their origins when exposed to related effects of climate change.

Material and methods

Selection of creole genotypes of maize

The materials evaluated were collected in the state of S.L.P., in which, with basis on the mean annual of temperature and precipitation; three areas were identified whose average temperature and precipitation are around 14.5, 18.5 and 22.5 °C; 400, 700 and 1200 mm respectively (Noyola-Medrano *et al.*, 2009a). Such areas were denominated *Altiplano*, *Media* and *Huasteca* respectively, and some features are described (Figure 1 and Table 1). A total of 37 distributed samples were obtained in the following way: 10 from the region of *Altiplano*, 11 from *Media* and 16 from *Huasteca*.

The collected samples were assessed as established by Carballo & Benitez (2003). This way a total of 14 variables were described: longitude (cm), diameter (mm) and conicity of cob, number of rows per cob, number

Table 1 - Denomination of evaluated genotypes, climatic characteristics and futures scenarios of temperature based on the mean annual temperatures (M.A.T.) of the three regions from the state of San Luis Potosí, México.

Genotypes	Region	Predominate climate based on modifications of the Köppen climate classification system and M.A.T.	Future mean annual temperature (M.A.T.) in short term (2010-2040) (M.A.T. + 0.75-1 °C)	Future mean annual temperature (M.A.T.) in long term (2070-2100 M.A.T. + 2.75-3.0 °C))
A3	*Altiplano*	BS1kw(e)gw" BSohw(e) gw"14.5 °C	15.25-15.5 °C	17.25-17.5 °C
A4				
A8				
A9				
A10				
M2	*Media*	Cb(w2)(w)(I') 18.5 °C	19.25-19.5 °C	21.25-21.5 °C
M4				
M11				
H4	*Huasteca*	(A)Cam(f)(e)w" Am(e)gw" 22.5 °C	23.25-23.5 °C	25.25-25.5 °C
H9				
H10				
H11				

References: García, 2004.IPCC, 2013b; Ávalos Lozano *et al.*, 2017b.

of grains per row, row arrangement, color and grain type, dry weight of 100 seeds (g), volume (mL) of 100 seeds in 50 mL, longitude (mm); thickness (mm) and wide (mm) of grain, phenological term (months). On the previous data were added,data on thermal and rainfall conditions facilitated by the producer. Such information was systematized with the following scale: low, regular and high.

With the objective of containing the samples in conglomerates (clusters) with high grade of internal homogeneity and external heterogeneity among the samples (Sanjinez and Julca, 2019), and to select representative samples from the all collected, a multivariate analysis was carried out to form groups. For

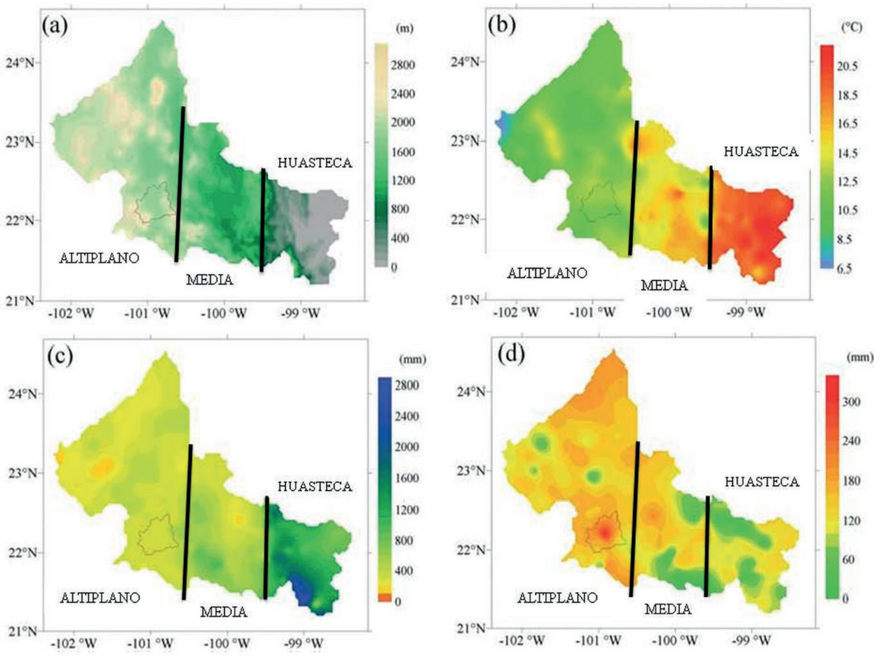

Fig. 1 - Horizontal distribution of (a) field elevation, (b) annual mean temperature, (c) annual mean precipitation, (d) annual mean evaporation of the three agroclimatics regions of the state of San Luis Potosí. Adapted from Noyola-Medrano et al. (2009b).

processing the statistical software Statistical Analysis System (SAS) 9 was used.The resulting groups of the cluster analysis used in this investigation were: white maize's of 5 months of life cycle (genotypes A3, A4 and A8), white maize of 3 months (genotype A9) and purple maize (genotype A10) of 4 months of the region of *Altiplano*; white maize of 4 months (genotype M2), purple maize of 3 months (genotype M4) and black maize of 3 months (genotype M11) of the region of *Media*, white maize's of 4 and 3 months (genotypes H4 and H11 respectively) and yellow maize's of 3 months (genotypes H9 and H10) of the region of *Huasteca*.

Treatments of temperature and simulation of water stress

Germination experiments were conducted in controlled conditions of constant temperature (20, 25, 30 and 35 °C) and water potential [0 (control), -0.5, -1.0, and -1.5 MPa]. The temperatures were proposed for having relationship with scenarios of increase temperature due to effects of climate change (Figure 1 and Table 1). The conditions of soil humidity were determined at different levels of water potential since a very big variation in the quantity of rain received in a month through the successive years is expected (Espinoza-Jimenez and Gómez-Mendoza, 2019b).

The simulation of water deficit in the substrates was carried out with polyethyleneglycol 8000 (PEG-8000) as solution, with the purpose of simulating variations in the availability of soil humidity (Villalobos and Peláez, 2001; Huang *et al.*, 2018). This solution was used because it has been documented that it doesn't present toxicity on seeds (Khalil *et al.*, 2001). A control was also used with water potential of 0 MPa from deionized water.

To know the quantity of necessary PEG-8000 to obtain the potential water desired, the formula proposed by Burlyn (1983) was used:

$$\mathrm{PEG} = \frac{4 - (5.16\,\varphi\,T - 560\,\varphi + 16)^{0.5}}{(2.58T - 280)}$$

Where:

PEG: Kg of PEG per liter of deionized water

φ: Required water potential in bars (1 bar= 0.1 MPa)

T: Temperature of prepared solution

The three water potentials (-0.5, -1 and -1.5 MPa) were obtained by mixing deionized water and 145, 290 and 400 g L^{-1} of PEG-8000 respectively. Water potential of each solution was measured in psychometric chambers (Wescor, Logan, UT, USA). Samples of the solutions were taken approximately 2 mL and were placed in plastic trays in circular way 40 mm of diameter by 12 mm deep. The measurements obtained allowed to verify the levels of the wanted potentials.

Experimental Design

The experiment included a total of 192 treatments that resulted to a factorial arrangement of 4 x 4 x 12, with four repetitions. The temperature factor with four levels (20, 25, 30 and 35 °C), water stress with four levels (0, -0.5, -1 and -1.5 MPa) and the last factor represented by the 12 creole genotypes. Each experimental unit consisted of 25 seeds for creole genotype and the experimental units were distributed at random in a design of complete blocks.

Before sowing, the seeds were disinfected submerging them during 3 min in a solution of commercial chlorine (hypochlorite of sodium to 10%) (Viloria and Méndez Natera, 2011) and were then washed with abundant water to eliminate the excess of chlorine. Later on, the seeds were placed on filter paper, previously humidified with the solution of corresponding PEG, inside a plastic tray of 14 cm of long, 18 cm of wide and 8 cm of height. At once, the seeds were placed under predefined temperatures inside a chamber for plant growth at a neuter photoperiod of 12 hours light with the different levels of water potential.

Germination variables

Percentage of germination (PG)

A germinated seed is considered as one which has a root length of more than or equal to 2 mm. PG was calculated using the following formula (Scott *et al.*, 1983):

$$PG = \frac{(\text{Number of germinated seeds})}{(\text{Number of seeds sowed})} \times 100$$

It was determined at 15 days after sowing, instead of the seven days indicated by the International Seed Testing Association (ISTA) methodology. Other investigators have evaluated the germination of maize at 12 days (Laynez-Garsaball*et al.*, 2007a), at 13, 14 and 15 days (Zagal-Tranquilino *et al.*, 2015), and at 16 days (Badr *et al.*, 2020).

Mean germination time (MGT)

It was determined according to the formula (Labouriau, 1983) at 15 days after sowing:

$$MGT = (\Sigma n_i t_i)/\Sigma n_i$$

Where:

n_i: is the number of seeds germinated at day i (not the accumulated number, but the number corresponding

Table 2 - Mean squares (MS) from the analysis of variance of the percentage of germination (PG) and the mean germination time (MGT) of creole genotypes of maize from the state of San Luis Potosi at 15 days after sowing.

Factors		PG		MGT	
	DF	MS	F-value	MS	F-value
Genotype (G)	11	9.1***	32.7	3.82***	23.29
Water stress (WS)	3	69***	906.8	83.75***	509.51
Temperature (T)	3	3.2***	42.05	5.6***	34.1
G x WS	33	3.4***	4.07	0.62***	3.79
G x T	33	8.5***	10.11	1.37***	8.34
WS x T	8	2.4***	11.77	1.38***	8.42
G x WS x T	74	7.5***	4.02	0.65***	3.97

DF: Degree of freedom; *** highly significant (P<0.001) according to Tukey test.

to the ith observation)

t_i: is the period from the start of the experiment to the ith observation (day)

Variables of growth

The variables of growth were determined for 15 seedlings per experimental unit at 16 days after sowing in two levels of water potential (0 MPa (control) and -0.5 MPa).

Rate of growth (RG) (mm.day^{-1})

Rate of growth (RG) was defined as the increment in longitude of the longest leaf and it was calculated in a period of 10 days. The following equation was used (Del Pozo*et al.*, 1987):

$$RG=(L2-L1)/(T2-T1)$$

Where:

$L1$ and $L2$ are the longitudes of the seedlings at 5 and 15 days respectively while $T1$ and $T2$ are the previously mentioned times.

Root length (RL) (cm)

Root length (RL) was determined with a rule graduated in cm starting from the root of major longitude.

Dry weight of shoots (DWS) and root (DWR) (g)

The samples were weighed, then dried off in stove at 70°C during 72 hours (Laynez-Garsaball *et al.*, 2007b) and weighed in an analytic balance (Ohaus Compass™).

Statistical analysis

The data were submitted to an analysis of variance, using the procedure PROC GLM of the program Statistical Analysis System (SAS, 2003). The model consists of three fixed factors,'genotypes', 'temperatures' and 'water stress' and their interaction 'genotype x temperature x water stress'. Significant differences among the treatment means were then analyzed using the Tukey tests. The effects were considered significant if P < 0.05. Prior to the analysis, data were checked for normality and log-transformation was used to correct them.The level of significance was set at 5%.

Results and discussion

Germination variables

Based on the analysis of variance it was possible to observe significant effects of the genotypes, the water stress and temperatures. Also the interactions of the factors evaluated were significant (P< 0.001) for the germination variables (Table 2).

Percentage of germination (PG)

The percentages of germination (PG) tend to reduce as water potential decreased; however, diminishing of PG varied depending on the creole genotypes and the temperatures (Table 2). At 0 MPa, the PG of genotypes from *Huasteca* was more affected by temperature variation than those from *Altiplano* and *Media*. The best germination percentages, with values highest than 96%, were registered in principally in genotypes from *Altiplano* and *Media*, even if genotypes A4 and A10 registered a reduced PG at 25 °C and 35 °C. The PG of the genotypes from *Huasteca* resulted highly reduced by variation of temperature in H4, H10 and H11 but in different way. In H4, 20-30 °C temperatures averaged a PG of 87% but it dropped to 13% at 35 °C, in H10 a gradual reduction of PG from 100% to 5% was registered along temperature increased. The PG of H11 was less than the half of all other genotypes (Figure 2a).

The temperatures promoted differentials reactions of PG in the water potential of -0.5 MPa. The genotypes

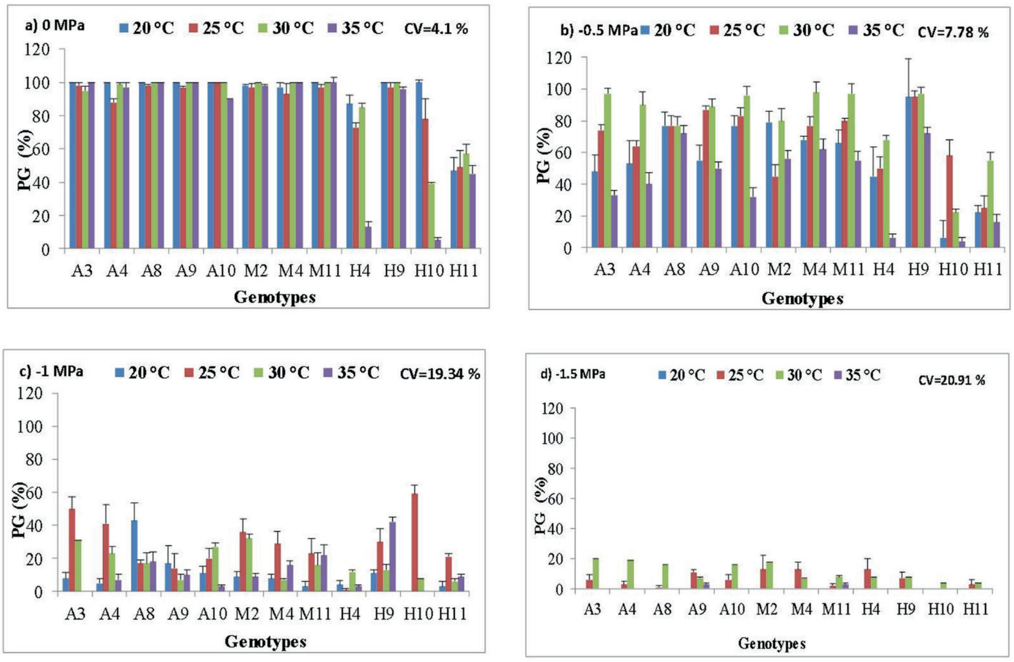

Fig. 2 - Effect of different water potentials [a) 0,b) -0.5,c) -1,d) -1.5 MPa] and temperatures (20, 25, 30 and 35 °C) in the percentage of germination (PG) of creole genotypes of maize from different regions of the state of San Luis Potosi. A: Altiplano, M: Media, H: Huasteca. The vertical bars indicate the standard error (n=4).

from *Altiplano*, *media* and H9 presented the highest PG at 25 and 30 °C. At 35 °C, the same genotypes reduced up to more than 50% their PG. The PG of the genotypes from *Huasteca* resulted highly influenced by variation of temperature in H4, H10 and H11. H4 and H11 registered an increment of PG between 20 and 30 °C but drastically reduced at 35 °C until 6% and 16% respectively. However H10 registered an average of 10.6% at 20, 25 and 35 °C while at 25 °C had the best PG with 58% (Figure 2b).

At -1 MPa, the PG of the creole genotypes of the *Media* was highly affected by the temperature factor while for those from *Altiplano* and *Huasteca* responded differently for temperature variation. In the same way, the creole genotypes from the *Media* registered the best PG at 25 °C with an average of 29% however those values decreased at the maximum temperature (35 °C) until 18%. For those from the *Altiplano* A3 and A4 registered the best values at 25 °C with an average of 46% while for the creole A8, A9 and A10 the best PG varied for each temperature. In addition the creole genotypes of the *Huasteca* were the most affected, specifically H4 and H11. However H9 and H10 responded differently by the variation of temperature. For that H9 registered best PG at 25 and 35 °C with 30 and 42% respectively (Figure 2c).

In a more extreme water stress (-1.5 MPa), germination was registered in all materials only at 30 °C although it was not more than 20%. At 25 °C, all of the materials germinated although all below 15%. At 20 °C none of the genotypes germinated. At 35 °C, only the creole genotypes A9 and M11 registered a PG value of 3%, all the other materials did not register any germination (Figure 2d).

The germination response of creole genotypes of maize seeds was significantly affected by drought stress induced by PEG solutions and temperature. These findings extend those of Queiroz *et al.* (2019a) and Pawar *et al.* (2020), confirming that a water potential in a negative gradient tends to reduce the PG of maize seeds. In addition, the results noted in our study were related to temperature and creole genotypes. This study therefore indicates that creole genotypes from different regions responded differently for temperature; results were more accentuated at -1 and -1.5 MPa. Ramírez-Tobias *et al.* (2014) found that the germination of Agave species seeds decreased on dependence of species by up to 50% when water potential drops to -1.5 MPa. For the extreme stress (-1.5 MPa) at 20 °C, the maize creole genotypes did not germinate. Fancelli and Dourado-Neto (2000) stated that the temperature suitable for the germination of maize varies between 25 and 30 °C. Sans& Santana (2005) reported germination of maize may not occur at temperatures higher than 40 °C or near to 10 °C. Also, Borba *et al.* (1995) and dos Santos *et al.* (2019) reported that temperatures above 35 °C cause a significant decline in germination percentage of maize.

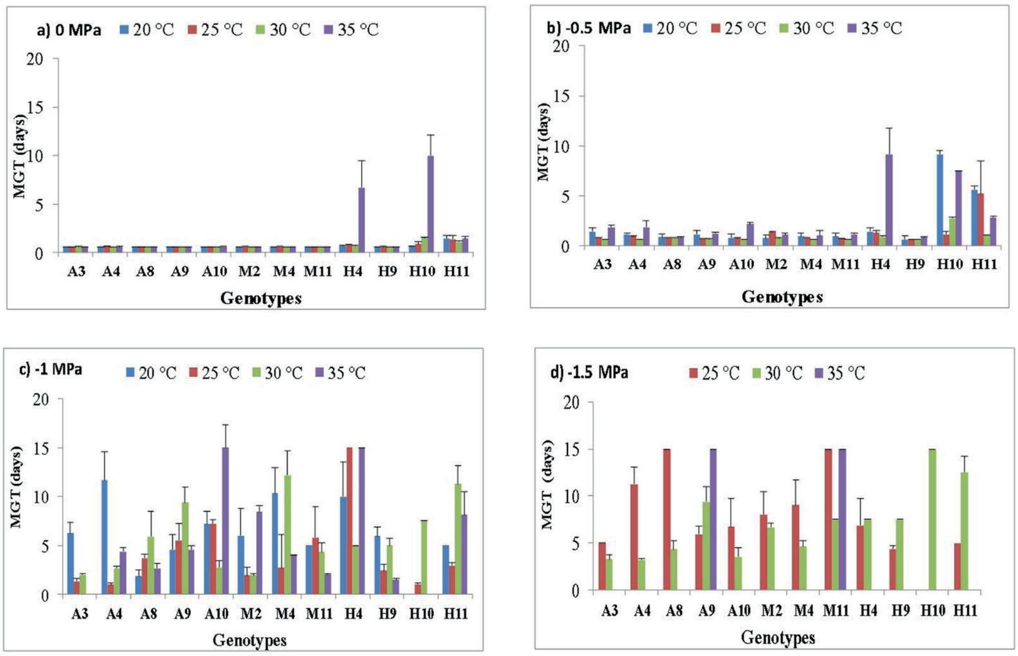

Fig. 3 - Effect of different water potentials [a) 0, b) -0.5, c) -1,d)-1.5 MPa] and temperatures (20, 25, 30 and 35 °C) in the mean germination time (MGT) of the creole genotypes of maize from different regions of the state of San Luis Potosi. A: Altiplano; M: Media, H: Huasteca. MGT at 20 °C in d) did not exist because the creole genotypes did not germinate at this temperature and water potential (-1.5 MPa). Vertical bars show the standard error (n=4).

Mean germination time (MGT)

The number of days for seeds to germinate increased when the water potential decreased; however, increment of the number of days for seed to germinate varied depending on the genotypes and temperatures. The genotypes from *Huasteca*, specifically H4 and H9, took more time to germinate at 35 °C and 0 MPa. In addition, all the others creole genotypes from *Altiplano* and *Media* took between 0.6 to 1.5 days to start germinating independently for the temperature (Figure 3a).

At water potential -0.5 MPa, the MGT varied by the creole genotypes and temperatures as in 0MPa. In the same way, the most affected creole genotypes were from *Huasteca* but at 20, 25 and 35 °C. The maximum time to start germination was between 9.2-5.2 days. However the genotypes from *Altiplano* and *Media* responded equals no matter the temperature. Besides, they took between 0.6-2.2 days to start germinating (Figure 3b).

At -1 MPa, all the creole genotypes took more time to germinate than those observed at 0 MPa. These values were associated with creole genotypes and temperatures. For genotypes from *Huasteca*, the majority of them took less time to germinate at 25 and 30 °C between 1.5-2.5 days. In addition for genotypes from *Media* and *Altiplano*, most of them registered less time at 25, 30 and 35 °C however this response depended for each genotype and took between 1.9-4.3 and 1.3-4.6 days respectively (Figure 3c).

At -1.5 MPa, the MGT varied depending creole genotypes and temperatures. Also they took more time to germinate in comparison to 0, -0.5 and -1 MPa. The genotypes did not germinate at 20 °C. In addition, all the genotypes from *Altiplano* and *Media* took less time to start germination at 30 °C with an average of 5-6 days while genotypes from *Huasteca* registered the less MGT at 25 °C with an average of 5 days (Figure 3d).

Our results reveal more negative is the water potential, longer it takes for the creole genotypes to germinate. This variable is important since it explains the time it takes for seeds to germinate after being embedded and thus take advantage of the short periods of rain, especially in arid and semi-arid areas (De la Barrera and Nobel, 2003). The results confirmed that the MGT dependent on the creole genotypes and temperatures (Tsougkrianis *et al.*, 2009). According to Dürr *et al.* (2015) the base temperature for 241 species (including maize) to germinate were below 0 °C and below 20 °C and this results may due to the climatic conditions where the species grow or originated. Low temperatures delay germination, decrease reserve mobilization, and consequently the emergence velocity (Cruz *et al.*, 2007). In the case of high temperatures, the biochemical processes of reserve mobilizationare negatively af-

Table 3 - Means squares (MS) from the analysis of variance of the growth variables of the creole genotypes of maize from the state of San Luis Potosi at 16 days after germination.

Factors	DF	RG		RL		DWS		DWR	
		MS	F	MS	F	MS	F	MS	F
Genotype (G)	11	21.5*	49.2	0.26*	19.34	0.02*	29.16	0.05*	47.2
Water Stress (WS)	1	19.2*	43.9	5.64*	419.1	0.45*	451.4	0.41*	367.4
Temperature (T)	3	905.3*	2074.8	2.39*	177.8	0.24*	240.8	0.09*	84.8
G x WS	11	4.47*	10.25	0.15*	11.66	0.002*	1.85	0.02*	16.5
G x T	33	11.67*	26.76	0.18*	14.03	0.014*	14.38	0.03*	27.2
WS x T	3	92.45*	211.9	0.33*	24.73	0.009*	8.8	0.03*	29.3
G x WS x T	33	6.5***	14.96	0.07***	5.75	0.002*	1.81	0.006*	5.2

DF: degree of freedom, F: F-value; RG: rate of growth; RL: root length; DWS: dry weight of shoots; DWR: dry weight of root; *, ***: significant at $P<0.05$ and $P<0.001$, respectively.

fected, due to low water availability. In addition, it may alter the constitution of cell membranes, affecting metabolic processes, especially cellular respiration (Taiz & Zeiger, 2004). For the factor water stress, Campos *et al.* (2020) recorded in succulents (*Agave lechuguilla* Torr. And *Agave salmiana* Otto ex Salm-Dyck) the time to reach maximum germination increases at more negative water potential. For corn germination in water stress conditions, the germination speed index expressed in seeds.day^{-1} decreases as the water potential decreases (Khatami *et al.* 2015; Santos *et al.,* 2016).

Variables of growth

The results of the analysis of variance showed significant effects ($P < 0.05$) for the main effects of creole genotypes, water potential levels and temperature, as well as significant interactions, for the variables evaluated. The significant interaction between the main effects of the factors (genotypes, water stress and temperature) indicates that genotypes have a distinct response when exposed to different drought levels and temperature (Table 3).

Rate of growth (RG)

High variation of the RG was registered among combination of temperatures, genotypes and water potential; however, tendencies due to reduction of water potential and temperature change were observed. Reduction of water potential promotes different patterns of RG values as temperature changed and a reduction of average RG. The RG of creole genotypes was drastically reduced with the decrease of water potential level from 0 to -0.5 MPa, in average of 30% respect to that obtained at 0 MPa. Maximum values of rate of growth (RG) were observed at 20 and 30 °C for all of the genotypes at 0 MPa and for genotypes from *Media* and *Huasteca* at -0.5 MPa. However, on genotypes from *Altiplano*, the maximum RG values only occurred at 30 °C. These maximum RG values doubled those registered at 25 and 35 °C (Figure 4). Then the seedlings growth velocity depended on the temperature and the origin of the genotypes.

According to Espinosa *et al.* (2015) the first process affected by the effect of water deficit is growth, which

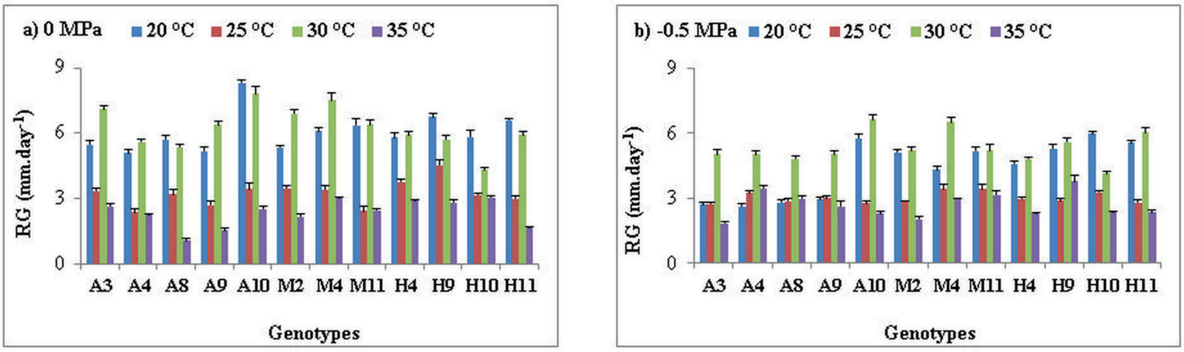

Fig. 4 - Effect of different water potentials [a) 0,b) -0.5 MPa] and temperatures (20, 25, 30 and 35 °C) on the rate growth (RG) of creole genotypes of maize from different regions of the state of San Luis Potosí. A: Altiplano; M: Media, H: Huasteca. Vertical bars indicate the standard error (n= 15).

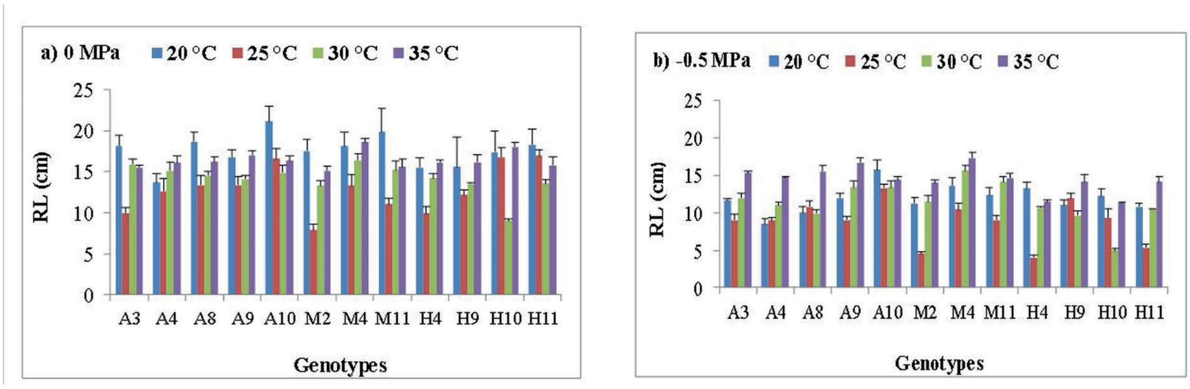

Fig. 5 - Effect of different water potentials [a) 0,b) -0.5 MPa] and temperatures (20, 25, 30 and 35 °C) on the root length (RL) of creole genotypes of maize from different regions of the state of San Luis Potosí. A: Altiplano; M: Media, H: Huasteca. Vertical bars indicate the standard error (n= 15).

begins with the germination, which comprises the imbibition, metabolism and growth start phases of the structures found in the embryo. Heat stress (27-35 °C during 14 days for maize (Virdi, 2016)) can induce irreversible damage to crop growth and yield (Fahad *et al.*, 2017). It was found that a combination of drought and heat stress had a significant detriment effect on the growth in two contrasting maize landraces (Castro-Nava *et al.*, 2014). Seedlings that emerge more quickly have higher time to develop compared to those that germinate later, and may have increased in seedling length (Queiroz *et al.*, 2019b). Our results agree with this seedling growth dynamic because less growth was registered in germinated seedlings under water stress and high temperature (35 °C). Also at 25 °C the creole genotypes reduced their RG no matter the water potential and this effect can be associated to the temperatures that they are adapted during the initial growth contrary to the recommended temperature for corn growth as indicated Sun *et al.* (2017).

Root length (RL)

The root length of the maize genotypes was significantly affected by the combination of different temperatures and drought stress. That response presented differences depending on precedence of the creole genotypes. All the creole genotypes registered their maximum values of RL at 20 and 35 °C, but a fall of 21% at 25 and 30 °C in 0 MPa (Figure 5a). The minimum values of RL were observed in genotypes from *Altiplano* and *Media* in the two water potentials at 25 °C however for some genotypes from *Huasteca* the minimum RL moved at 30 °C. Reduction of water potential from 0 to -0.5 MPa decreased average RL to 35%. At -0.5 MPa, the RL at 20 °C tended to go down respect to 0 MPa (Figure 5b).

Trachsel *et al.* (2010) found that high temperature reduced RL of tropical maize seedlings. Similarly, Seiler *et al.* (1998) showed that increasing the root-zone temperature for sunflowers in growth pouches from 25 to 35 °C largely reduced length of the primary and lateral roots as well as the number of lateral roots. An increase in root-zone temperature from 22 to 38 °C for wheat grown hydroponically reduced the overall root length by 40

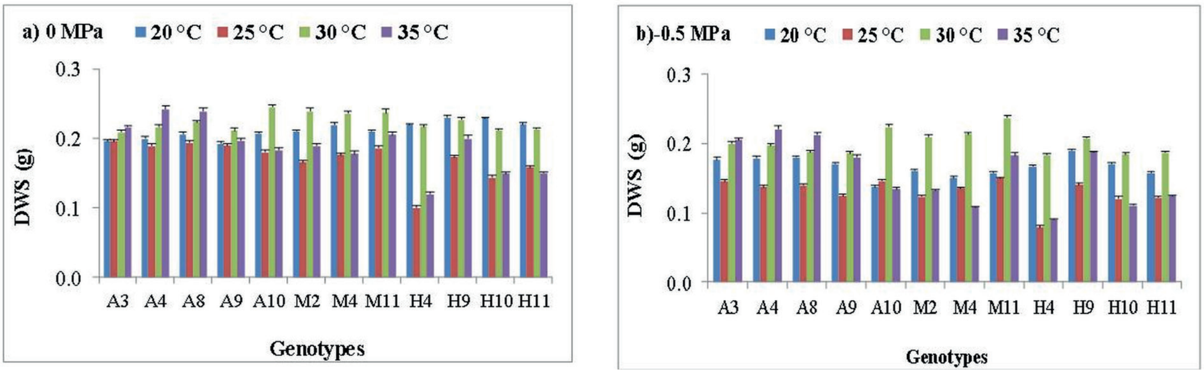

Fig. 6 - Effect of different water potentials [a) 0,b) -0.5 MPa] and temperatures (20, 25, 30 and 35 °C) on dry weight of shoots (DWS) of creole genotypes of maize from different regions of the state of San Luis Potosí. A: Altiplano; M: Media, H: Huasteca. Vertical bars indicate the standard error (n= 15).

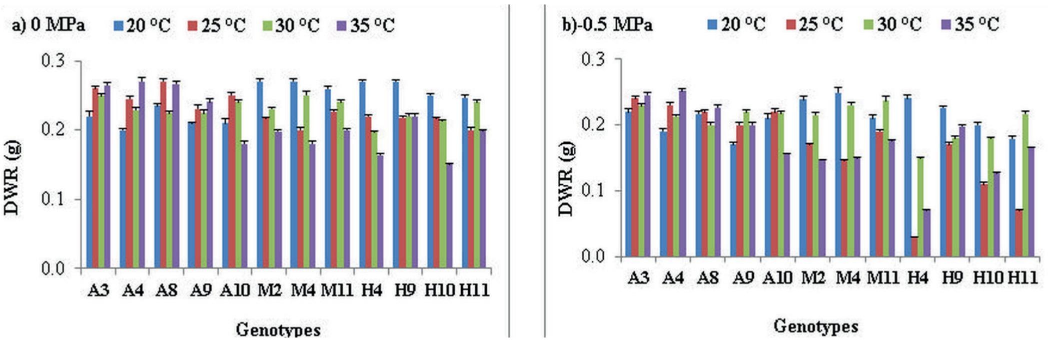

Fig. 7 - Effect of different water potentials [a) 0,b) -0.5 MPa] and temperatures (20, 25, 30 and 35 °C) on dry weight of roots (DWR) of creole genotypes of maize from different regions of the state of San Luis Potosí. A: Altiplano; M: Media, H: Huasteca. Vertical bars indicate the standard error (n= 15).

to 60% depending on the level of tolerance of the evaluated genotypes (Tahir *et al.*, 2008). Radhouane (2007) recorded a significant decrease in root length at -2 MPa with a reduction of more than 88% from Tunisian autochthonous pearl millet (*Pennisetum glaucum* (L.) R. Br.). Ren *et al.* (2020) showed that growth variables (root length, seedling, fresh weights of the root and aerial part decreased significantly under saline stress conditions in corn. Our results did not agree with this seedling growth dynamic where, in the combination of the abiotic factors, more growth of the RL was registered in germinated seedlings under water stress and at higher temperature (35 °C) in most of the genotypes. These results explain that genotypes with more roots at seedling stage subsequently developed stronger root system for the combination of the abiotic factors (high temperature and water stress), produced more biomass and had higher values for most characters determining seed yield (Bocev, 1963). However they decreased their RL in respect to control conditions.

Dry weight of shoots and roots

The DWS under control water potential (0 MPa) showed different responses of the genotypes for each temperature and agroclimatic region. In most of the genotypes from *Altiplano*, it was observed that the maximum values were found at 30 and 35 °C while 20 °C normally had low DWS (in average 80% respect to maximum values). A10 response was different, the temperatures 25 and 35 °C were not the ideal for his growth because it was significantly affected and their DWS decreased. Seedlings from *Media* and *Huasteca* registered their best DWS at 20 and 30 °C and their minimum ones at 25 and 35 °C; minimums were22% and 32% reduced respect to the maximum values (Figure 6a).

The DWS of the genotypes was reduced with the decrease ofwater potential level but responses varied with genotypes. The genotypes from *Altiplano* (A3, A4, A8 and A9) registered their maximum values at 30 and 35 °C while A10 only at 30 °C. A3, A4, A8 and A9 reduced drastically their DWS at 25 °C under water stress where they lost until 30% in comparison to 0 MPa. All the genotypes from *Media* obtained their maximum values at 30 °C, with 36% respect to those at 20, 25 and 35 °C. The genotypes from *Huasteca* registered their maximum values of DWS at 20 and 30 °C with 33% more weight for those found at 25 and 35 °C (Figure 6b).

As temperature increased, a slighted and discontinuous trend of DWR to increase was perceived in most of genotypes from *Altiplano* while in genotypes from *Media* and *Huasteca* the tendency was opposite and the water potential variation changed the trend (Figure 7). At 0MPa, most of the genotypes from *Altiplano* (A3, A4, A8 and A9) obtained their maximum values at 25 and 35 °C with 15% more to those registered at 20 and 30 °C. Also, genotypes from *Media* and *Huasteca* registered their best values at 20 °C but it was observed a decrease of 33% of their values with the increase of temperature (Figure 7a).

At -0.5 MPa, a reduction of the DWR occurred respect to 0 MPa. The genotypes from *Altiplano* delayed at least 10% of the weight at -0.5 MPa. Genotypes from *Media* were the most affected in the combination of 25 and 35 °C with -0.5 MPa. All the genotypes from *Media* significantly decreased their DWR and delayed at least 15% respect to 20 and 30 °C. Genotypes from *Huasteca* responded differently for each temperature at -0.5 MPa, they registered the maximum weight at 20°C but decreased up to 35% of their weight respect to 25, 30 and 35 °C. For *Huasteca* genotypes, the increase of the temperature reduced the DWR on H4 and H10 but increased on H9 and an absence of tendency was registered on H11 (Figure 7b).

In our investigation, the combination of each temperature (20, 25, 30 and 35 °C) with -0.5 MPa decreased the dry weights of the shoots and roots in most of the creole genotypes except in some from *Altiplano* (A3 and A10 at 20 °C, A9 and M11 at 30 °C). Ashagre *et al.* (2014) found different results in the evaluation of highland maize cultivars under moisture stress at germination and seedling growth stages, they registered statistically higher values with the use of PEG-6000 (60, 120 and 180 mg. L^{-1}) for the variables shoot and root dry weight. Farsiani & Ghobadi (2009), Khayatnezhad *et al.* (2010), Bibi *et al.* (2012), Radic *et al.* (2019), reported that drought drastically affected the fresh and dry weights of seedlings and roots in cultivars of sorghum, wheat, corn and sunflowers. These results agree with ours in the combination 20, 25 °C and water stress levels. However not in temperatures 30 and 35 °C; where creole genotypes A9 (at 30 °C), A8 and A9 (at 35 °C) were statistically equals. Toscano *et al.* (2017) recorded similar results in three sunflower cultivars at different water potentials (0, -0.15, -0.3, -0.45 and -0.65 MPa) at 20 °C. They found a significant decrease in root length, seedling length, fresh and dry seedling weights at the most negative water potential. Significant losses of germination and accumulation of dry matter were reported when using potentials of -0.5 MPa in creole of corn and beans (Aguilar-Benítez *et al.*, 2014).

In most of the evaluated variables, the creole genotypes from *Huasteca* were the most affected and that results can be related to the particular conditions different to *Altiplano* and *Media* where they were collected. The region of *Huasteca* is the one with higher mean annual temperature and rainfall in comparison to *Altiplano* and *Media* (Figure 1); then their genetics materials are already adapted to no stress conditions. Then, these results can be associated to their local conditions where they grow with less stress in respect to those from the others regions of the state (Jiang *et al.*, 1999). In addition, according to Mercer *et al.* (2008), maize landraces from tropical temperate conditions do not tolerate warmer climates due to local adaptation. In the state of San Luis Potosí, the sowing date of maize corresponds to the dates from May 15 to July 10 for *Altiplano*, May 15 to July 15 for *Media* while for the *Huasteca* it is from May 15 to 31 of July. On those dates, less monthly evapotranspiration, more cloudiness, more monthly average temperature and therefore more intensity in terms of the amount of water received in 24 hours in the *Huasteca* were recorded compared to the two others agroclimatics regions of the state. These environmental characteristics explain some of the responses obtained from the creole genotypes.

Similarly, maize is planted throughout Mexico, from very warm and humid climates at sea level to temperate and dry in the central plateau (equivalent to *Altiplano*). Distinct races and or genotypes of maize have been associated with particular environmental conditions since they were first classified (Wellhaussen *et al.*, 1952). Corral *et al.* (2008) classified Mexican maize taking account rainfall, photoperiod and the most significantly temperature of their local adaptations or origins. These results have important implications for thinking about the effect of climate change adaptation of maize in the country because they indicated the way to take for contrasting the negative effects of climate change taking account the local conditions. Most notably, this is the first study to our knowledge to investigate effects of the increase of temperature and drought in creole genotypes of maize in San Luis Potosí taking account the three agroclimatics regions.

With the combination of the heat and water stress, the results obtained were null or below 20% for PG. The MGT was delayed by the lower osmotic potential and the different temperature while for the growth variables most of them decreased under water stress conditions and depended to temperatures. However at high temperature and water stress (35 °C/-0.5 MPa) the results decreased compared at 20, 25 and 30 °C.

Additionally, it has been documented that the effects of climate change will affect the grain yield of corn crops (Mina *et al.*, 2012; Guerrero-Jiménez, 2016; Yang *et al.*, 2017; Amouzou *et al.*, 2019; Martins *et al.*, 2019; Chen & Pang, 2020; Ureta *et al.*, 2020); in this work, some of the effects related to climate change (drought and high temperatures) drastically affected the germination and initial growth of creole genotypes of maize from the state of S.L.P. under laboratory conditions. Then in this work, it has documented how the increase of temperature and the decrease of precipitation will affect negatively the germination and initial growth of creole genotypes from different agroclimatic regions. Besides the local particular conditions of each agroclimatic region has influenced the dynamic of germination and growth of the creole genotypes. Also, the materials were selected based on successful results from different environments, with different levels of water and thermal stress. Therefore, materials from less stressed areas (in this case *Huasteca*) will be less resilient to the related effect of climate change.

Conclusions

The germination and initial growth of creole genotypes of maize coming from different agroclimatic regions were drastically affected by the increase of temperature and drought. The creole genotypes from the region with more high mean annual temperature and precipitation (*Huasteca*) were the most affected and this is associated to the local conditions adaptations of their genetic material with less conditions of stress in comparison to the materials from *Altiplano* and *Media*, regions of unfavorable conditions are associated with stress for the combination of less mean annual temperature and precipitation. The creole genotypes from *Altiplano* and *Media* can represent an important phylogenetic potential to counteract negative effects of the increase of temperature and drought in the state of S.L.P for being the less affected in laboratory conditions and coming from unfavorable conditions for the development of maize plants.

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