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Seed yield of simple and tri-linear corn (*Zea mays* L.) hybrids for the mexican humid tropics

Rendimiento de semilla de híbridos simples y trilineales de maíz (*Zea mays* L.) para el trópico húmedo mexicano

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Abstract

The objective of the work was to evaluate the agronomic performance and seed yield of tropical corn (*Zea mays* L.) of single and tri-linear crosses. In the spring-summer of 2015 and 2016, two essays were established in the states of Veracruz and Tabasco, Mexico. In the first essay, a group of 12 single crosses was evaluated, and in the second, a group of 18 tri-linear crosses was evaluated. In both essays, the treatments were distributed under a completely randomized block design with three replicates in 5 m long, two-row plots and 0.8 m between rows, with an initial population density of 62.500 plants ha⁻¹. Within the simple cross trial, hybrids HE-3W, COMERCIAL 1, LT-164xLT-165, and HE-1W presented seed yields above the general mean (3384 kg ha⁻¹). Within this outstanding group is the LT-164xLT-165 cross, which participates as a female parent in the formation of the recently released commercial hybrid H-567. In the tri-linear crosses essay, a group of varieties and hybrids including H-567, (LT-164xLT-165) xLT-156, (LT-164xLT-165) xLT-155, (LT-154xLT-155) xLT-165, VS-536, H-520, VS-563, (LT-154xLT-155) xLT-170, (LT-171xLT-172) xLT-156, (LT-164xLT-165) xLT-164, and (LT-171xLT-172) xLT-170 recorded seed yields of 6669.8, 6515.4, 6498.6, 6431.1, 6260, 6024.7, 5935.4, 5664.3, 5580.8, and 5527.1 kg ha⁻¹, respectively. The LT-154, LT-155, and LT-156 lines are common as a male and female parent, suggesting a good genetic combination. The prevailing environmental conditions during the development of the experiments did not significantly influence the productivity of the crosses. There is genetic variability that can be used to continue developing lines, open pollination varieties, and corn hybrids.

Keywords: agronomic performance, genetic variation, heterosis, hybridization, productivity.

Resumen

El objetivo del estudio fue evaluar el comportamiento agronómico y el rendimiento de semilla de maíz tropical (*Zea mays* L.) de cruza simples y trilineales. En primavera-verano del 2015 y 2016, se establecieron dos ensayos en los estados de Veracruz y Tabasco, México. En el primer ensayo se evaluó un grupo de 12 cruza simples y en el segundo se evaluó un grupo de 18 cruza trilineales. En ambos ensayos los tratamientos se distribuyeron bajo un diseño de bloques completamente al azar con tres repeticiones en parcelas de dos surcos de 5 m de largo espaciados a 0.8 m entre surcos, con una densidad de población inicial de 62.500 plantas ha⁻¹. Dentro del ensayo de cruza simples, los híbridos HE-3B, COMERCIAL 1, LT-164xLT-165 y HE-1B presentaron rendimientos de semilla por arriba de la media general (3384 kg ha⁻¹). Dentro de este grupo sobresaliente se encuentra la cruza LT-164xLT-165 que participa como progenitor hembra en la formación del híbrido comercial H-567 de reciente liberación. En el ensayo de híbridos trilineales un grupo de variedades e híbridos, entre ellos el H-567, (LT-164xLT-165) xLT-156, (LT-164xLT-165) xLT-155, (LT-154xLT-155) xLT-165, VS-536, H-520, VS-563, (LT-154xLT-155) xLT-170, (LT-171xLT-172) xLT-156, (LT-164xLT-165) xLT-164 y (LT-171xLT-172) xLT-170 registraron rendimientos de semilla de 6669.8, 6515.4, 6498.6, 6431.1, 6260, 6024.7, 5935.4, 5664.3, 5580.8 y 5527.1 kg ha⁻¹, respectivamente. Las líneas LT-154, LT-155 y LT-156 son comunes como progenitor macho y hembra, sugiriendo buena combinación genética. Las condiciones ambientales imperantes durante el desarrollo de los experimentos no influyeron de manera significativa en la productividad de las cruza. Existe variabilidad genética que puede aprovecharse para seguir desarrollando líneas, variedades de polinización libre e híbridos de maíz.

Palabras clave: comportamiento agronómico, heterosis, hibridación, variación genética, productividad.

Introduction

Corn (*Zea mays* L.) is one of the most important cereals in the world. In 2018, corn was grown in approximately 192 million hectares with a mean yield of 5600 kg ha⁻¹ (FAOSTAT, 2020). In Mexico, approximately 5.54 million hectares are cultivated under rainfed conditions, and 1.58 million hectares are cultivated under irrigation conditions. In these areas, a production volume of 27.2 million is obtained and a mean grain yield of 3.83 t ha⁻¹ (SIAP, 2019). Nevertheless, there is a deficit of this grain, and each year, it is necessary to resort to importing between 15 and 17 million tons (FAS-USDA, 2020).

According to statistical data, rainfed land is cultivated in small production units that use traditional systems, although as a heterogeneous group with regard to resource management. Most of the national corn production comes from these small production units. The rainfed land fraction includes 1.5 million hectares of good to excellent agricultural quality and 3.5 million hectares are of medium quality, where the use of hybrids is feasible (Turrent *et al.*, 2012, p.17).

In the tropical area of Mexico, the development of corn genetic improvement was initiated by the predecessor organisms of the current National Institute of Forest, Agricultural, and Livestock Research (NIFALR) such as the National Institute of Agricultural Research (NIAR) and the Office of Special Studies (OSS). The purpose was to obtain hybrids with higher yields than the regional native varieties; furthermore, to provide producers with the technology to increase their yield, to improve their profits, and to supply this basic grain. These works led to the use of three heterotic populations or groups: Synthetic Tropical Dent (STD), Tuxpeño Tropical Crystalline (TTC), and Elite Tropical Population (ETP), which formed the germplasm base of the tropics genetic improvement program in Mexico and other countries in the world.

Progress in genetic improvement was successful during the years 1950 to 1990, in which more than 16 open-pollinated varieties (OPV) and tropical hybrids of corn were released and were commercialized among producers (Technow *et al.*, 2020); however, most of these hybrids were double-crossed, generating a high cost in seed production by the seed companies (Sumalini *et al.*, 2018). For example, in 1994, the H-513 single cross hybrid was released (Sierra-Macias *et al.*, 2017), which outperformed commercial varieties and hybrids by 30 % up to now; however, one problem was the low seed yield *per se* of the inbred lines that participate in the formation of the hybrid. Seed production of single-cross hybrids in maize is not economically feasible due to high-cost cultivation (Sumalini *et al.*, 2018).

Due to the disadvantages in seed production of single cross hybrids starting in the year 2000, the genetic improvement program for the tropics began the formation of tri-linear crosses. These allowed to make use of the advantages offered by heterosis in commercial corn production and seed production, when using a high-yield simple cross as a female parent and inbred lines with good performance *per se* as a male, with a good general combinatorial aptitude and with good pollen production. Through this strategy, hybrids H-518, H-520 (Sierra-Macias *et al.*, 2004, p.17), H-564C (Sierra-Macias *et al.*, 2011), and recently hybrids H-567 and H-568 (Sierra-Macias *et al.*, 2017) were released.

Meanwhile, concerning the production of corn seed the study of the agronomic traits is important in the evaluation of hybrids (Sesay *et al.*, 2016). Likewise, it is essential to know the environment (amount and distribution of rainfall and temperature, soil, etc.) and the genotype-environment interaction (Virgen-Vargas *et al.*, 2014). Although many studies have been done to estimate seed yield in hybrids and their parents (Andrés-Meza *et al.*, 2013; Nelson *et al.*, 2016; Al-Naggar *et al.*, 2017), it is important to continue assessing the superiority of new hybrids across environments and years to benefit seed producers. Therefore, the objective of this research work was to evaluate the agronomic performance and seed yield of single and tri-linear crosses of tropical maize.

Materials and methods

Study site. The present study was an advance focused on the development of single and tri-linear crosses from tropical elite germplasm, led by the Cotaxtla Experimental Field Corn Program belonging to the NIFALR. Table 1 shows different tests performed in environments of the state of Veracruz and Tabasco, Mexico during the years 2015 and 2016, respectively.

Used germplasm. The present study was done through two evaluation essays: 1) during 2015, a single cross essay with 12 treatments was established, and 2) in 2016, tri-linear cross essays were done through three environments with 18 treatments (Table 2).

Experiment design. Essay 1 was sown on July 15, 2015; two seeds were hand planted per hill and later thinned to one to obtain a plant population density of 62,500 plants ha⁻¹. Essay 2 was established during the 2016 spring-summer cycle, through three environments with different sowing dates: Medellín de Bravo, Veracruz, Mexico (July 5), Carlos A. Carrillo, Veracruz, Mexico (July 6), and Huimanguillo, Tabasco, Mexico (July 8), respectively. In three environments, the hybrids were planted in each block in a randomized complete block design with three replications. The hybrids in each block were planted

Table 1. Physical characteristics of the evaluation environments.

Env.	Year	Type of essay	Altitude (m)	Soil type	Geographic coordinates	
					NL	WL
E1	2015	Evaluation of single crosses	26	Vertisol	18°57'	96°12'
E2	2016	Evaluation of tri-linear crosses	26	Vertisol	18°57'	96°12'
E3	2016	Evaluation of tri-linear crosses	16	Gleysol	18°16'	95°57'
E4	2016	Evaluation of tri-linear crosses	23	Umbrisol	17°50'	93°56'

Env. = environment; E1 = Medellín de Bravo, Veracruz, Mexico (2015); E2 = Medellín de Bravo, Veracruz, Mexico (2016); E3 = Carlos A. Carrillo, Veracruz, Mexico (2016); E4 = Huimanguillo, Tabasco, Mexico (2016); NL = north latitude; WL = west longitude.

Table 2. Germplasm evaluated in two types of essays.

Essay 1			Essay 2		
No.	Genealogy	Genetic structure	No.	Genealogy	Genetic structure
1	LT-161xLT-162	Single cross	1	(LT-164xLT-165)xLT-156	Tri-linear cross
2	LT-164xLT-165	Single cross	2	(LT-171xLT-172)xLT-165	Tri-linear cross
3	LT-169xLT-170	Single cross	3	(LT-171xLT-172)xLT-156	Tri-linear cross
4	LT-171xLT-172	Single cross	4	(LT-164xLT-165)xLT-164	Tri-linear cross
5	LT-158xLT-159	Single cross	5	(LT-154xLT-155)xLT-165	Tri-linear cross
6	LT-154xLT-155	Single cross	6	(LT-171xLT-172)xLT-170	Tri-linear cross
7	HE-1Y (17)	Tri-linear cross (check)	7	(LT-164xLT-165)xLT-155	Tri-linear cross
8	HE-1W	Tri-linear cross (check)	8	(LT-164xLT-165)xLT-170	Tri-linear cross
9	HE-3W	Tri-linear cross (check)	9	(LT-171xLT-172)xLT-172	Tri-linear cross
10	HE-4W	Tri-linear cross (check)	10	(LT-164xLT-165)xLT-165	Tri-linear cross
11	COMERCIAL 1	Tri-linear cross (check)	11	(LT-158xLT-159)xLT-170	Tri-linear cross
12	H-520	Tri-linear cross (check)	12	(LT-154xLT-155)xLT-170	Tri-linear cross
			13	(LT-154xLT-155)xLT-164	Tri-linear cross
			14	(LT-154xLT-155)xLT-166	Tri-linear cross
			15	H-520	Tri-linear cross (check)
			16	H-567	Tri-linear cross (check)
			17	VS-563	Synthetic variety (check)
			18	VS-536	Synthetic variety (check)

LT = tropical line; HE = experimental hybrid; VS = synthetic variety; W = white grain; Y = Yellow grain.

in two rows of 5.0 m length spaced 0.8 m apart with 0.2 m spacing between plants within a row, the useful plot had an area of 4 m², with a planned population density of 62.500 plants ha⁻¹. Both essays were sown manually, and band fertilized with a dose of 161-46-00 kg ha⁻¹ of nitrogen, P₂O₅, and K₂O, respectively, Urea with 46-00-00 analysis and diammonium phosphate 18-46-00 (DAP) were used as nutritional sources. The physical mixture was done with 100 kg Urea + 100 kg DAP, divided into two stages: half of the nitrogen and all the DAP were applied 15 days after sowing (das) in the V2 stage of the crop; the rest of the nitrogen was applied before panning between stages V4 and V5 of the crop. The weed control was

applied with herbicide Atrazine in dose of 3 kg ha⁻¹ to achieve complete control. The control of pests was carried out with the application of permethrin, and monochotophos to control *Phyllophaga* spp., *Agrotis lineatus*, *Spodoptera frugiperda* Smith, and *Heliothis zea*.

Data recording. During the essays, the climatic conditions such as mean monthly temperature and accumulated monthly rainfall was recorded through the meteorological stations: Paso del Toro (19° 02' 16.8" N, 96° 08' 06" W), and Carlos A. Carrillo (18° 16' 15.6" N, 95° 33' 25.2" W) Veracruz, Mexico, and Cardenas (18° 00' 3.6" N, 93° 22' 33.6" W) Tabasco, Mexico (SMN-CONAGUA, 2020). The following agronomic traits was quantified: days to

50 % anthesis, days to 50 % silking, plant and ear height, plant qualification (where 1 is the best and 5 is the worst), root lodging, and the number of ears with poor coverage, respectively. At approximately 120 das, the experiment was harvested manually, where harvest traits such as ear grade, number of rotten ears, and seed yield (kg ha^{-1}) was recorded. Seed yield was calculated with the formula: $\text{Yield} = (\text{PC} \times \% \text{DM} \times \% \text{G} \times \text{FC}) / 8600$; where: PC = total field weight harvested in the experimental unit, % DM = percentage of dry matter of a sample of seeds from five ears, % G = percentage of grain estimated from five ears, FC = conversion factor to obtain the seed yield per hectare, the quotient of dividing 10.000 m^2 by the useful plot in m^2 and, 8600 = is a constant to estimate the seed yield at a humidity of 14 %.

Statistical methods. Analyses of variance (ANOVA) and multiple comparisons of means (Duncan, < 0.05) were done on all the quantified traits. The mean values were considered significantly different when $P < 0.05$. Using additive main effects and

multiplicative interaction (AMMI) model seed yield data was subjected to analysis of variance across environments (Genotype-environment interaction). Statistical analyses were done with the PROC GLM of the SAS/STAT® version 9.0 software (Gupta *et al.*, 2015, p.37).

Results and discussion

Environmental characteristics of the evaluation sites.

In the evaluation of single crosses of tropical corn (Table 1) during the study period that comprised the months of July to November 2015 in the Medellín de Bravo, Veracruz, Mexico environment (Figure 1A), the monthly accumulated rainfall was 643.3 mm, and the mean temperature was 27.6°C ; in this regard, a higher mean temperature occurred in August (30.1°C) compared to November (24.3°C) (Figure 1A). In spring-summer 2016, which corresponded to the second essay of tri-linear crosses, the mean monthly temperature conditions during July to November in the environments of Medellín de

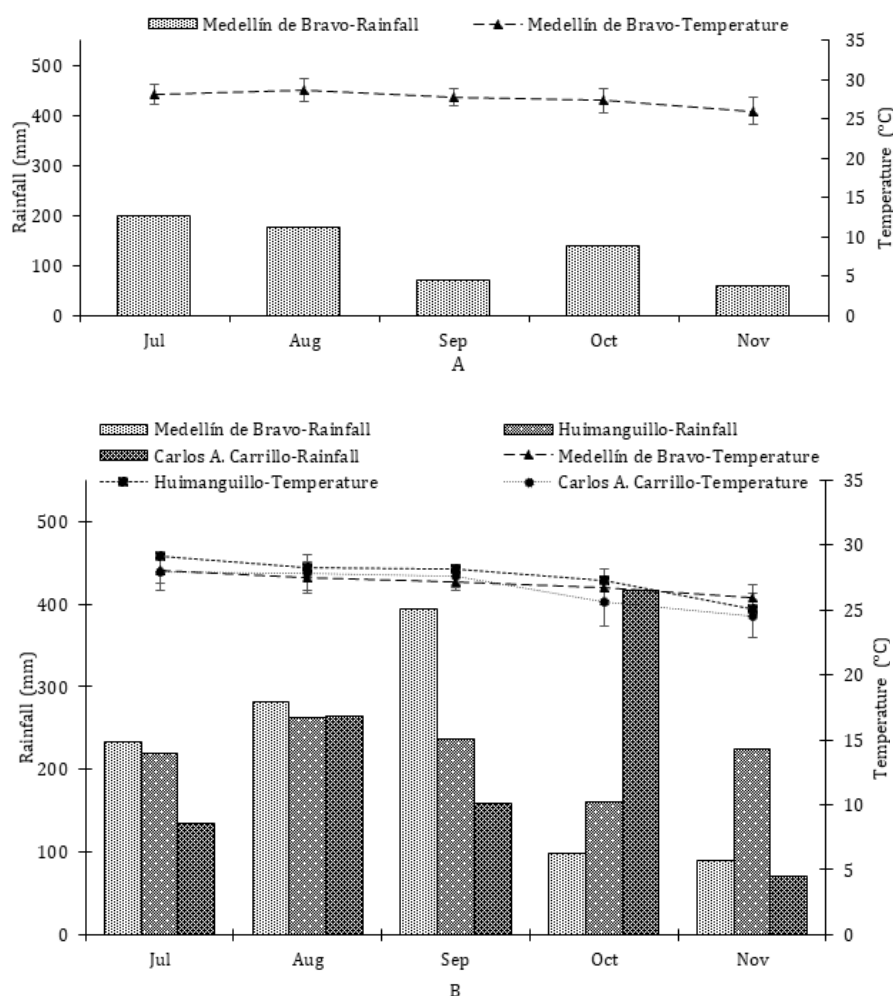


Figure 1. A) 2015 spring-summer cycle; B) 2016 spring-summer season.

Bravo, Carlos A. Carrillo, Veracruz, Mexico, and Huimanguillo, Tabasco, Mexico (Table 1) was 27.1, 26.7, and 27.5 °C, respectively; while the recorded rainfall was 1097.1, 1046.9, and 1103.1 mm for each environment, respectively (Figure 1B). Essentially, rainfall amounts and distribution were more suitable for plant growth in 2016.

According to Aguilar *et al.* (2015), the minimum recommended temperature for proper plant development is > 15 °C; contrastingly, at temperatures above 30 °C, all the physiological processes of the plant decreased significantly (Rincón-Tuexi *et al.*, 2006). Extreme temperatures of < 15 and 35 °C during grain fill reduced number of kernels ear⁻¹ and kernel weight (Cicchino *et al.*, 2010). The total accumulated rainfall throughout the development of the crop in the three experiments was greater than the reported demand for this crop finding optimal water conditions from 550 to 575, up to 800 mm (Martínez Álvarez, 2015).

Evaluation of single crosses. The data indicated that the single crosses was significantly different ($P < 0.05$) for all the traits evaluated, except for ear coverage

variable. This suggests genetic variation within the evaluated genotypes, a situation that has already been reported in another research by Boakyewaa *et al.* (2019). The variation coefficients recorded ranged from 1.67 to 68.57 %, where high values were obtained in traits recorded in percentages such as: root lodging, ear cover, and rotten ears (Table 3). Also, low values of this parameter indicate reliability in the conduction of the experiment (Gupta *et al.*, 2015, p.37).

The mean general seed yield of the evaluated hybrids was 3384 kg ha⁻¹ (Table 4). The seed yield of the 12 single crosses fluctuated between 4880 and 376 kg ha⁻¹ (HE-3W and LT-161xLT-162, respectively). An outstanding significant group ($P < 0.05$) was obtained with the HE-3W, COMERCIAL 1 (check), LT-164xLT-165, and HE-1W hybrids. Within this group, the HE-3W hybrid produced the highest seed yield with 4880 kg ha⁻¹; the agronomic performance of this hybrid can be attributed to its genetic makeup. Likewise, it is important to point out that the LT-164xLT-165 single cross participates as a female parent in the formation of the recently released tri-linear hybrid H-567 (Sierra Macías *et al.*, 2017).

Table 3. Statistical significance in agronomic traits in single crosses of tropical corn.

SV	DF	Yield (kg ha ⁻¹)	Mf (days)	Ff (days)	Plht (cm)	Eht (cm)	Plgr (1-5)	Egr (1-5)	Rlo (%)	Eco (%)	Ero (%)
Crosses	11	7359.09**	10.46**	8.30**	972.11**	410.23**	0.17**	0.12**	1.60*	0.08NS	3.68**
Block	3	531.61*	5.84**	5.5**	114.41NS	76.39NS	0.01NS	0.01NS	2.43	15.25**	0.79NS
Error	33	203.49	0.96	1.06	79.18	69.19	0.01	0.01	0.78	0.05	0.97
Mean		3 384	59	59	177.39	86.25	2.75	2.8	2.12	1.24	8.29
CV (%)		13.32	1.67	1.75	5.02	9.64	4.45	4.31	68.57	18.58	37.04

*Significant at 0.05; ** Highly significant at 0.01, according to the Duncan Test ($P < 0.05$); NS = non-significant; SV = source of variation; DF = degrees of freedom; Mf = male flowering; Ff = female flowering; Plht = plant height; Eht = ear height; Plgr = plant grade; Egr = ear grade; Rlo = root lodging; Eco = ear cover; Ero = ear rot; CV = coefficient of variation.

Table 4. Mean values of single crosses of tropical corn.

Single crosses	Yield (kg ha ⁻¹)	Mf (days)	Ff (days)	Plht (cm)	Eht (cm)	Plgr (1-5)	Egr (1-5)	Rlo (%)	Eco (%)	Ero (%)
9	4880 a	59 cd	59 bc	195 ab	98.8 a	2.3 ef	2.3 cd	0.0 c	2.0 a	2.2 c
11	4656 ab	57 ef	57 de	197.5 a	98.8 a	2.0 f	2.4 cd	0.4 bc	0.5 a	7.9 bc
2	4268 abc	58 de	58 cde	170 d	83.3 bc	2.7 cde	2.2 d	2.5 abc	0.5 a	2.1 c
8	4228 abc	58 d	58 cde	186.7 abc	96.7 ab	2.0 f	2.5 cd	2.8 abc	0.7 a	4.9 bc
12	4048 bcd	56 f	57 e	180 bcd	86.7 abc	2.5 de	2.5 cd	5.4 ab	1.1 a	10.3 abc
6	3899 bcd	58 de	58 cde	180 bcd	88.3 abc	2.5 de	2.2 d	4.4 abc	0.0 a	8.7 abc
10	3663 cde	60 bc	60 ab	180 bcd	85 abc	2.3 ef	2.7 bc	0.0 c	1.4 a	4.2 bc
5	3317 def	59 cd	59 bc	185 abcd	87.5 abc	2.5 de	3.1 b	0.0 c	0.0 a	10.9 abc
7	3031 ed	58 d	59 bcd	177.5 cd	93.8 ab	3.0 bc	3.0 b	0.6 bc	0.6 a	9.2 abc
4	2631 f	61 ab	61 ab	185 abcd	88.3 abc	2.8 bcd	3.0 b	0.6 bc	0.6 a	4.2 bc
3	1322 g	60 abc	60 ab	172.5 cd	76.3 c	3.1 b	4.0 a	6.2 a	0.0 a	16.2 ab
1	376 h	62 a	62 a	135 e	61.3 d	5.0 a	4.0 a	2.5 abc	0.0 a	20.8 a
Mean	3384	58.7	58.9	177.4	86.3	2.8	2.8	2.1	1.2	8.3

*Averages with different letters in the same column show significant differences ($P < 0.05$), according to Duncan's test; Mf = male flowering; Ff = female flowering; Plht = plant height; Eht = ear height; Plgr = plant grade, where 1 is the best and 5 is the worst; Egr = ear grade, where 1 is the best and 5 is the worst; Rlo = root lodging; Eco = ear cover; Ero = ear rot; 1 = LT-161xLT-162; 2 = LT164xLT165; 3 = LT-169 x LT-170; 4 = LT-171xLT-172; 5 = LT158xLT159; 6 = LT154xLT155; 7 = HE-1Y (17) (check); 8 = HE-1W (check); 9 = HE-3W (check); 10 = HE-4W (check); 11 = COMERCIAL 1 (check); 12 = H-520 (check).

The evaluation environment was characterized for presenting a total accumulated rainfall of 643.3 mm during the development of the crop, which corresponded to 68 % of the accumulated annual total (Figure 1A). This value is higher than that reported by Martínez Álvarez (2015).

Regarding the days to flowering (Table 4), the COMMERCIAL 1 (check) hybrid was the earliest with 57 days to 50 % anthesis and 50 % silking; in contrast, the LT-161xLT-162 single cross was the latest at 62 das. NIFALR breeders are increasingly emphasizing flowering synchronizations of male inbred lines and single cross seed parents when advancing new hybrids tri-linear. Ángeles-Gaspar *et al.* (2010) mention that precocity is an important variable to denote the adaptation of genotypes to prevailing humidity conditions. The mean plant height varied from 135 to 197 cm, while ear height varied from 61 to 98 cm, respectively, with the lowest values for the single crosses of tropical lines, compared with the experimental and commercial tri-linear hybrids. Our results also revealed that plant and ear height were greatly influenced by the environment. The result for plant height corroborates with the findings of Sesay *et al.* (2016). These values coincide with those reported by De la Cruz-Lázaro *et al.* (2009) in a group of tropical corn populations. Likewise, Sener *et al.* (2004) reported important variations for plant height in corn hybrids.

The lowest plant and ear grades were for hybrids HE-3W, COMERCIAL 1, and HE-1W. These same hybrids registered low percentages in the traits of root lodging, ear coverage, and ear rot (Table 4). The last trait is important since in the tropical humid region of Mexico, the combination of high temperatures and humidity causes an ideal environment for the presence of fungi like *Diplodia* spp., and *Fusarium* spp. (De Leon, 2004, p. 118). Lastly, the LT164xLT165 single cross proved to be highly productive, which represents a competitive advantage in commercial seed production (Gómez *et al.*, 2017).

Evaluation of tri-linear crosses. The combined analysis of variance revealed significant differences ($P < 0.05$) between genotypes (G) in 70 % of the 10 traits registered (Table 5). Between environments (E),

significant differences ($P < 0.05$) were also detected in 80 % of the traits, while for the GxE interaction, significant differences ($P < 0.05$) were found in 70 % of the traits. The variance due to the environments was found to be more important, this is to say, there was strong environmental pressure on the evaluated genotypes. The variation coefficients registered ranged from 1.69 to 74.04 %, relatively low values, suggesting that the handling of the experiments and the obtained results are reliable (Gupta *et al.*, 2015, p.37).

A group of tri-linear crosses was obtained that exceeded or equaled the recommended commercial hybrids for tropical humid regions (Table 6). Nine tri-linear hybrids and two open pollinated varieties: H-567, (LT-164xLT-165) xLT-156, (LT-164xLT-165) xLT-155, (LT-154xLT-155) xLT-165, VS-536, H-520, VS-563, (LT-154xLT-155) xLT-170, (LT-171xLT-172) xLT-156, (LT-164xLT-165) xLT-164, and (LT-171xLT-172) xLT-170 were placed in the higher yield group with 6669.8, 6515.4, 6498.6, 6431.1, 6260, 6024.7, 5935.4, 5664.3, 5580.8, and 5527.1 kg ha⁻¹, respectively. Particularly, in this outstanding group, we can observe the presence of the H-567 tri-linear hybrid, recently released by the NIFALR corn program. Likewise, inbred lines LT-154, LT-155, and LT-156, female and male parents of the H-520 commercial hybrid are common; this hybrid is used in more than 84,000 hectares in the Mexican southeast (Sierra Macías *et al.*, 2016). Results showed that the yielding genotypes at the testing location were different suggesting cross-over interactions for some genotypes. Yield improvement in tropical maize has been attributed to increased grain filling period, changes in morphology, and better tolerance to biotic and abiotic stresses (Gasura *et al.*, 2013; Sierra Macías *et al.*, 2017).

The better performance and adaptation of the tri-linear crosses with respect to the improved varieties and commercial hybrids used as controls, indicates a good source of genes from the elite genetic base of the genetic improvement program for the tropical area of Mexico. Our results suggest following the use of breeding schemes through hybridization (Hallauer *et al.*, 2010, p.663). However, we recommend that in later studies, the proportion that the additive

Table 5. Combined analysis of variance across three environments in the state of Veracruz and Tabasco, Mexico.

SV	DF	Yield (kg ha ⁻¹)	Mf (days)	Ff (days)	Plht (cm)	Eht (cm)	Plgr (1-5)	Egr (1-5)	Rlo (%)	Eco (%)	Ero (%)
Gen. (G)	17	5820236.7**	7.88**	8.13**	1180.82**	901.34**	0.03**	0.06**	2.09	1.55NS	0.62NS
Env. (E)	2	89898624.9**	124.59**	50.7**	3267**	48NS	1.04**	2.02**	1.73	17.65**	21.21**
GxA	34	5573051.8**	6.79**	6.88**	667NS	488.59*	0.04**	0.04**	3.17*	1.34NS	0.66NS
Error	106	1548115.7	0.81	0.82	394.18	235.97	0.01	0.01	1.74	0.99	0.59
CV (%)		22.41	1.69	1.69	8.86	14.03	6.68	6.12	74.04	43.95	42.62

*Significant at 0.05; **Highly significant at 0.01, according to the Duncan Test ($P \leq 0.05$); NS = non-significant; SV = source of variation; Gen. = genotype; Env. = environment; DF = degrees of freedom; Mf = male flowering; Ff = female flowering; Plht = plant height; Eht = ear height; Plgr = plant grade; Egr = ear grade; Rlo = root lodging; Eco = ear cover; Ero = ear rot; CV = coefficient of variation.

Table 6. Mean values of tri-linear crosses through three environments in the states of Veracruz and Tabasco, Mexico.

Tri-linear cross	Yield (kg ha ⁻¹)	Mf (days)	Ff (days)	Plht (cm)	Eht (cm)	Plgr (1-5)	Egr (1-5)	Rlo (%)	Eco (%)	Ero (%)
16	6669.8 a*	52 ef	53 ef	261.7 a	139.7 a	2.4 abc	2.4 fg	12.5 ab	5.8 abcd	2.6 a
1	6515.4 ab	51 fg	52 fg	221.5 bcd	105.3 cde	2.6 abc	2.1 g	15.5 a	6.0 abcd	2.6 a
7	6498.6 ab	53 bcde	53 cde	237.8 abc	109.0 bcde	2.8 a	2.9 abcd	6.2 abc	5.3 abcd	1.9 a
5	6431.1 ab	53 bcd	54 bcd	232.2 bcd	129.0 ab	2.4 abc	2.6 def	4.2 bc	4.1 bcd	2.5 a
18	6260.0 abc	53 cde	53 de	240.3 ab	126.0 abc	2.3 bc	2.4 efg	5.3 bc	9.6 abc	5.0 a
15	6024.7 abc	51 g	51 g	230.8 bcd	113.5 bcd	2.5 abc	2.7 cdef	7.0 abc	4.1 bcd	4.3 a
17	5935.4 abc	53 bcde	54 bcde	224.0 bcd	114.0 bcd	2.7 a	2.9 abcd	0.9 c	8.2 abcd	4.3 a
12	5664.3 abcd	52 ef	53 ef	224.0 bcd	113.3 bcd	2.7 a	2.4 efg	4.0 bc	2.9 d	2.6 a
3	5610.3 abcd	53 bcd	54 bcd	221.2 bcd	102.7 de	2.5 abc	2.7 abcde	3.6 bc	3.2 cd	3.8 a
4	5580.8 abcd	54 b	54 bcd	222.8 bcd	104.7 de	2.7 ab	2.7 abcde	3.8 bc	6.3 abcd	4.0 a
6	5527.1 abcd	53 bcd	54 bcd	204.5 d	92.0 e	2.2 c	3.1 abc	3.0 bc	7.4 abcd	2.7 a
2	5184.1 bcd	54 b	55 abc	212.8 cd	100.0 de	2.2 c	2.9 abcd	3.6 bc	5.3 abcd	4.2 a
11	5149.2 bcd	54 bc	55 abc	208.3 d	96.0 de	2.6 abc	3.0 abc	0.9 c	10.6 ab	4.5 a
13	4944.3 cd	52 de	53 e	227.7 bcd	112.7 bcde	2.6 abc	2.8 abcde	5.3 bc	5.4 abcd	3.6 a
14	4897.4 cde	54 b	55 abc	216.8 bcd	110.7 bcde	2.8 a	3.1 abc	3.4 bc	11.1 a	4.5 a
10	4888.2 cde	54 b	55 ab	230.5 bcd	105.7 cde	2.7 a	3.1 ab	1.6 c	3.6 cd	4.3 a
8	4503.9 de	55 a	56 a	209.5 d	101.7 de	2.4 abc	3.0 abc	3.1 bc	3.6 cd	5.0 a
9	3648.4 e	54 b	55 abc	207.5 d	96.0 de	2.5 abc	3.2 a	2.9 c	5.7 abcd	4.7 a
Mean	5551.83	53	54	224.11	109.46	2.52	2.78	4.80	6.00	3.72

*Averages with different letters in the same column show significant differences ($P < 0.05$), according to Duncan's test; Mf = male flowering; Ff = female flowering; Plht = plant height; Eht = ear height; Plgr = plant grade, where 1 is the best and 5 is the worst; Egr = ear grade, where 1 is the best and 5 is the worst; Rlo = root lodging; Eco = ear cover; Ero = ear rot; 1 = (LT-164xLT-165)xLT-156; 2 = (LT-171xLT-172)xLT-165; 3 = (LT-171xLT-172)xLT-156; 4 = (LT-164xLT-165)xLT-164; 5 = (LT-154xLT-155)xLT-165; 6 = (LT-171xLT-172)xLT-170; 7 = (LT-164xLT-165)xLT-155; 8 = (LT-164xLT-165)xLT-170; 9 = (LT-171xLT-172)xLT-172; 10 = (LT-164xLT-165)xLT-165; 11 = (LT-158xLT-159)xLT-170; 12 = (LT-154xLT-155)xLT-170; 13 = (LT-154xLT-155)xLT-164; 14 = (LT-154xLT-155)xLT-166; 15 = H-520; 16 = H-567; 17 = VS-563; 18 = VS-536.

variance and dominance of the base population, where the inbred lines are derived represent, with respect to the total genetic variation, be reported.

All genotypes were observed to behave with an intermediate vegetative cycle with 53 days to 50 % anthesis and 54 days to 50 % silking, respectively (Table 6). It is desirable to have early genotypes whose flowering occurs before 60 days; this helps to avoid the crop coinciding with the canícula, a meteorological phenomenon where there is a short period of drought and increased temperature. Previous studies confirm that the flowering phase is the most sensitive to water stress, producing a detrimental effect on the final yield of grain or seed (Harrison *et al.*, 2011). Liaqat *et al.* (2018) point that the delay in sowing decreases days to tasseling, silking and maturity, plant height, ear height, ear length, number of the row per ear, respectively. In addition, when the production of maize occurred in the rainfall season, plant height was higher because of the rainfall incidence in 2016 (224 cm), in contrast with the rainfall season in 2015 (177 cm) (Figure 1A and 1B).

On the other hand, the hybrids presented an average of 224 and 109 cm of plant and ear height, respectively. These traits are desirable, as most commercial materials commonly sown in the region

are taller, which is unfavorable due to the increased risks of root lodging of the crop from the combination of rainfall with strong cold winds (Norte) prevailing in the Gulf coast (Sierra Macías, 2002). In addition, among hybrids root lodging was different, results showed that the hybrid (LT-164xLT-165) xLT-156 were the most susceptible with more than 15 %. These results agree with those observed in other studies by Cervantes Ortiz *et al.* (2013) and Sánchez Hernández *et al.* (2019) for tropical, subtropical, and temperate areas.

About plant and ear grades, the hybrids exhibited ratings between 2 and 3, suggesting acceptable plant and ear characteristics (Table 6). The importance of recording these two traits from a subjective angle is to observe uniformity in plant height, archetype, insertion, and position of the ear, among others; in ear, the length and diameter of the ear, type of kernel, kernel size, health, among others, are observed. The analysis showed that hybrid (LT-154xLT-155) x166 had problems with more than 11 % of cover harvested ears. These traits are very important, because during grain drying, the relative humid in combination with extreme temperatures causes the presence of the fungal disease that caused ear rot. However, the observed values are not as high as those recorded in other studies (Mendoza *et al.*, 2019). Regarding the

percentages of the ear rot displayed the same trend to ear cover. This indicates that the hybridization progress has been effective; the new tri-linear crosses have been effective.

Conclusions

This work revealed that the productivity of NIFALR's tropical maize has improved over the last 20 years. The most recently released single crosses offers easy, inexpensive, and viable technology to local seed companies in the formation of tri-linear hybrids. Furthermore, a group of highly productive tri-linear crosses with good agronomic performance was identified, which may be an option for rainfed corn producers. The LT-154, LT-155, and LT-156 lines are common as a male and female parent, suggesting a good genetic combination. The prevailing environmental conditions during the development of the experiments did not significantly influence the productivity of the hybrids. The genetic base of the corn improvement program shows high variability that can be used to continue developing inbred lines, open-pollination varieties, and highly productive corn hybrids.

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