Cienc. Tecnol. Agropecuaria, *25*(3): e3501 ISSN: 0122-8706 ISSNe: 2500-5308
DOI: https://doi.org/10.21930/rcta.vol25_num3_art:3501

Plant Breeding Scientific and Technological Research Article

Agronomic Performance, Adaptability, and Stability of Maize Hybrids under Tropical Conditions in Ecuador

Comportamiento agronómico, adaptabilidad y estabilidad de híbridos de maíz bajo condiciones tropicales en Ecuador

Ricardo Limongi Andrade [1] Fernando David Sánchez-Mora [2 *] Raúl V. Mora Yela [3]
José Pico Mendoza [2] Bernardo Navarrete Cedeño [4] Daniel Alarcón Cobeña [1]
Geover Peña Monserrate [4] Jim Ochoa Ramos [3] Iris Perez-Almeida [5]
Felipe R. Garcés-Fiallos [2]

[1]Colegio de Ingenieros Agrónomos de Manabí, Manabí, Ecuador.
[2]Facultad de Ingeniería Agronómica, Universidad Técnica de Manabí, Manabí, Ecuador.
[3]Instituto Nacional de Investigaciones Agropecuarias, Estación Experimental Tropical Pichilingue, Los Ríos, Ecuador.
[4]Instituto Nacional de Investigaciones Agropecuarias, Estación Experimental Portoviejo, Manabí, Ecuador.
[5]Centro de Estudios para el Desarrollo Sostenible, Universidad Tecnológica ECOTEC, Guayas, Ecuador.

* Corresponding Author: Fernando Sánchez-Mora. Universidad Técnica de Manabí. Facultad de Ingeniería Agronómica. Carrera de Agronomía. Lodana, Ecuador. fernando.sanchez@utm.edu.ec

Received: August 30, 2023
Approved: July 15, 2024
Published: September 25, 2024

Subject editor: Caren Dayana Rodríguez, Corporación Colombiana de Investigación Agropecuaria [AGROSAVIA], Mosquera, Colombia

To cite this article: Limongi Andrade, R., Sánchez-Mora, F. D., Mora Yela, R. V., Pico Mendoza, J., Navarrete Cedeño, B., Alarcón Cobeña, D., Peña Monserrate, G., Ochoa Ramos J., Pérez-Almeida I., & Garcés-Fiallos, F. R. (2024). Agronomic Performance, Adaptability, and Stability of Maize Hybrids for Tropical Conditions in Ecuador. *Ciencia y Tecnología Agropecuaria, 25*(2), e3501. https://doi.org/10.21930/rcta.vol25_num3_art:3501

Abstract: Maize is one of the most planted and consumed cereals worldwide. Environmental conditions are essential in the genotype × environment interaction and its productive potential. During the rainy season of 2016, 2017, and 2018, the agronomic, phytosanitary, productive, and adaptive potential were consecutively evaluated in 18 hybrids of yellow corn in five localities with tropical environments: Lodana, Jipijapa, and Tosagua (Manabí); Mocache (Los Ríos); and Zapotillo (Loja). Analysis of variance and comparison of means with Tukey's test (p <0.05) were used to determine the effect of hybrids between and within environments. The parameters of adaptability and stability were estimated using the bi-segmented regression method. Phytosanitary characteristics correlated significantly with productive ones. Likewise, grain yield correlated significantly with cob insertion height, plants harvested per plot, number of cobs harvested, aspect of cob, and rust. The genotype × environment interaction analysis showed a differentiated hybrid response in each environment. Genotype G1 (G.I.2.10-1-1-1xL.I.4) was the best adapted to most localities, showing higher yields than the other materials. In contrast, Genotype G10 (G.I.3.39-3-1-1xPORT.PHAEO.1AS2.4-1-1-1) was the most responsive to favorable environments. Promising hybrids G1, G2, G3, G5, G7, G9, and G11 could be of interest for favorable environments, while G8 could be explored for unfavorable environments. Jipijapa, Tosagua, and Zapotillo had the best potential for corn production in at least two years of evaluation, with Tosagua being the most stable in producing corn hybrids in Ecuador.

Keywords: Ecuadorian tropics, fungal diseases, genotype × environment interaction, stability analysis, *Zea mays* L.

Resumen: El maíz es uno de los cereales más sembrados y consumidos a nivel mundial. Las condiciones ambientales juegan un papel esencial en la interacción genotipo × ambiente y su potencial productivo. Durante la época lluviosa de 2016, 2017 y 2018, se evaluó el potencial agronómico, fitosanitario, productivo y adaptativo en 18 híbridos de maíz amarillo, en cinco localidades de ambiente tropical: Lodana, Jipijapa y Tosagua (Manabí); Mocache (Los Ríos); y Zapotillo (Loja). Para determinar el efecto de híbridos entre y dentro ambientes se utilizó el análisis de varianza y la prueba de Tukey (p <0,05). Los parámetros de adaptabilidad y estabilidad se estimaron mediante la regresión bisegmentada. Las características fitosanitarias se correlacionaron significativamente con las productivas. El rendimiento de grano se correlacionó con altura de inserción de la mazorca, plantas cosechadas por parcela, número de mazorcas cosechadas, aspecto de mazorca y roya. La interacción genotipo × ambiente mostró una respuesta diferenciada de los híbridos en cada ambiente. El genotipo G1 (G.I.2.10-1-1-1xL.I.4) se adaptó mejor a la mayoría de las localidades, mostrando rendimientos mayores que los demás materiales. El genotipo G10 (G.I.3.39-3-1-1xPORT.PHAEO.1AS2.4-1-1-1) respondió mejor a los ambientes favorables. Los híbridos prometedores G1, G2, G3, G5, G7, G9 y G11 podrían ser de interés para entornos favorables, mientras G8 podría explorarse para entornos desfavorables. Jipijapa y Tosagua (Manabí) y Zapotillo (Loja) mostraron un mejor desempeño en la producción de maíz, en al menos dos años de evaluación, siendo Tosagua la más estable para producir híbridos de maíz en el Ecuador.

Palabras clave: trópico ecuatoriano, enfermedades fúngicas, interacción genotipo x ambiente, análisis de estabilidad, *Zea mays* L.

Introduction

In Ecuador, around 255,376 hectares are devoted to corn, with an estimated production of 5.93 t ha^{-1} (Ministerio de Agricultura y Ganadería del Ecuador [MAG], 2020; Zambrano & Andrade, 2021). Corn grain production has grown over the years, increasing more than 20 % since 2014. This crop is mostly established in Ecuador's Guayas, Los Ríos, Manabí, and Loja provinces. In 2021, the highest grain yield of 7.09 t ha^{-1} was recorded in Loja, while Los Ríos and Manabí's production ranged between 6.29 and 5.57 t ha^{-1}, respectively (MAG, 2020; Zambrano & Andrade, 2021).

The yield per hectare of corn has increased in Ecuador, but it is still lower than in other countries such as Brazil and Mexico, where yields between 9 and 12 t ha^{-1} are reported (Gabriel et al., 2018; Vázquez-Carrillo et al., 2020). The increase in corn yield in Ecuador can be attributed to the development of technological components and the introduction of new hybrids by public and private companies; the performance of the modern hybrids responds to greater absorption of nutrients (Caviedes et al., 2022; Vásconez-Montúfar et al., 2021). Thus, it is necessary to continue developing and evaluating new hybrids adapted to the country's agricultural areas.

Developing corn hybrids with high productivity and sound stability is a dynamic process that allows evaluating their potential yield over time, in which new hybrids can be included for evaluation and environmental adaptation (Gordón et al., 2018). In plant breeding programs, it is common to evaluate the response of genotypes in various environments in order to assess the magnitude and type of genotype × environment (G × E) interaction and the degree of phenotypic stability of genotypes subjected to all predominant environments in a potential region of adaptation (Tirado et al., 2019). The G × E interaction becomes important in evaluating hybrids developed for multiple production circumstances, so it is necessary to integrate the concepts of adaptability and stability to define the behavior of genotypes evaluated through contrasting environments (Gordón et al., 2018).

In Ecuador, there are few studies on the adaptability or stability of corn genotypes. However, some have identified more adapted and stable hybrids in different environments. Many promising hybrids have a high production of grains and less intensity of diseases such as leaf spots (*Exserohilum turcicum* and *Curvularia* sp.) and rust (*Puccinia sorghi*; Garcés-Fiallos et al., 2012; Limongi-Andrade et al., 2018; Vera-Avilés et al., 2013). There are several methods to evaluate the adaptability and stability of corn hybrids, including the bi-segmented linear regression proposed by Cruz et al. (1989). This method describes the response pattern of each hybrid and its predictability under favorable and unfavorable conditions. Several studies have used this method to recommend hybrids (Cardoso et al., 2000; Carvalho et al., 2002; Santos et al., 2019). For Cruz et al. (1989), the ideal hybrid, according to the model, is the one with a high mean (high b_0), the lowest possible b_1 (less demanding in unfavorable environments), the highest possible $b_1 + b_2$ (responsive to environmental improvement), and variance of the regression deviations close to or equal to zero (high stability in the environments studied).

The National Maize Breeding Program of the Instituto Nacional de Investigaciones Agropecuarias de Ecuador (INIAP) has developed hybrids that must be analyzed in terms of their adaptation and adaptability to Ecuador's main productive areas before being released to farmers. Thus, this work aimed to evaluate the agronomic behavior, adaptability, and stability of promising and commercial hybrids of yellow corn in the Ecuadorian tropics.

Material and Methods

Genetic Material and Evaluation Localities

Twelve promising experimental hybrids and six commercial hybrids were evaluated, the latter used as controls (Table 1). The experiments were established in five localities in the tropics (Lodana, Jipijapa, and Tosagua, province of Manabí, and Mocache, province of Los Ríos) and Ecuadorian highlands (Zapotillo, province of Loja; Figure 1); sowing was done in January (rainy season) of 2016, 2017 and 2018 (Table 2).

Table 1. Maize hybrids used in the adaptability and stability study during 2016, 2017, and 2018 in Lodana, Jipijapa, and Tosagua (Manabí); Mocache (Los Ríos); and Zapotillo (Loja), Ecuador

Genotype	Genealogy	Type of hybrid	Development phase
G1	G.I.2. 10-1-1-1 X L.I.4	Simple	Experimental
G2	G.I.1. 14-2-1-1 X G.I.2. 18-2-1-1	Simple	Experimental
G3	G.I.2. 10-1-1-1 X POB.3F4.27-1-1-1	Simple	Experimental
G4	G.I.2. 38-3-1-1 X G.I.1. 9-2-1-1	Simple	Experimental
G5	G.I.2. 25-1-1-1 X L.I.4	Simple	Experimental
G6	G.I.2. 25-1-1-1 X POB.3F4.27-1-1-1	Simple	Experimental
G7	G.I.1. 9-2-1-1 X G.I.2. 18-2-1-1	Simple	Experimental
G8	G.I.2. 10-1-1-1 X PORT.PHAEO. 1AS2. 4-1-1-1	Simple	Experimental
G9	G.I.2. 27-3-1-1 X G.I.1. 9-2-1-1	Simple	Experimental
G10	G.I.3. 39-3-1-1 X PORT.PHAEO. 1AS2. 4-1-1-1	Simple	Experimental
G11	G.I.2. 25-1-1-1 X G.I.3. 39-3-1-1	Simple	Experimental
G12	G.I.3. 4-3-1-1 X G.I.1. 9-2-1-1	Simple	Experimental
G13	INIAP H-553 (T)	Simple	Commercial
G14	INIAP H-601 (T)	Simple	Commercial
G15	INIAP H-602 (T)	Simple	Commercial
G16	INIAP H-603 (T)	Simple	Commercial
G17	DEKALB-7088 (T)	Simple	Commercial
G18	TRUENO (T)	Double	Commercial

Source: Own elaboration.

DOI: https://doi.org/10.21930/rcta.vol25_num3_art:3501

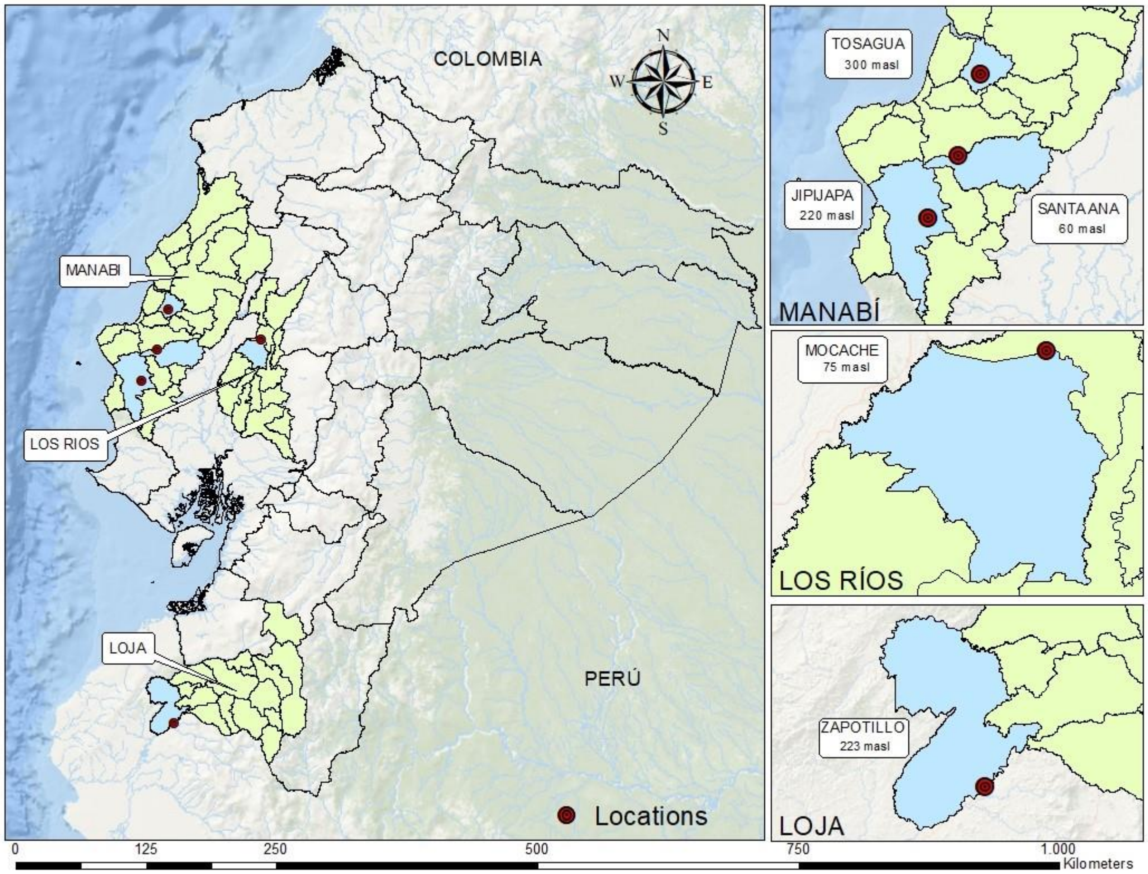

Figure 1. Location of provinces and sites where the experiments were carried out.
Source: Own elaboration.

Table 2. Environmental conditions recorded in experiments conducted during the rainy season (January to June) at five localities in Ecuador from 2016 to 2018

Localities	Altitude (masl)	Average temperature (°C)			Relative humidity (%)			Solar radiation (Hours)			Rainfall (mm)		
		2016	2017	2018	2016	2017	2018	2016	2017	2018	2016	2017	2018
Santa Ana	60	27.8	26.9	26.9	84.5	82.3	80.3	597	658	610	750	947	650
Jipijapa	220	26.2	26.5	26.3	80.5	83.8	84.2	596	417	439	851	1,101	831
Tosagua	300	27.1	26.8	26.0	82.0	83.8	82.2	545	666	533	933	1,295	698
Mocache	75	26.0	25.7	25.0	86.2	86.7	86.2	548	548	466	1,996	3,129	1,374
Zapotillo	223	27.9	27.6	27.5	83.0	83.8	84.0	620	670	650	820	950	760

Source: Own elaboration based on INAMHI (National Institute of Meteorology and Hydrology) data retrieved from https://www.inamhi.gob.ec/.

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Experiment Management

Seeds were sown at a distance of 0.2 m and rows 0.8 m apart to a final population of 62,500 plants ha^{-1}. The weeds were managed before and after sowing with pre-emergent and selective herbicides Alaclor (4 $L.ha^{-1}$) and Terbutryn (0.8 $L.ha^{-1}$), plus a manual weeding complemented by the application of paraquat (1.5 $L.ha^{-1}$), mainly to handle lianas or vines. Insect pests (sucking insects and Lepidoptera) were controlled by seed treatment (thiodicarb + imidacloprid; 0.25 $L.ha^{-1}$), and foliar sprays with thiodicarb + imidacloprid (0.25 $L.ha^{-1}$) and cyhalothrin-lambda (0.2 $L.ha^{-1}$). Three applications were made for fertilization; the first was performed 10 days after sowing (das) with Nutrimenores II® (Zn 4 %, Mn 2.5 %, Cu 1 %, B_2O_3 1.5 %, S 5 %, and Zeolite; 75 $kg.ha^{-1}$) + magnesium sulfate ($MgSO_4$; 50 $kg.ha^{-1}$) + potassium chloride (KCL; 100 $kg.ha^{-1}$); for the second and third fertilization YaraMila® (23 N, 10 P_2O_5, 5 S; 92 kg of N ha^{-1}) was applied at 20 and 40 das.

Analysis of Agronomic Parameters

The recommendations of the International Maize and Wheat Improvement Center (CIMMYT, 1995) were followed for genotype evaluation. Female flowering (FF; days), plant height (PH; cm), cob insertion height (CIH; cm), root lodging (RL; %), stalk lodging (SL, %), number of plants harvested (NPH), number of cobs per plot (NCP), and grain yield (GY; t ha^{-1} adjusted to 13 % moisture) were evaluated.

Evaluation of Diseases

Diseases affecting the leaf area, as well as cobs, were evaluated at 80 das. The severity of Curvularia leaf spot (CLS; *Curvularia lunata* Wakker Boedijn), gray leaf spot (GLS; *Cercospora zeae-maydis* Tehon & E.Y. Daniel), northern leaf blight (NLB; *Exserohilum turcicum* Pass. K.J. Leonard & Suggs), corn stunt (CS; *Spiroplasma kunkelii* Whitcomb et al. 1986), and common rust (CR; *Puccinia sorghi* Schwein) were estimated according to the CIMMYT (1995) scale from 1 (absence of disease) to 5 (very severe infection). After harvest, the aspect of the cob (AC) was assessed, considering damage by diseases and insects, cob size, grain filling, and uniformity of cobs according to a scale of 1 to 5, where 1 is optimum and 5, very deficient (CIMMYT, 1995). The cob rot incidence (CRI; %) was also measured.

Experimental Design and Statistical Analysis

A randomized complete block design was used with three replications in each locality and year. Before performing the analysis of variance (ANOVA) in each variable for each year, the normality of residuals (Shapiro-Wilk test) and homogeneity of variances (Bartlett's test) were verified. When there was statistical significance, mean comparisons were made using Tukey's test (p <0.05). Spearman correlation analysis (p <0.05) among all quantitative variables was performed. The analyses were performed with the free R Development Core Team package (2022) version 4.0.4.

The parameters of adaptability and stability were estimated using the bi-segmented regression method proposed by Cruz et al. (1989). The adaptability parameters considered were the mean

(b_0) and the linear response to both unfavorable (b_1) and favorable environments ($b_1 + b_2$). The stability of the genotypes was assessed by the deviations of the regression σ^2ij of each material, according to the environmental variances (Eberhart & Russel, 1966), using the following model:

$$Y_{ij} = b_{0i} + b_{1i}I_j + b_{2i}T(I) + \delta_{ij} + e_{ij}$$

Where: Y_{ij}: average of hybrid i in environment j and I_j: environmental index; $T(I_j) = 0$ if $I_j < 0$; $T(I_j) = ij - I$ if $ij > 0$, where I is the mean of the positive I_j indices; b_{0i}: overall mean of hybrid i; b_{1i}: linear regression coefficient associated with unfavorable environments; $b_{1i} + b_{2i}$; linear regression coefficient associated with favorable environments; δij: deviation from linear regression; e_{ij}: experimental error. The analyses related to the adaptability and stability of corn genotypes were performed with the GENES program version 1900.2019.120 (Cruz, 2013).

Results and Discussion

Environmental conditions varied among the localities studied (Table 2). Jipijapa showed solar radiation averages of 417 and 439 light hours year^{-1}, with a relative humidity varying from 80.5 % to 84.2 % and precipitation between 831 and 1,101 mm year^{-1}. The average temperature was 26 °C in the three years. In Zapotillo, solar radiation fluctuated between 620 and 670 light hours per year, with an average temperature of 27 °C and relative humidity of 83–84 %. In this locality, the precipitation varied from 760 to 950 mm year^{-1}. Santa Ana had average relative humidity values of 80.3–84.5 % and total precipitation of 650–750 mm year^{-1}. Solar radiation was 597658 light-hours year$^{-1,}$ and the average temperature was 26.9–27.8 °C. In Mocache, total precipitation was between 1,374 and 3,129 mm year^{-1}, with a relative humidity of 86 %. The average temperature was 25–26 °C, with solar radiation of 466–548 light hours year^{-1}. In Tosagua, the humidity values were 82–83.8 %, with precipitation of 698–1,295 mm year^{-1}. The average temperature was 26 °C–27.1°C, and solar radiation was 533–666 light hours year$^{-1.}$

Agronomic Performance of Hybrids

In 2016 and 2017, the overall average recorded in FF was 53.6 days, while in 2018, it increased by 1.8 days; the hybrids G13 with 51.7 days in 2016, G8 with 52.1 and 53.0 days in 2016 and 2017, and G7 with 53.5 days in 2018 stood out for their greater precocity. G5 flowered later than the other genotypes (Figure 2). Regarding PH (Figure 2), the commercial hybrid G18 (TRUENO) reported the lowest heights during the three years of evaluation, with an average of 242.7 cm. Contrarily, G15 (INIAP H-602) recorded the highest heights during 2016 and 2018, with 292.7 and 305. 6 cm, respectively. In terms of CIH, in 2016, the promising hybrid G9 had the lowest value at 132.3 cm, while G5, G6, and G10 showed the highest means (between 156.5 and 157.7 cm). In 2017, the commercial hybrid G13 (INIAP H-553) exhibited the lowest CIH of 121.5 cm, while the promising hybrid G1 showed the highest CIH of 146.3 cm. During the 2018 evaluation, G13 again reported the lowest CIH of 138.6 cm (Figure 3B). Our results show that specific phenotypic characteristics are intrinsic responses of each hybrid and do not result from climatic variations (Figure 2).

DOI: https://doi.org/10.21930/rcta.vol25_num3_art:3501

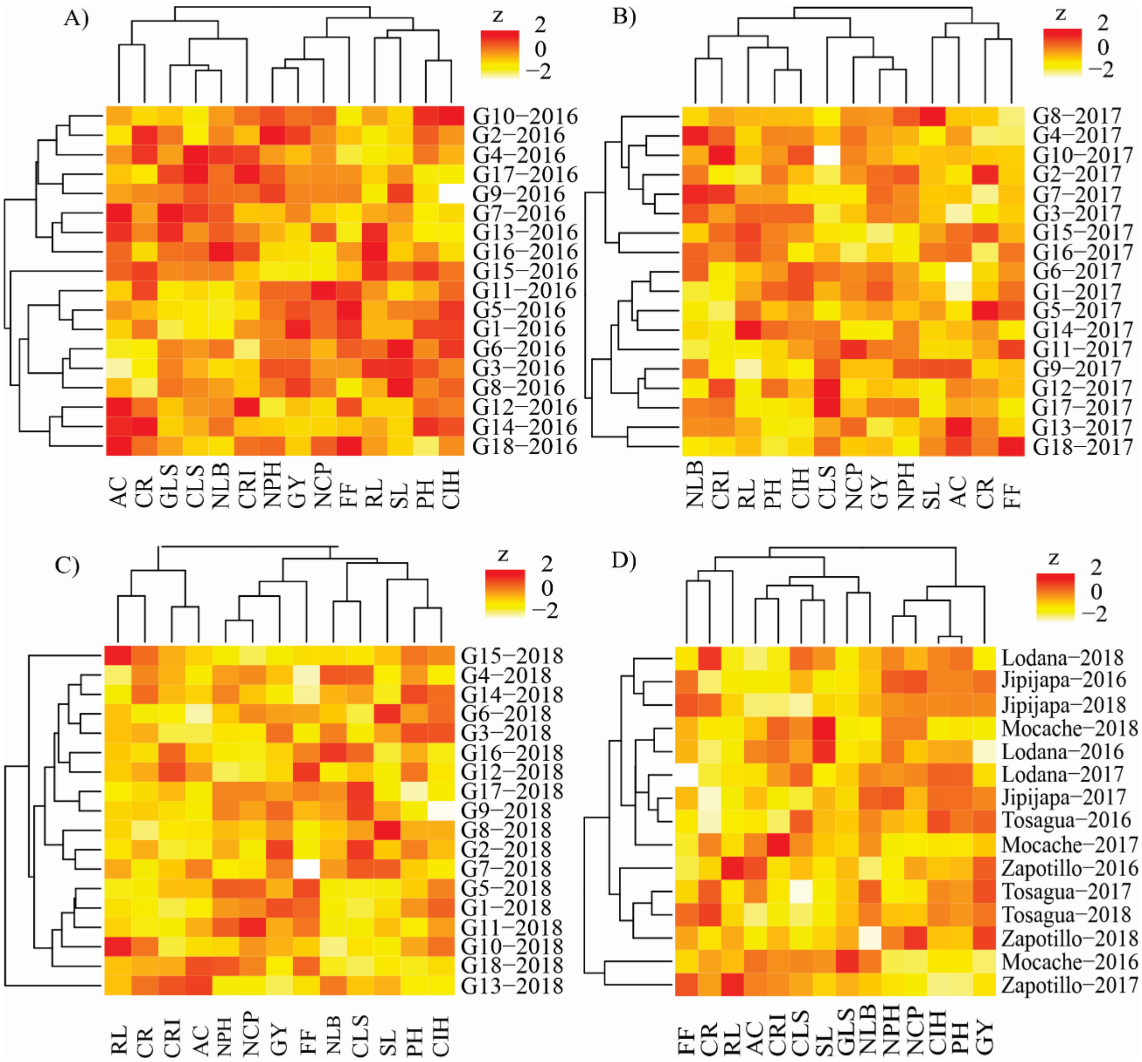

Figure 2. Heat map diagram corresponding to 14 traits evaluated in 18 corn hybrids. Genotype behavior in the harvest for A) 2016, B) 2017, and C) 2018. D) Environmental conditions evaluated. Female flowering (FF), plant height (PH), cob insertion height (CIH), root lodging (RL), stalk lodging (SL), number of plants harvested (NPH), number of cobs per plot (NCP), Curvularia leaf spot (CLS), gray leaf spot (GLS), northern leaf blight (NLB), common rust (CR), aspect of the cob (AC), cob rot incidence (CRI), and grain yield (GY) in t ha^{-1}. The intense red color indicates the highest value, while shades ranging from yellow to white indicate lower values. Source: Own elaboration.

The differences of maize hybrids in their phenological and reproductive phases evaluated in different environments denote specific behaviors in genotypes for various environmental conditions, which would confirm the effect of G × E interaction. In the production of corn, farmers prefer hybrids with lower PH to avoid plant lodging and ensure good grain production. Temperature is one of the components that most influence the phenological characteristics of corn (Yzarra et al., 2009). Therefore, instead of modifying or selecting a single gene that leads to a desired attribute, it is necessary to give a holistic view of the flowering process. Likewise,

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determining the genes that particularly affect flowering in each family and/or genus of plants would allow a guided selection of varieties, hybrids, or ecotypes according to the desired characteristics (early, intermediate, or late flowering), their responses to specific environmental stimuli or internal signaling mechanisms such as age and the circadian cycle, and external ones such as photoperiod and temperature, which result in a certain flowering time in plants (Sánchez-Villarreal, 2016).

In 2016, the promising hybrid G12 showed the lowest RL with an average of 0.3 %, while commercial hybrids G13, G15, and G16 had values higher than 8 % (Figure 2). In 2017, G2, G11, and G17 reported lower values of RL at 1.1 %, while G14 and G15 showed higher lodging at 6.8 % and 8.9 %, respectively. Finally, in 2018, the highest mean lodging was found in G15, with 6.8 %. Conversely, in this same year, G2, G11, G12, G17 (DEKALB-7088), and G18 (TRUENO) showed no lodging. In general, G17 (2017) and G18 (2016 and 2018) recorded the lowest lodging values (<1.2 %), while G3, G6, G8 (2016), and G8 (2017 and 2018) reported the highest means (>8.8 %). Corn plants can be affected by strong winds combined with heavy rains, which partially uproot the soil, significantly reducing their interception of light and GY (weight and quality), something that is increasingly frequent worldwide (Lindsey et al., 2021), as well as in different localities in Ecuador. Another problem resulting from the lodging of corn plants is that they become more susceptible to insect pests because of the wounds they generate (Guo et al., 2019). Farmers on the Ecuadorian coast and in the spurs of the Andes generally establish their corn crops at the beginning of the winter season to take advantage of precipitations. However, these precipitations in many localities are abundant and usually associated with excessive winds that can cause corn plants to become lodged, significantly affecting yields and causing higher incidences of leaf spots.

Evaluation of Aerial Organ Diseases

One of the major attributes to consider in a corn breeding program is the resistance or tolerance of corn genotypes to diseases of aerial organs. In general, the response of corn hybrids to the natural infection of pathogens each year was differentiated (Figure 2). For example, G3 recorded the best AC, showing lower damage by biotic factors and optimal cob size in all years evaluated (Figure 2).

The cob rot incidence in 2016, 2017, and 2018 was 8.2 %, 10.8 %, and 5.3 %, respectively. G13, G17, and G10, with 12.3 %, 13.1 %, and 14.7 %, respectively, had the highest incidence of cob rot compared to the other genotypes, where G6 (4 %, 2016), G11 (7 %, 2017), G18 (6.8 %, 2017), and G1 (2.4 %, 2018) stood out, with a lower incidence in at least one of the years evaluated (Figure 2). Although cob rot can be associated with pathogenic fungi, *i.e.*, *Fusarium proliferatum*, *F. subglutinans*, *F. verticillioides*, *Stenocarpella macrospora*, *S. maydis*, among others (Casa et al., 2006; Lanza et al., 2017; Logrieco et al., 2002), there are still no reports on their etiology or incidence in Ecuador. From the point of view of food safety, we must consider that some pathogens, such as *F. verticillioides* (teleomorph *Gibberella moniliformis*), produce mycotoxins in corn kernels that include fumonisins, being potentially dangerous when consumed by animals and humans (Lanubile et al., 2017; Lanza et al., 2017). On the other hand, it is known that fungi, such as *Stenocarpella* spp. and *E. turcicum*, can be spread by seeds (Casa et al., 2006; Kumar et al., 2022), serving as a source of inoculum. Even both pathogens can cause leaf spots in corn crops.

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In recent years, the cob rots in corn have been increasing. Thus, genotypes such as G1 could be a good option when selecting genotypes of that crop against this biotic factor.

In 2016, greater NLB damage was observed in G4 (3.2) compared to G1, G5, and G18, which recorded the lowest incidence (2.3). In 2017, G4 and G6 recorded the highest values of NLB (3.3 on average), while in 2018, G13 (2.9) was the most affected. G18 was the least affected during the three years of evaluation. Regarding the CLS attack, G18 obtained the lowest incidence of the disease during the years evaluated, while G1 and G11 showed the lowest incidence only in 2018. G17 was the most affected by the disease (Figure 2). G8 was shown as the most tolerant to CR in 2016 (1.2) and 2018 (2.4), and G4 had good behavior in 2017 (1.8). Concerning the GLS, G18 showed the lowest incidence (1.6) in 2016; the highest value was obtained by G7 and G17 (1.8). In 2017 and 2018, GLS was absent in all hybrids (Figure 2).

All diseases detected and evaluated in corn genotypes indirectly affect crop yield (Garcés-Fiallos et al., 2012; Kumar et al., 2022; Limongi-Andrade et al., 2018). In our study, we noticed variations in the severity of diseases impacting the leaf area of different types of corn plants. Notably, the commercial hybrid "TRUENO" (G18) stood out. Until now, there has been a lack of information regarding this specific genotype. Hence, its favorable reaction to NLB, CLS, and GLS diseases holds significant commercial value in Ecuador. Although we assessed diseases in several corn genotypes, there are still many things to investigate, for example, the characterization of the causal agents of leaf diseases, the possible relationship between leaf spots and cob rot, and the implication of possible mycotoxins associated with fungi in cobs.

Grain Yield

Regarding GY, statistically significant differences (p <0.01) were found for localities, hybrids, and their interaction (Table 3). This behavior is predictable because environmental influence can adversely affect or favor the productive performance of corn hybrids (Gabriel et al., 2018; Tirado et al., 2019; Vázquez-Carrillo et al., 2020). In 2016, GY varied from 3.5 t ha^{-1} (G18 - TRUENO) in Lodana, Manabí, to 11.2 t ha^{-1} (G1) in Zapotillo, Loja, noting a 3.2-fold difference between one value and another. When all locations were grouped this year, G1 had the highest yield (7.6 t ha^{-1}), while INIAP H-602 (G15) and TRUENO (G18) had a lower yield with 5.3 and 5.7 t ha^{-1}, respectively. For 2017, the highest yield was found in G6 in Jipijapa, Manabí, with 9.6 t ha^{-1}, while the lowest production was detected in G13 (INIAP H-553) and G15 (INIAP H-602) in Zapotillo, Loja, with a mean of 3.6 t ha^{-1}. In 2018, experimental hybrid G1 (G.I.2. 10-1-1-1 X L.I.4) had the highest GY in most of the locations studied, with an overall mean of 8.9 t ha^{-1}, while G13 (INIAP H-553) showed the lowest yield in all the locations studied, with an average of 4.7 t ha^{-1} (Table 3; Figure 2).

The average GY of commercial hybrids was higher (7.2 t ha^{-1}) than experimental hybrids (5.9 t ha^{-1}; Figure 2). These results are like those recorded by Gordón et al. (2018) in an evaluation of yellow corn hybrids in the agroclimatic conditions of the corn zone of the Azuero Region (Panamá), where the average yield was 7.53 t ha^{-1}, with a variation of 6.20–8.95 t ha^{-1}. However, these yields are lower than those reported by Gabriel et al. (2018), who identified a variation of 9.45–11.1 t ha^{-1} in topcrosses corn hybrids in Brazil and yields in corn hybrids in Mexico (9–12.4 t ha^{-1}; Vázquez-Carrillo et al., 2020).

DOI: https://doi.org/10.21930/rcta.vol25_num3_art:3501

G1 was the most outstanding, registering 8.15 t ha^{-1} in the average yield of corn grains (Table 3; Figure 2), values higher than those reported by other authors such as Vera-Avilés et al. (2013) and Caicedo et al. (2017), who evaluated different promising and commercial hybrids of corn in different locations of the Ecuadorian Coast, finding yields between 4.5 and 8.3 t ha^{-1}. In corn productivity, the genotype-environment interaction is crucial in GY. Due to the varying behavior of genotypes across environments, it is necessary to evaluate experimental genotypes in multiple environments before recommending hybrids. This evaluation aims to estimate productivity associated with adaptability and stability, thereby making technological recommendations to maximize hybrid productivity.

Correlation Between Agronomic and Sanitary Variables

Significant associations were found between the characteristics evaluated in corn hybrids (Figure 3). There was a correlation between CLS and GLS (*r* = 0.8***) and CR (*r* = -0.85***) and between GLS and CR (*r* = -0.78***). Few studies have shown correlations between diseases, particularly in maize or other grasses. For example, Garcés-Fiallos and Gamarra-Yánez (2014) identified a relationship between charcoal rot (*Macrophomina phaseolina*) and root rot (*Rhizoctonia solani*) in common bean. However, the biological interaction between foliar diseases in maize is not yet understood.

AC was positively correlated (*r* = 0.41** to 0.58***) with the severity of almost all diseases analyzed except CR. In fact, this disease latter was negatively correlated with AC (*r* = -0.58***). These results could be explained by the fact that all leaf spot pathogens also cause ear rot or affect the kernel in maize. For example, *Bipolaris maydis*, *C. lunata*, and *E. turcicum* can cause kernel rot on corn (Bankole et al., 2022; Levy & Leonard, 1990). On the other hand, CRI correlates positively with NLB (*r* = 0.73***) and AC (*r* = 0.60***) and negatively with GY and its components. This would prove the possible biological link between foliar diseases with cob rot and GY reduction.

Our research also found a positive correlation between flowering and CR (*r* = 0.56***) and yield components (*r* = 0.34* to 0.54***) and a negative correlation with disease severity (*r* = -0.34** to -0.58***) and AC (*r* = -0.59***). Although it is known that diseases such as GLS (Reis et al., 2007) and NLB (De Rossi et al., 2022) are negatively correlated with GY, reaching damage of up to 47.6 kg ha^{-1} in susceptible corn hybrids, in Ecuador, it is unknown. However, the relationship between diseases and GY significantly contributes to understanding the relationship between diseases and corn crop production. Perhaps, in the future, it would be interesting to quantify the damage caused by diseases in crop yield by generating damage models such as those developed by De Rossi et al. (2022) and Reis et al. (2007)

There were significant correlations between GY and the component variables of yield (NCP, *r* = 0.69***; NPH, *r* = 0.75***). GY was also positively correlated with PH (*r* = 0.42**) and CIH (*r* = 0.51***), indicating that adequate densities that conserve all their production units maintain uniformity in PH and cob production. According to Briones-Ochoa et al. (2023), in the locality of Jauneche, Palenque canton, Los Ríos province, Ecuador, the highest yields were observed in the plots of the ADV-9139 hybrid treated and untreated with pesticides, whose plants showed the lowest values of cob height and insertion, while the lowest yields were detected in INIAP-551, with a significantly higher cob height and insertion.

DOI: https://doi.org/10.21930/rcta.vol25_num3_art:3501

Cienc. Tecnol. Agropecuaria, *25*(3): e3501 ISSN: 0122-8706 ISSNe: 2500-5308
DOI: https://doi.org/10.21930/rcta.vol25_num3_art:3501

Table 3. Average grain yield (t ha^{-1}) of 18 maize hybrids evaluated in five localities during the rainy seasons of 2016, 2017, and 2018.

Localities	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	G12	G13	G14	G15	G16	G17	G18	Average
Genotype (year 2016)																			
Lodana	6.5 a	4.6 b-f	5.6 a-d	4.4 b-f	5.4 a-e	6.0 ab	4.6 b-f	5.7 abc	5.0 a-f	5.2 a-f	5.3 a-f	3.7 ef	4.0 c-f	4.1 c-f	3.8 def	4.4 b-f	4.7 b-f	3.5 f	4.8 C
Jipijapa	9.1 abc	9.8 ab	10.3 a	8.8 a-d	8.8 a-d	9.2 abc	10.0 a	9.5 ab	9.0 a-d	9.4 abc	10.2 a	8.1 b-e	8.6 a-d	7.6 cde	6.6 e	7.2 de	8.7 a-d	6.5 e	8.7 A
Tosagua	8.1 ab	8.2 ab	8.0 ab	7.5 abc	8.2 ab	7.7 abc	7.2 abc	8.0 ab	7.5 abc	8.4 a	8.2 ab	6.8 abc	6.5 bc	5.9 c	7.2 abc	6.7 abc	7.7 abc	6.6 abc	7.5 B
Mocache	3.2 a	3.3 a	3.3 a	3.0 a	3.5 a	3.8 a	2.8 a	3.1 a	3.4 a	3.9 a	3.3 a	2.7 a	3.4 a	3.4 a	2.6 a	3.7 a	4.3 a	3.2 a	3.3 D
Zapotillo	11.2 a	9.6 abc	9.3 bc	8.7 b-e	10.1 ab	8.8 b-e	9.0 bcd	8.9 b-e	9.2 bcd	9.3 bc	9.6 abc	8.3 cde	7.1 ef	8.0 c-f	6.4 f	7.4 def	9.4 abc	8.1 c-f	8.8 A
Average	7.6 a	7.1 ab	7.2 ab	6.6 b-e	7.2 ab	6.9 ab	6.9 ab	7.3 ab	6.8 abc	7.1 ab	7.3 ab	6 c-f	5.9 def	5.9 ef	5.3 f	5.8 ef	6.8 bcd	5.7 f	
Genotype (year 2017)*																			
Lodana	8.1 a	6.6 a-e	6.9 a-e	6.2 a-e	7.7 abc	7.3 a-d	5.9 b-f	8.1 a	5.7 c-f	6.7 a-e	7.9 ab	4.9 ef	3.8 f	5.8 b-f	5.3 def	5.4 def	5.6 c-f	5.5 def	6.3 D
Jipijapa	9.4 ab	7.9 a-e	6.9 d-g	8.7 a-d	7.9 a-e	9.6 a	7.3 b-f	7.2 c-g	7.1 c-g	6.5 efg	8.1 a-e	8.1 a-e	5.4 fg	5.6 fg	5.1 g	6.7 d-g	9.1 abc	6.2 efg	7.4 B
Tosagua	9.0 a	8.2 ab	8.6 a	8.9 a	7.9 abc	8.7 a	9.1 a	8.7 a	8.9 a	8.3 ab	8.2 ab	8.1 abc	5.9 c	7.5 abc	6.3 bc	7.4 abc	8.5 a	5.9 c	8.0 A
Mocache	8.3 a	7.5 ab	6.8 abc	6.7 abc	7.4 ab	6.8 abc	7.2 abc	7.9 ab	6.6 abc	7.7 ab	7.1 abc	6.2 abc	5.1 c	6.1 bc	5.1 c	6.0 bc	7.3 ab	6.4 abc	6.8 C
Zapotillo	4.7 ab	5.0 ab	5.1 ab	5.1 ab	4.4 ab	5.0 ab	4.9 ab	5.2 ab	5.7 ab	5.5 ab	5.5 ab	4.4 ab	3.6 b	4.3 ab	3.6 b	4.2 ab	6.3 a	4.4 ab	4.8 E
Average	7.9 a	7 cde	6.9 ef	7.1 c	7.1 cd	7.5 b	6.9 def	7.4 b	6.8 f	6.9 c-f	7.4 b	6.4 g	4.7 k	5.9 hi	5.1 j	5.9 h	7.4 b	5.7 i	
Genotype (year 2018)																			
Lodana	8.6 a	6.7 a-d	8.1 ab	6.8 a-d	7.1 abc	8.1 ab	6.9 a-d	7.9 ab	7.0 abc	7.3 abc	6.7 a-d	5.5 bcd	4.3 d	5.9 bcd	5.1 cd	7.5 abc	6.9 a-d	5.9 bcd	6.8 C
Jipijapa	9.5 ab	9.0 abc	8.7 abc	9.7 a	8.4 abc	8.9 abc	7.3 a-d	8.2 a-d	8.6 abc	7.6 a-d	8.3 abc	7.4 a-d	5.6 d	8.2 a-d	6.9 bcd	8.4 abc	9.1 abc	6.6 cd	8.1 A
Tosagua	7.8 abc	7.6 abc	8.2 abc	7.3 a-d	8.0 abc	7.8 abc	8.5 abc	9.2 ab	9.4 a	7.1 a-d	6.6 bcd	7.8 abc	4.8 d	7.2 a-d	8.2 abc	7.9 abc	8.9 ab	6.2 cd	7.7 B
Mocache	9.2 a	7.2 abc	7.8 ab	6.3 bcd	7.3 abc	6.3 bcd	6.5 abc	6.3 bcd	6.2 bcd	7.4 abc	7.4 abc	6.0 bcd	3.7 d	5.5 bcd	4.8 cd	5.2 bcd	7.2 abc	5.6 bcd	6.4 C
Zapotillo	9.6 a	9.0 a	9,1 a	9.3 a	9.2 a	9.3 a	9.1 a	9.1 a	10.5 a	9.3 a	8.7 a	8.2 a	5.4 b	8.4 a	8.1 a	8.4 a	8.2 a	7.8 ab	8.7 A
Average	8.9 a	7.9 abc	8.4 ab	7.9 abc	8.0 abc	8.1 abc	7.6 b-e	8.1 abc	8.3 ab	7.7 a-d	7.6 b-e	7.0 cde	4.7 f	7.1 cde	6.6 de	7.5 b-e	8.1 abc	6.4 e	

Means followed by the same letter do not differ statistically according to Tukey's test (p <0.05). *Analysis of variance performed with data transformed by the square root of the primary values. Lowercase letters in the lines represent the comparison of the hybrids in each locality, while the uppercase letters in the last column represent the comparison between localities. Source: Own elaboration.

This type of criterion is supported by Possatto-Junior et al. (2017), who found that the environments where greater responses were observed in PH were associated with a higher GY in the Central-South regions of Paraná and Northwest of Minas Gerais, Brazil. This would demonstrate that increased corn production is conditioned by hybrids that have good phenotypic characteristics and manage to stabilize their genotype to the various environments where they are established.

SL was also positively correlated with PH (*r* = 0.42**) and CIH (*r* = 0.43**), suggesting that SL in corn could be conditioned by high PH. Cardoso et al. (2000) mentioned that in addition to establishing a greater number of plants per area, corn cultivars with lower PH and CIH allow a greater tolerance to RL and SL. Furthermore, García and Watson (2003) found that PH and CIH had a moderate and negative correlation with low rates of plant lodging. In this way, PH should be used as selection criteria for corn breeding programs.

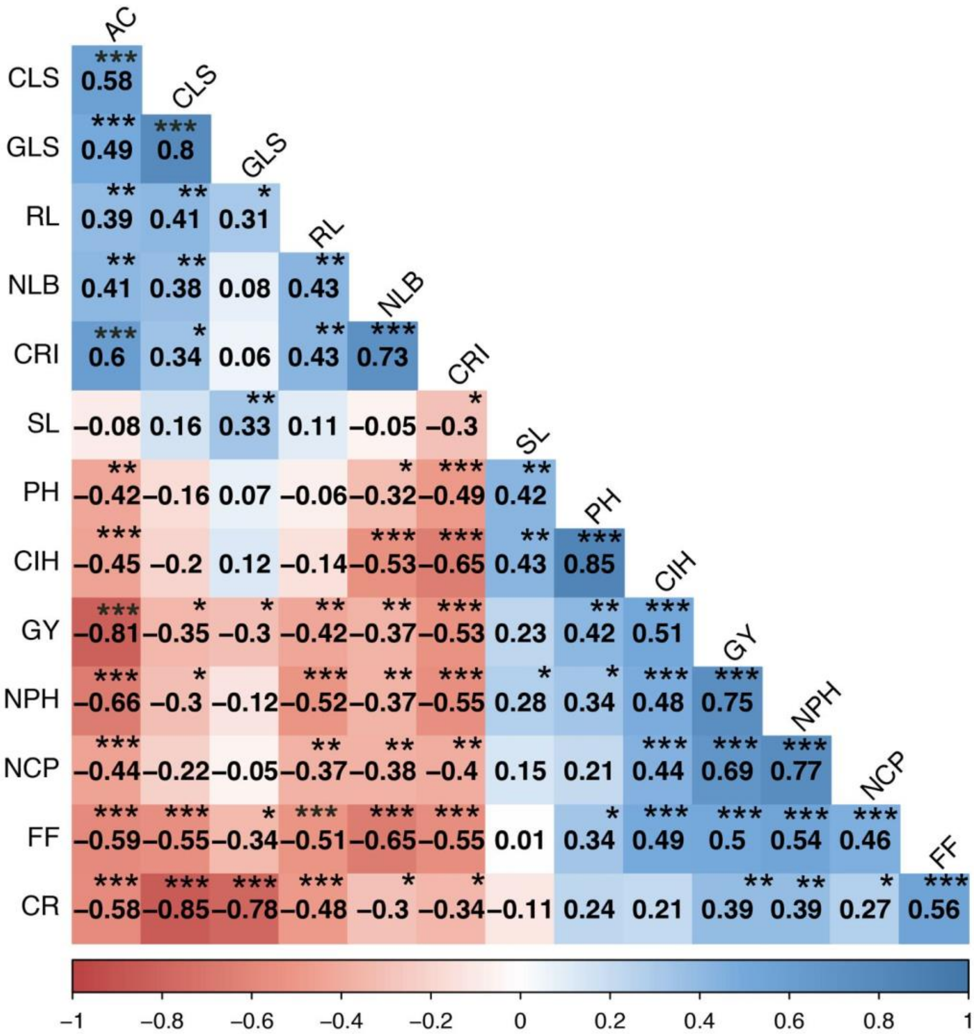

Figure 3. Spearman correlation analysis (p <0.05) between female flowering (FF), plant height (PH), cob insertion height (CIH), root lodging (RL), stalk lodging (SL), number of plants harvested (NPH), number of cobs per plot (NCP), Curvularia leaf spot (CLS), gray leaf spot (GLS), northern leaf blight (NLB), common rust (CR), aspect of the cob (AC), cob rot incidence (CRI), and grain yield (GY) in t ha^{-1}.
Source: Own elaboration.

DOI: https://doi.org/10.21930/rcta.vol25_num3_art:3501

Adaptability and Stability

Jipijapa, Manabí, and Zapotillo, Loja showed the best performance in corn grain production in at least two years of evaluation (Table 4; Figure 2). It is important to point out that Tosagua (Manabí) is the most stable to produce corn hybrids because it performed well in all three years evaluated. Lodana (Manabí) and Mocache (Los Ríos) were classified as unfavorable environments, exhibiting lower performance for corn production with the hybrids used in the study (Table 4).

Table 4. Environmental indices of the localities for each year of evaluation

Environments		Average ± SEM	Index (Ij)	Condition
Year	Locality			
2016	Lodana	4.80 ± 0.13	-2.14	Unfavorable
2016	Jipijapa	8.74 ± 0.17	1.79	Favorable
2016	Tosagua	7.47 ± 0.11	0.53	Favorable
2016	Mocache	3.33 ± 0.09	-3.62	Unfavorable
2016	Zapotillo	8.80 ± 0.18	1.85	Favorable
2017	Lodana	6.29 ± 0.17	-0.66	Unfavorable
2017	Jipijapa	7.38 ± 0.21	0.43	Favorable
2017	Tosagua	8.01± 0.16	1.06	Favorable
2017	Mocache	6.79 ± 0.14	-0.16	Unfavorable
2017	Zapotillo	4.83 ± 0.12	-2.12	Unfavorable
2018	Lodana	6.79 ± 0.17	-0.16	Unfavorable
2018	Jipijapa	8.13 ± 0.20	1.18	Favorable
2018	Tosagua	7.70 ± 0.20	0.76	Favorable
2018	Mocache	6.43 ± 0.19	-0.52	Unfavorable
2018	Zapotillo	8.70 ± 0.17	1.75	Favorable

SEM: standard error of the mean
Source: Own elaboration.

The adaptability and environmental stability estimators of corn hybrids have been widely used for productive and phytosanitary performance in the final stages of the commercial development of new materials, taking a wide range of univariate and multivariate procedures as tools (Akbar et al., 2021; González et al., 2007). Their selection is a function of the homogeneity of the area under study. For example, Possatto-Junior et al. (2017) mention that environments with average productivity above the general average are classified as favorable environments, and environments with lower averages are considered unfavorable. This would result in an environmental index that would first allow setting the parameters of environmental differentiation between the hybrids studied.

For the evaluation of localities when studying corn hybrids, the factors that can be controlled and affect grain production should be minimized because they could mask the real potential of both the locality and the evaluated hybrids. In our study, the G × E interaction is evident in all the years analyzed. These differences between hybrids and inconsistencies in their behavior with environmental fluctuations make it necessary to study the adaptability and stability of hybrids (Carvalho et al., 2002). Other researchers have selected both Lodana (Manabí) and Mocache (Los Ríos) as suitable environments for evaluating hybrids.

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According to Caicedo et al. (2017), the hybrids evaluated in Lodana, Santa Ana (Manabí) obtained the highest GY (7.0 t ha^{-1}), thus showing greater efficiency when discriminating genotypes. In the same way, in the study by Tirado et al. (2019), the locality of Pichilingue, Mocache (Los Ríos) was one of the most representative and discriminating environments for the evaluation of corn hybrids.

The average GY of the hybrids (b_0) ranged from 5.14 t ha^{-1} (G13) to 8.15 t ha^{-1} (G1). Considering the adaptation criterion of Mariotti et al. (1976), G1 is the best adapted (Table 4). Of all hybrids evaluated, 61.1 % (11 hybrids) registered averages higher than the general mean (6.94 t ha^{-1}), thus having a better adaptation (Table 5). It should be considered that the most detailed description of the performance and behavior of a hybrid requires information on its phenotypic stability (Santos et al., 2019).

Table 5. Average values of grain yield (t ha^{-1}) of 18 maize hybrids in favorable and unfavorable environments and estimates of adaptability and stability parameters based on the bi-segmented regression method

Genotype	Means of the environments			b_1	b_2	$b_1 + b_2$	Mean square of desviation	R^2 (%)
	General (Average ± SEM)	Unfavorable	Favorable					
G1	8.15 ± 0.31 a	6.94	9.20	1.12	0.03	1.15	2.78**	80.49
G8	7.60 ± 0.26 b	6.47	8.59	0.91	0.03	0.94	1.12*	87.06
G3	7.48 ± 0.29 c	6.15	8.64	1.10	0.44	1.54	1.02	91.98
G6	7.48 ± 0.29 c	6.02	8.75	1.14	-0.70*	0.45	1.47**	88.37
G11	7.42 ± 0.27 cd	6.19	8.50	0.98	0.39	1.38	1.48**	86.21
G5	7.41 ± 0.28 cde	6.09	8.57	1.06	0.03	1.1	0.81	92.67
G17	7.40 ± 0.28 cde	5.9	8.70	1.07	-0.86**	0.21**	1.31*	88.02
G2	7.34 ± 0.28 def	5.83	8.66	1.13	0.13	1.27	0.41	96.67
G9	7.31 ± 0.31ef	5.62	8.78	1.15	0.23	1.38	1.46**	89.38
G10	7.26 ± 0.26 fg	6.14	8.24	0.95	0.64*	1.59*	0.94	90.63
G4	7.18 ± 0.29 gh	5.56	8.61	1.14	-0.41	0.73	1.03	91.65
G7	7.14 ± 0.28 h	5.67	8.44	1.06	0.3	1.36	0.98	91.45
G12	6.43 ± 0.27 i	4.82	7.84	1.10	-0.65*	0.45	0.78	93.00
G16	6.39 ± 0.26 i	5.11	7.51	0.96	-0.41	0.56	1.2*	87.05
G14	6.26 ± 0.25 j	5.07	7.30	0.83*	0.67*	1.5	0.77	90.30
G18	5.93 ± 0.20 k	5.02	6.73	0.70**	0.23	0.93	0.94	83.20
G15	5.68 ± 0.25 l	4.35	6.84	0.91	-0.57	0.34*	1.9**	78.73
G13	5.14 ± 0.22 m	3.99	6.15	0.68**	0.45	1.13	2.83**	61.86
Average	6.94							

Means followed by the same letter do not differ statistically according to Tukey's test. Significantly different from the unit to b_1 and $b_1 + b_2$, and different from zero to b_2, at *p <0.01* (**) and *p <0.05* (*) according to Student's test. SEM: standard error of the mean.
Source: Own elaboration.

When the hybrids were analyzed in unfavorable environments (b1), INIAP H-553, INIAP H-601, and TRUENO showed little demand in these conditions (b1 < 1). However, no hybrid exhibited high demand under these conditions, evidenced by the non-significance of the estimates of b1 > 1. In favorable environments (b1 + b2), G10 (G.I.3.39-3-1-1 X PORT.PHAEO.1AS2.4-1-1-1) was the most responsive to environmental improvement; 27.8 % of the hybrids (G6, G10, G12, G14, and G17) had a regression coefficient (b2) different from zero, which would imply a better performance by the model used. This behavior was also observed by Santos et al. (2019) in analyzing the stability of 12 corn hybrids in the States of Minas Gerais and Goias, Brazil, where only 33.3 % of the hybrids had a better performance with the bi-segmented regression model.

Fifty percent of the hybrids recorded regression deviations different from zero, indicating unpredictable behavior in the environments studied. However, Cruz et al. (1989) mention that hybrids with coefficients of determination (R^2) >80 % should not have their degrees of predictability compromised. In this way, G2, G3, G4, G5, G7, G10, G12, G14 (INIAP H-601), and G18 (TRUENO) show good stability in the environments evaluated.

According to the model used, the hybrids recommended for unfavorable environments should have high average performance (b_0 > than the overall average), $b_1 < 1$ and $b_1 + b_2 < 1$; while for recommendations in favorable environments, it is b_0 > the overall average, $b_1 > 1$ and $b_1 + b_2 > 1$ (Santos et al., 2019). This study did not identify hybrids that fulfill these conditions in unfavorable and favorable environments. Although our results have also been found in other studies of the adaptability and stability of corn genotypes, our model has allowed us to make recommendations for hybrids for favorable and unfavorable environments (Cardoso et al., 2000; Carvalho et al., 2002; Santos et al., 2019). Thus, G10 could be recommended for favorable environments. In contrast, G18 (TRUENO) could be recommended for its high resilience but with a yield below the mean for unfavorable conditions. In general, considering grain trends and yields, and without statistical significance, promising hybrids G1, G2, G3, G5, G7, G9, and G11 could be interesting in favorable environments, while G8 might be better explored in unfavorable environments.

This research has provided valuable insights into the agronomic performance, adaptability, and stability of maize hybrids for tropical conditions in Ecuador. Nevertheless, a three-year evaluation period may not fully capture long-term environmental variability and climate trends that could affect hybrid performance differently, potentially influencing stability and adaptability estimations. Future studies should extend the evaluation period to encompass more diverse climatic conditions and geographical locations to enhance robustness in hybrid performance assessments. Also, incorporating other statistical models can enhance the understanding of stability estimations and strengthen recommendations for maize hybrid selection across varying environmental conditions.

Conclusions

PH and CIH were strongly correlated. GY was significantly correlated with PH and CIH, NPH, and total cobs harvested. The G × E interaction showed a differentiated behavior of hybrids in each environmental condition studied. G1 (G.I.2. 10-1-1-1 X L.I.4) had better adaptation by registering a high yield of grain in most of the localities studied, while G10 (G.I.3. 39-3-1-1 X PORT.PHAEO. 1AS2. 4-1-1-1) was the most responsive to the environment. In favorable environments, promising hybrids G1, G2, G3, G5, G7, G9, and G11 could be interesting, while G8 could be explored more in unfavorable environments. In at least two years of evaluation, Jipijapa and Tosagua, belonging to Manabí, and Zapotillo, located in Loja, were the best performers in corn grain production. Tosagua was the most stable in producing corn hybrids.

Acknowledgments

We are grateful to Instituto Nacional de Investigaciones Agropecuarias, Estación Experimental Portoviejo (EEP), for developing these genotypes research through Programa Nacional de Maíz.

Authors' Contributions

All authors made written contributions and corrections to the manuscript, as follows: Ricardo Limongi Andrade: conceived the study idea, designed and supervised the experiment; Fernando David Sánchez-Mora: helped in analysis of data, interpretation of the results, writing and reviewing the manuscript; Raúl V. Mora Yela: conducted the experiment and data collection; José Pico Mendoza: conducted the experiment and data collection; Bernardo Navarrete Cedeño: conducted the experiment and data collection; Daniel Alarcón Cobeña: conceived the study idea, designed and supervised the experiment; Geover Peña Monserrate: conducted the experiment and data collection; Jim Ochoa Ramos: conducted the experiment and data collection; Iris Pérez-Almeida: formal analysis, draft writing, and final manuscript; Felipe Garcés-Fiallos: writing up and editing of the manuscript.

Ethical Implications

This research has no ethical implications.

Conflict of Interest

The authors have declared no conflict of interest.

Funding

This study was financed by Instituto Nacional de Investigaciones Agropecuarias through Research Project 527-042: "Generación de híbridos convencionales de maíz para el trópico seco, 2015 – 2025".

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