GENOTYPE-ENVIRONMENT INTERACTION IN TROPICAL MAIZE VARIETIES DEVELOPED FOR THE TROPICAL REGION OF VERACRUZ, MEXICO

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SUMMARY

*In the humid tropics of Mexico, maize (*Zea mays *L.) improved varieties with desirable plant agronomic characteristics and grain quality protein are required. The synthetic varieties of maize are adequate for rainfall agriculture the farmers do not need to buy seeds every year. In order to identify the best synthetics with high grain yield and lower genotype-environment interaction (GEI), eight maize synthetic varieties were evaluated in four sites of the State of Veracruz, Mexico, during 2009, 2010 and 2011. A randomized complete block design with two replications was used. The GEI effect was estimated by using the model of additive main effects and multiplicative interaction (AMMI). Results showed that the two main principal components (PCA) of the model AMMI had not significance (P≥0.05); however, accumulatively they contributed 73% of the total variation. The variance due to environments was greater than that due to genotype differences. According to PCA1, the 'synthetic-2' had a more stable behavior. The AMMI model allowed grouping the environments in two relatively homogeneous groups: the first one formed by the environments E2 and E3, and the second, by E1 and E4. The biplot technique was used to identify genotypes for general or specific adaptability. In conclusion, there were different responses among the synthetic varieties evaluated in the environments, and little association among the high grain yielding varieties and the more productive environments. The best grain yielding genotypes are appropriate to further develop a better variety or to develop inbred lines to form better maize hybrids.*

Introduction

The high consumption of maize (*Zea mays* L.) as a staple food in Mexico requires the production of more nutritive maize grain (Gómez *et al.*, 2003) with agronomic traits that are of interest to the rainfall farmer (Andrés-Meza *et al.*, 2011). Therefore, it is necessary to obtain open-pollinated maize varieties (OPV) with a high performance, which requires new criteria of selection and correct application of improvement methodologies (Padilla *et al.*, 2002). In the humid tropics of Mexico improved maize varieties are needed with favorable agronomic characteristics that are competitive and represent new options to varieties that have already been released, as V-537 C and V-538 C (Gómez *et al.*, 2003; Espinosa *et al.*, 2009).

Synthetic varieties of corn are an accessible alternative because farmers do not require buying seed each year and they are suitable for rainfall agriculture (Márquez, 2008). Genotypes with high and stable yield are thus needed. The genotype-environment interaction (GEI) has an important role in the selection process during the stages of the genetic improvement (Crossa *et al.*, 1990). Stability allows genotype to adjust their productive capacity to wider environmental variations (Lin *et al.*, 1986). The GEI is a source of variation that allows to identify populations with less interaction with the environment and, therefore, broader adaptation; or, in any case, to delineate geographical areas where there is a better adaptability of certain varieties (Carballo and Márquez, 1970). As improved varieties are used in large agricultural areas, their true value will allow to set them appropriate environments (Sierra *et al.*, 1992; Espinosa *et al.*, 1998;

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INTERACCIÓN GENOTIPO–AMBIENTE DE VARIEDADES TROPICALES DE MAÍZ DESARROLLADOS PARA LA REGIÓN TROPICAL DE VERACRUZ, MÉXICO

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RESUMEN

*En el trópico húmedo de México se requieren variedades mejoradas de maíz (*Zea mays *L.) con características agronómicas favorables y de calidad proteínica. Las variedades sintéticas de maíz son una alternativa accesible, porque los agricultores no requieren comprar semilla cada año y son adecuadas para la agricultura de temporal. Con el objetivo de identificar sintéticos de maíz con buen rendimiento y menor interacción genotipo-ambiente (G×A), se sembraron ocho variedades de maíz en cuatro ambientes, durante 2009, 2010 y 2011 en el estado de Veracruz, México. El diseño experimental fue de bloques completos al azar con dos repeticiones. La interacción G×A se estimó con el modelo de efectos principales aditivos e interacción multiplicativa (AMMI). Los resultados mostraron que los dos primeros componentes principales (ACP) del modelo AMMI no fueron significativos (P≥0,05); sin embargo, contribuyeron acumulativamente con 73% de la variación total. La varianza debido a ambientes fue mayor que debido a las diferencias genotípicas. El modelo AMMI permitió agrupar los ambientes en dos grupos relativamente homogéneos: uno formado por los ambientes E2 y E3 y otro por E1 y E4. La técnica de biplot fue usada para identificar variedades para adaptabilidad general o específica. En conclusión, hubo respuestas diferenciales entre variedades sintéticas de maíz en los ambientes evaluados. Se detectó poca asociación entre las variedades de mayor rendimiento y los ambientes más productivos. Los genotipos más productivos identificados pueden ser objeto de mejoramiento adicional para obtener un cultivar superior o implementar estrategias para impulsar el desarrollo de mejores híbridos.*

INTERAÇÃO GENÓTIPO–AMBIENTE DE VARIEDADES TROPICAIS DE MILHO DESENVOLVIDOS PARA A REGIÃO TROPICAL DE VERACRUZ, MÉXICO

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RESUMO

*No trópico úmido de México são requeridas variedades melhoradas de milho (*Zea mays *L.) com características agronômicas favoráveis e de qualidade proteica. As variedades sintéticas de milho são uma alternativa acessível, porque os agricultores no requerem comprar sementes cada ano e são adequadas para a agricultura de subsistência. Com o objetivo de identificar sintéticos de milho com bom rendimento e menor interação genótipo-ambiente (G´A), se plantaram oito variedades de milho em quatro ambientes, durante 2009, 2010 e 2011 no estado de Veracruz, México. O desenho experimental foi de blocos completos aleatório com duas repetições. A interação G´A se estimou com o modelo de efeitos principais aditivos e interação multiplicativa (AMMI). Os resultados mostraram que os dois primeiros componentes principais (ACP) do modelo AMMI não foram significativos (P≥0,05); no entanto, contribuíram cumulativamente com 73% da variação total. A variância devido a ambientes foi maior que devido às diferenças genotípicas. O modelo AMMI permitiu agrupar os ambientes em dois grupos relativamente homogêneos: um formado pelos ambientes E2 e E3 e outro por E1 e E4. A técnica de biplot foi usada para identificar variedades para adaptabilidade geral ou específica. Em conclusão, houve respostas diferenciais entre variedades sintéticas de milho nos ambientes avaliados. Detectou-se pouca associação entre as variedades de maior rendimento e os ambientes mais produtivos. Os genótipos mais produtivos identificados podem ser objeto de melhoramento adicional para obter um cultivar superior ou implementar estratégias para impulsionar o desenvolvimento de melhores híbridos.*

Mejía and Molina, 2003; Sierra *et al*., 2003).

In this regard, multivariate statistical procedures have been developed to estimate the stability and the GEI (Brennan *et al*., 1981; Crossa *et al*., 1990). AMMI (additive main effects and multiplicative interactions) model is one of the most used to estimate the GEI through variance analysis (Gauch and Zobel, 1988; Crossa *et al.,* 1990), as it considered that the effects of the main factors (genotypes and environment) are additive and linear. However, GEI has multiplicative effects which can be explained by principal components analysis (PCA) (Vargas and Crossa, 2000). The AMMI method together with the use of the ‘biplot’, a technique of graphic representation, is a useful tool for interpreting response patterns of genotypes, environments and the GEI (Vargas and Crossa, 2000; Yan *et al*., 2000).

During 1999, after releasing the V-537 C variety, different elite inbred lines of the maize program from the Cotaxtla Experimental Station (CECot) of the National Institute of Forestry, Agricultural and Livestock Research (INIFAP) were converted to the version of quality protein through backcrosses using the line CML-144 as the donor of the character (Andrés-Meza *et al*., 2011), from which seven synthetics with a different number of lines varieties were formed. However, only four of the seven synthetics were included in this study. In order to know the magnitude of the GEI and be able to identify genotypes with good genetic potential in specific environments defined by climate, soil and crop management, the present study was carried out with the object of identifying synthetic maize with good performance and lower GEI.

Materials and Methods

Genetic material

Eight maize genotypes were used, of which four are new synthetic QPM maize varieties (synt-2, synt-3, synt-4, synt-6), integrated with the possible crosses between 9, 11 and 12 lines, with different levels of inbreeding and selected for their high general combining ability (GCA; Andrés-Meza *et al.*, 2011). Two synthetics selected for tolerance to drought (synt-TS6, synt-3 Drought) obtained through recurrent selection during the summer of 1987 (Gómez *et al.*, 2003) and two commercial types (VS-536 and V-537 C) of normal grain and QPM, respectively.

Study area

The genotypes were sown in four environments of the State of Veracruz, Mexico, during the spring 2009 season (Cotaxtla 2009B), spring 2010 season (two environments: Cotaxtla and Tlachiconal 2010B) and winter 2011 season (Cotaxtla 2011A). The sites are located in the region of the Sotavento in the central area of the State at 18°56´N, 96°11´W, at an altitude of 15m. The climate is classed as AW_1 (w), with average rainfall annual of 1350mm, distributed from June to November, and a dry season comprising of December to May (García, 1981).

Experimental

Sowing was made to 'cover foot', which is the traditional procedure in the region. Three seeds were planted by mound every 0.4m and was thinned at two plants (62500 plants/ha). It was fertilized with the 161-46-00 (N, P, K) formula; urea was the source of nitrogen and phosphorus was triple calcium superphosphate. At 10 days after sowing (das) all phosphorus and half of the nitrogen was applied; the rest of the nitrogen was applied 30 das.

A randomized complete block design was used in each environment with two replications. Two-row plots 5m long and row widths at 0.8m were used. The establishment of trials in each location coincided with the start of the rainy season, except for the autumn-winter season, when sufficient irrigation was applied to avoid plant water stress.

Multiplicative statistical models

Grain yield ($t \cdot ha^{-1}$) was the analyzed variable, adjusted to 12% grain moisture. The AMMI model, which considers the variance analysis for effects of genotype and environment, was used and an analysis of major components for the GEI was applied (Gollob, 1968; Gauch and Zobel, 1988; Vargas and Crossa, 2000). The model is

$$Y_{ij}=\mu+g_i+e_j+\sum_{k=1}^{n}\lambda_k\alpha_{ik}\gamma_{jk}+R_{ij}$$

where Y_{ij}: response of the i^{th} genotype in the j^{th} environment j, μ_j: general mean, g_i: effect of the i^{th} genotype, e_j: effect of the j^{th} environment, λ_k: square root of the characteristic of the k^{th} axis vector of the PCA, γ_{ik}: qualification of the PCA for the k^{th} axis of the i^{th} genotype, α_{jk}: qualification of the PCA for the k^{th} axis of the j^{th} environment, and R_{ij}: residual model.

Genotypic and environmental coordinates on the PCA1 and PCA2 were estimated and a two-dimensional graph 'biplot' built, where the variables measured according to these coordinates are represented. The statistical package SAS (SAS, 1990) was used.

Results and Discussion

The combined analysis of grain yield variance (Table I) detected significant differences ($P \leq 0.05$) both environments (E) to genotypes (G); that is, at least one genotype showed different response to the others; the same can be said about the environments. On the contrary, GEI was not significant ($P \geq 0.05$), and thus the decomposition by AMMI (PCA1 and PCA2) does not lead to significance. This implies that, largely, the observed changes are the behavior of genotypes taking place 'parallel' to changes in the environment.

TABLE I
AMMI ANALYSIS FOR GRAIN YIELD ($t \cdot ha^{-1}$) OF EIGHT QPM MAIZE GENOTYPES EVALUATED IN FOUR ENVIRONMENTS (VERACRUZ, MEXICO; 2009-2011)

Sources of variation	DF	Sum of squares	Mean square
Genotypes (G)	7	10.5576	1.51 *
Environments (E)	3	21.0795	7.03 **
GEI	21	8.8261	0.42 ns
PCA1	9	38.6129	4.29 ns
PCA2	7	33.8299	4.83 ns
Error	31	20.0648	0.65
Total			
CV(%)	17		

* $P \leq 0.05$, ** $P \leq 0.01$; ns: non-significant; DF: degrees of freedom; GEI: genotype-environment interaction; CV: coefficient of variation; PCA: principal component analysis.

TABLE II
AVERAGE YIELD AND PCA1 VALUES FOR EIGHT MAIZE GENOTYPES QPM IN FOUR ENVIRONMENTS (VERACRUZ, MÉXICO; 2009-2011)

Núm.	Genotype	Yield ($t \cdot ha^{-1}$)	PCA1
G1	synthetic-2	5.21 a	0.06105
G2	synthetic-3	4.39 ab	0.12960
G3	synthetic-4	4.87 ab	-0.23917
G4	synthetic-6	4.93 ab	-0.23938
G5	synthetic-TS6	4.58 ab	-0.09660
G6	synthetic-3 Drought	4.17 c	0.06483
G7	VS-536	5.13 a	-0.64900
G8	V-537 C	4.06 c	0.96868

Means with different letter are statistically different (Duncan, $P \leq 0.05$); PCA: principal component analysis.

In accordance with the values of PCA1 (Table II) the variety 'synthetic-2' presented a more stable behavior (0.06, which is closest to zero) (Zobel *et al.*, 1988). On the contrary, the more unstable genotypes were 'VS-536' and 'V-537 C', with values of -0.65 and 0.97 PCA1, respectively. It is noteworthy that genotype 'synthetic-2', although it exhibited low values of PCA1, presented an average yield that is higher than the overall average performance, which would determine this genotype as a candidate for its release in the region of influence.

The 'synthetic-2' performance was statistically similar to the variety VS-536 and superior to V-537 C. Even when the protein quality of 'synthetic-2' is less than that of V-537 C, its stable behavior and performance, reveal good prospects for commercial use. The 'synthetic-2' variety, which presented stable behavior, is the product of the genetic recombination of 11 inbred lines. This variety, according to Cordova and Márquez (1979) and Márquez *et al.* (1983) would not exceed the overall average because of strong inbreeding depression caused by the large number of parents involved. However, the above is not met perhaps because the lines that form this synthetic have been selected by their performance *per se* and also by their general combining ability (GCA) effects (Gómez *et al.*, 2003; Andrés-Meza *et al.*, 2011). The most productive genotypes identified may be subject to additional improvement to obtain a superior cultivar or to implement strategies to promote the development of lines to form better hybrids.

The E1 environment (Cotaxtla 2009B) yielded less than E2 (Cotaxtla 2010B), with PCA1 values of -0.92 and 0.22, respectively. The E4 environment (Cotaxtla 2011A) had a performance below the overall average (Table III). The same locality submit

TABLE III
AVERAGE YIELD AND PCA1 VALUES FOR FOUR ENVIRONMENTS (VERACRUZ, MEXICO; 2009-2011)

Nº	Location	Yield ($t\cdot ha^{-1}$)	PCA1
E1	Cotaxtla 2009B	4.56 b	-0.22308
E2	Cotaxtla 2010B	4.87 ab	0.92200
E3	Tlachiconal 2010B	5.41 a	0.07716
E4	Cotaxtla 2011A	3.82 c	-0.77608

Means with different letter are statistically different (Duncan, $P\leq0.05$); PCA: principal component analysis; A: Spring-Summer; B: Autum-Winter; E: environments.

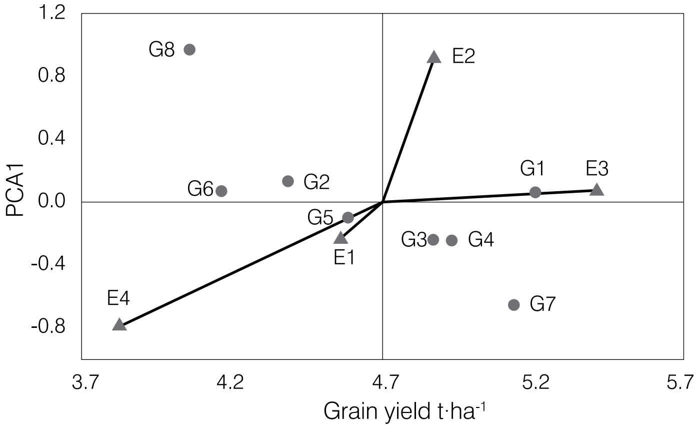

Figure 1. Response pattern to the genotype-environment GE interaction of eight QPM maize genotypes evaluated in four environments (Veracruz, Mexico; 2009-201) E: environments (E1: Cotaxtla 2009B, E2: Cotaxtla 2010B, E3: Tlachiconal 2010B, E4: 2011A); G: genotypes; (G1: Synthetic-2, G2: Synthetic-3, G3: Synthetic-4, G4: Synthetic-6, G5: Synthetic-TS6, G6: Synthetic-3 Drought, G7: VS-536, G8: V-537 C).

PCA1 positive and negative values in different years, indicating that the environmental variation among years is large, so it is convenient to continue with the evaluation of the genotypes through several cycles in that same site, before selecting the genotypes of interest (Mejía and Molina, 2003; Alejos *et al.*, 2006; Gonzalez *et al.*, 2007; Salas *et al.*, 2009; Williams *et al.*, 2010).

Little association was found between higher yield performance of the varieties synthetic-2, synthetic-4, synthetic-6 and VS-536, and the more productive environments (E2 and E3). The same effect was detected in poor environments. Although the AMMI analysis showed that the two first PCA (Table I) have no significance, the effects of the first principal component PCA1 regarding the performance of grain yield using the graphical 'biplot' (Figure 1) indicates that E3 and E4 environments tend to rank similarly to the genotypes, and thus one of these environments can be discarded without losing precision in results (Crossa *et al.,* 1990; Gauch and Zobel, 1996). Otherwise, environments E1 and E2 showed a tendency to sort genotypes in a contrasting way (Alejos *et al.*, 2006).

With regard to environments Yan *et al.* (2000) state that the environments that exhibit an angle below 90° between them have the quality of classifying genotypes in the same manner; and environments with an angle close to 180° tend to group in reverse to the genotypes, which turns difficult the selection for being so contrasting.

The AMMI model allowed grouping environments in two relatively homogeneous groups: the first one consisting of environments E2 and E3 and the second of E1 and E4. This means that the genotypes can be analyzed for adaptability, either broad or specific (Kempton, 1984; Vargas and Crossa, 2000), which makes more efficient the process of selection of genotypes for a region in particular (Williams *et al.*, 2010; Yan *et al.*, 2000).

Conclusions

There are differential responses among synthetic varieties of maize in the various environments evaluated. The most stable maize genotype was 'synthetic-2'. Little association between higher yielding varieties and the most productive environments was observed. The 'biplot' obtained from the AMMI model proved effective to obtain profiles of subgroups of environments and genotypes with a positive interaction, and likewise, an optimal interpretation of the effects of the model is generated. It is suggested that these varieties be evaluate in a multiplication trial on large scale for adaptation to wider agro-climatic conditions before their commercial cultivation.

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