Indian J. Genet., 69(3): 225-231 (2009)

Interpreting the effects of genotype x environment interaction on cane and sugar yields in sugarcane based on the AMMI model

Sanjeev Kumar, S. S. Hasan[1], P. K. Singh, D. K. Pandey and J. Singh

Division of Crop Improvement, [1]ARIS Cell, Indian Institute of Sugarcane Research, Lucknow

(Received: April 2009; Revised: June 2009; Accepted: July 2009)

Abstract

Field experiments were conducted in six environments (2 water regimes x 3 crops) during 2005-07 to study the effect of genotype x environment interaction (GEI) on cane and sugar yields in sugarcane (*Saccharum* spp.). Analysis of variance of 11 genotypes revealed that genotype, environment, and GEI were highly significant. Highly significant GEI effects indicated the necessity for testing newly developed genotypes under different environments. The additive main effects and multiplicative interaction (AMMI) model was used to interpret the GEI. The first two IPCAs of the AMMI analysis of GEI accounted for 90.39% of this variation for cane yield and 92.54% for sugar yield. AMMI-1 biplot showed that genotype LG 03001 had very good cane yield with specific adaptation to the 1st year and 2nd year plant crop under optimum condition. For sugar yield, LG 03001 and LG 03002 were better adapted to the 2nd year plant crop under normal and moisture-deficit conditions, respectively, Considering only the IPCA-1 scores, BO 91 (average yielder) and LG 03007 (poor yielder) were the most stable for cane yield, whereas BO 91 was more stable in terms of sugar yield. AMMI-2 biplot indicated that LG 03003 for cane yield and LG 03007 and BO 91 for sugar yield had small interaction with environments, reflecting their stability in yield performance across environments.

Key words: Sugarcane, AMMI model, G x E interaction, stability

Introduction

Sugarcane is an important commercial crop providing about 75% of the total sugar produced in the world. In addition, a number of by-products and co-products are being produced from sugarcane, which is also receiving considerable attention as a source of bio-energy. A major part of the sugarcane region in subtropical India is under an irrigated agro-ecosystem, with periodic shortages of water that cause the crop to suffer yield losses. The formative phase of sugarcane, which is the most critical stage for water requirement, coincides with high temperature and hot winds in subtropical India. Skipping irrigation at this stage severely affects tillering and subsequent growth of the crop at later stages.

Genotypic differences in stress compensation and subsequent recovery exists among sugarcane varieties developed for subtropical India. An ideal genotype for moisture-deficit environments must combine a reasonably-high yield potential with stress-specific plant characters that buffer yield against severe moisture stress [1]. The phenotype of an individual plant is determined by both its genotype and the growth environment. These two effects are not always additive because of the presence of genotype and environment interaction (GEI), measured as inconsistent performance of a genotype across environments. An ideal or stable variety should have high mean yield with a low degree of GEI, when grown over diverse environments. Two main concepts of stability are 'static' (Type I) and 'dynamic' (Type II) [2, 3]. For static stability, the best genotype tends to maintain a constant yield across environments. Dynamic stability implies a stable genotype with a yield response in each environment that is always parallel to the mean response of the tested genotypes. Breeders deal with the GEI challenge by evaluating genotypes in several environments to ensure that those genotypes with high yield and stable performance are selected [4].

Several methods have been proposed to analyze GEI and phenotypic stability [5, 4]. These methods can be divided into two major groups, viz. univariate and multivariate stability statistics [2]. Among multivariate methods, the additive main effects and the multiplicative interaction analysis (AMMI) is widely used in GEI studies for different crops [6, 7], to separate the additive portion from the interaction by way of an analysis of variance. AMMI biplot analysis is considered to be an effective tool to diagnose GEI pattern graphically, whereby a principal component analysis (PCA) provides a multiplication model to analyze the interaction effects. The results of AMMI analysis are useful in supporting decision in a breeding program regarding specific adaptation and selection of environments for testing.

The objectives of this study were to (i) interpret the GEI, if any, for cane and sugar yields of sugarcane genotypes tested in two crop years under two water regimes, (ii) assess cane and sugar yield performance across the environmental conditions based on the biplot and (iii) determine genotypes with high cane and sugar yields, depending on the differential genotypic response to environments.

Materials and methods

The experiment was conducted at the main farm of Indian Institute of Sugarcane Research, Lucknow, India ($26^0$56' N, $80^0$52' E and 111 msl) during the 2005-06 and 2006-07 crop seasons, to determine the yield performance of elite sugarcane genotypes under normal and moisture-deficit conditions. The normal condition refers to an irrigation schedule (six irrigations) recommended for subtropical India, provided after planting and before the onset of monsoon. Under moisture-deficit condition, two irrigations were given such to impose a stress during the critical formative/ tillering in sugarcane. This second condition represents the field situation of farmers with limited ability to irrigate during the hot summer months. Lucknow has a subtropical climate and soils of the sandy loam-type in the A-horizon and of the clay loam-type in the B-horizon.

Eleven sugarcane genotypes were grown under six environments (Table 1). Out of 11 genotypes, nine being newly developed at the IISR , and the other two being check varieties, BO 91 and CoJ 64, included for moisture-stress tolerance and for juice quality, respectively. The six environments were E_1 (1st year plant crop under normal condition), E_2 (1st year plant crop under moisture-deficit condition), E_3 (2nd year plant crop under normal condition), E_4 (2nd year plant crop under moisture-deficit condition), E_5 (ratoon of 1st year planting under normal condition) and E_6 (ratoon of 1st year planting under moisture-deficit condition).

Randomized complete block designs (RCBD) were used with three replications in both years. Manual planting was done in 3m wide x 6m long plots, consisting of four rows spaced 75 cm apart. Three budded setts were used for planting with seed rate of 16 buds per m^2 in both normal and moisture-deficit conditions. Cane and sugar yields were measured on plot basis and presented as tons ha^{-1}. A combined analysis of variance across test environments and an AMMI analysis were carried out using the program IRRISTAT version 5.

Table 1. Sugarcane genotypes and their respective parentage used in the study.

Genotype	Parentage
LG 03001	BO 91 GC*
LG 03002	CoLk 8102 GC
LG 03003	BO 91 GC
LG 03004	CoH 106 x CoLk 9412
LG 03005	BO 91 GC
LG 03006	CoH 107 x LG 72115
LG 03007	CoLk 8102 GC
LG 03008	BO 91 GC
LG 03009	CoLk 8102 GC
BO 91	BO 55 x BO 43
CoJ 64	Co 976 x Co 617

*GC = General Cross

Results and discussion

Analysis of variance for cane and sugar yields revealed highly significant differences among genotypes, environments, and their interaction GEI (Table 2). Bartlett's test for homogeneity of variances indicated significant error variances among environments. GEI resulted from changes in the relative rankings of the genotypes, implying that genotypes responded differently to the environmental conditions considered and that testing in multi-environment trials (METs) will be necessary to understand the adaptation pattern and stability of newly-made available genotypes

The AMMI analysis showed that 47.07 % of the variation in cane yield was attributable to environmental effects, 31.72 % to the genotypic effects, and 21.20% to GEI (Table 2). The larger variation associated with environments indicated that the environments were diverse with large differences in their means. The significant G x E indicated differential and inconsistent responses of the genotypes across environments. The ANOVA for sugar yield indicated that 49.99% of the variation was due to environmental effect, 29.30% to genotype effect, and 20.71% to their interaction.

The most accurate model for AMMI can be predicted by using the first two interaction principal component axes (IPCA) in sugarcane [8]. This model made it possible to construct the biplot and calculate genotype and environment effects [9]. IPCA scores for genotypes that are closer to zero indicate greater stability of that genotype over the testing environments. Two types of biplot, AMMI-1 and AMMI-2, were used to interpret GEI interaction in this study. In AMMI-1, the genotypic and environmental means were plotted on the abscissa and the IPCA-1 scores for the genotypes and environment on the ordinate. However, in AMMI-2, the IPCA-1 scores were plotted on the abscissa and IPCA-2 scores on the ordinate.

The first two IPCAs of the AMMI analysis of the GEI for cane yield accounted for 90.39% of the G x E sum of squares and used 26 of the total 50 degrees of freedom available in the interaction component. For sugar yield, IPCA-1 and IPCA-2 of the AMMI analysis, accounted for 92.54% of the G x E sum of squares and used more than half of the degrees of freedom available in the GEI.

Table 3 shows mean cane and sugar yields of the studied genotypes in each and across environment(s) along with their respective IPCA-1 and IPCA-2 scores. Interpretation can be extracted by considering the GEI component from the multiplicative term of the model using the grand mean and IPCA-1 scores. Positive interaction effects are attributed to genotypes and environments showing IPCA-1 scores of the same sign whereas a combination of IPCA-1 scores of opposite sign indicates negative specific interaction.

Genotypes with high IPCA-1 scores showed yield advantage in the environment that had high IPCA-1 scores. For cane yield, LG 03005 and LG 03002, because of their high positive multiplicative interaction with E_3, were specifically adapted to the normal growing condition. LG 03005, with a high negative multiplicative interaction score with E_2, was poorly adapted to the moisture-deficit condition. For sugar yield and based on the same reasoning, LG 03004 and LG 03008 performed better in the 1^{st} year plant and ratoon crops under normal condition. However, LG 03004 did poorly in the 2^{nd} year plant crop under normal condition. The check variety BO 91 had the lowest absolute IPCA-1 score, an indication of a small interaction with environments, and can be considered the most stable among the genotypes.

The environments E_1 and E_3 have high significantly positive main cane yield effects (Table 4), whereas E_2 exhibited high negatively significant main cane yield effects. For sugar yield, E_3 had shown significant positive main effect whereas E_2 had highly negative significant main effects. The genotype LG 03001 had greatest positive significant main effects for both cane and sugar yields. In addition to this, LG 03004 had also shown positive significant main effect for sugar yield. On the other hand, LG 03007 and CoJ 64 recorded significant negative main effects for cane and sugar yield

Table 2. Analysis of variance of cane and sugar yields for AMMI model based on 11 sugarcane genotypes tested under 6 environments

Source	d.f.	Cane yield (t/ha)			Sugar yield (t/ha)		
		S.S.	M.S.	Explained (%)	S.S.	M.S.	Explained (%)
Total	65	22424.40	344.99		297.13	4.57	
Genotype (G)	10	7113.94	711.39**	31.72	87.06	8.70**	29.30
Environment (E)	5	10556.20	2111.24**	47.07	148.53	29.71**	49.99
G x E	50	4754.25	95.08**	21.20	61.54	1.23**	20.71
IPCA1	14	3098.32	221.31	65.17	46.97	3.36	76.32
IPCA2	12	1198.85	99.90	25.22	9.98	0.83	16.22
IPCA3	10	415.86	41.59	8.75	2.78	0.28	4.51
IPCA4	8	22.28	2.78	0.46	1.07	0.13	1.74
Residual	6	18.94	3.16	0.40	0.73	1.83	1.18
Error	120	3241.23	27.01		43.63	0.36	

** $P < 0.01$

Table 3. Mean cane (CY) and sugar yields (SY) of 11 sugarcane genotypes tested under six environments and IPCA scores for genotypes and environments

Genotype	Environment												Grand mean		IPCA-1		IPCA-2	
	E1		E2		E3		E4		E5		E6							
	CY	SY	CY	SY	CY	SY	CY	SY	CY	SY	CY	SY	CY	SY	CY	SY	CY	SY
LG 03001	93.30	6.99	50.91	4.44	98.34	12.29	52.61	9.12	79.43	7.16	58.03	5.92	72.10	7.66	-1.603	-1.005	-3.974	-0.1376
LG 03002	53.43	5.77	31.20	3.55	95.50	10.98	73.32	8.72	48.24	5.53	37.26	4.48	56.49	6.51	4.030	-1.166	0.1503	-0.0711
LG 03003	61.08	5.43	38.05	4.11	80.86	9.37	62.60	7.02	56.78	5.98	43.87	5.05	57.21	6.16	0.9221	-0.3335	0.2901	0.422
LG 03004	68.38	9.45	37.10	4.93	70.98	8.30	76.54	6.05	60.07	8.88	45.73	5.44	59.80	7.18	0.7751	1.112	1.660	-1.058
LG 03005	64.63	5.41	21.34	1.72	95.05	10.05	72.46	7.31	51.45	4.71	24.72	2.85	54.94	5.34	4.280	-1.140	-2.133	-0.7395
LG 03006	56.38	4.80	34.28	3.46	59.66	6.50	47.79	4.78	54.69	5.27	38.52	3.89	48.55	4.78	-1.249	0.4724	0.7499	0.3938
LG 03007	39.74	4.47	23.24	2.39	49.19	5.89	42.49	4.52	38.93	4.31	26.63	2.56	36.70	4.02	-0.3486	0.3006	1.769	-0.0789
LG 03008	77.01	7.90	41.82	4.99	66.24	7.15	55.12	5.67	66.34	7.68	45.06	5.09	58.60	6.41	-1.953	1.103	-0.4803	-0.3583
LG 03009	81.21	4.69	42.28	4.03	65.18	8.04	45.96	5.15	66.74	6.09	48.62	5.28	58.33	5.55	-3.070	0.2699	-1.377	0.8222
Bo 91	58.47	6.25	42.99	4.68	68.84	8.64	59.30	7.54	54.86	6.05	45.21	4.76	54.95	6.32	-0.3585	-0.0884	1.643	0.1907
CoJ 64	37.83	3.80	25.14	2.80	43.43	5.58	31.81	4.02	33.81	4.34	26.37	3.14	33.07	3.95	-1.425	0.4757	1.703	0.5435
Grand mean	62.86	5.91	35.30	3.74	72.11	8.44	56.36	6.36	55.58	6.00	40.00	4.41	53.07	5.81				
IPCA-1	-2.150	0.8313	-2.280	0.8008	4.372	-1.697	4.239	-1.269	-1.986	0.9319	1.658	0.4024						
IPCA-2	-3.039	-1.252	2.061	0.8426	-2.909	-0.1584	3.044	-0.0148	-0.8150	0.2940	-1.315	0.8769						

both and LG 03006 for sugar yield only. Specific GEI with highly significant positive effects was shown by the genotype LG 03005 for both cane and sugar yield and LG 03002 for cane yield in E_3. However LG 03001 had highly negative significant effect in E_4.

The IPCA-1 scores for both genotypes and environments were plotted against the mean cane and sugar yield (Fig. 1a and 1b, respectively). The IPCA-1 scores of a genotype in the AMMI analysis are an indication of adaptability over the environments. The genotype LG 03001 had very good cane yield with specific adaptation (large IPCA-1 score) to E_1 and E_3 i.e. plant crops grown under normal condition. Genotypes located near the plot origin were less responsive to the environments than the vertex genotypes. Considering only the IPCA-1 scores, it became clear that genotype LG 03007 (poor yielder) and BO 91 (average yielder) were most stable genotypes across the environments. With respect to the environments, E_3, i.e. 2^{nd} year plant crop under normal condition, was most discriminating as indicated by the largest distance between its mark and the origin, whereas E_5, represented by ratoon crop under normal conditions, was least discriminating as it marks nearer to the plot origin.

Fig. 1b indicated that LG 03001 and LG 03002 had shown good adaptation to E_3 and E_4 for sugar yield. BO 91 posed in close to zero of IPCA-1, showed that it had more stability with moderate sugar yield. The genotypes LG 03006, LG 03007, LG 03009 and CoJ 64 had shown large GEI due to the fact that the sugar yield of these genotypes was below average and they showed large IPCA-1 score values. As a result, these genotypes may be suitable for sugar yield under poor environment.. The biplot showed that the genotypes LG 03004 and LG 03008 had high mean sugar yield but also high IPCA-1 scores indicating their specific adaptation to the favorable environments. Also for sugar yield, E_3 was most discriminating as indicated in Fig. 1b.

AMMI-2 biplots were constructed with IPCA-1 score on the abscissa and IPCA-2 on the ordinate for cane and sugar yield (Fig. 2a and 2b, respectively). For cane yield this explained 90.39% of GEI compared with 65.17% in AMMI-1. The genotype and environment can be seen as vectors from the origin of axis to the end points determined by their scores. If any two vectors for the environments form an angle exceeding the right angle, it indicates that genotypes have different interaction pattern in these environments. Genotypes

Table 4. Effects of genotypes and environments obtained from an additive G x E model for cane (CY) and sugar yield (SY) of 11 sugarcane genotypes tested under six environments

Genotype	Environment												Genotype effects	
	E1		E2		E3		E4		E5		E6			
	CY	SY	CY	SY	CY	SY	CY	SY	CY	SY	CY	SY	CY	SY
LG 03001	12.04	-0.52	-2.79	-1.34	7.82	1.92	-22.15*	0.92	5.45	-1.05	0.37	0.07	18.40**	1.85**
LG 03002	-12.21	-0.77	-6.89	-0.81	20.59*	1.91	14.17	1.58	-10.12	-1.29	-5.53	-0.63	2.79	0.70
LG 03003	-5.29	-0.79	-0.76	0.18	5.24	0.69	2.73	0.19	-2.30	-0.47	0.37	0.19	3.50	0.35
LG 03004	-0.58	2.16*	-4.30	-0.15	-7.23	-1.49	14.08	-1.68	-1.61	1.54	-0.37	-0.37	6.10	1.37**
LG 03005	0.53	-0.26	-15.20	-1.49	21.70*	2.08*	14.86	1.50	-5.36	-0.47	-16.52	-1.36	1.24	-0.46
LG 03006	-1.33	-0.28	4.13	0.45	-7.31	-1.15	-3.42	-0.26	4.26	0.64	3.66	0.59	-5.15	-1.03*
LG 03007	-6.12	0.28	4.91	0.15	-5.92	-0.97	3.13	0.16	0.36	0.24	3.62	0.14	-17.00**	-1.79**
LG 03008	9.25	1.56	1.62	0.78	-10.77	-1.76	-6.14	-1.47	5.87	0.79	8.17	0.10	4.89	0.61
LG 03009	13.72	-1.08	2.35	0.64	-11.56	-0.10	-15.03	-0.94	6.53	0.52	3.99	0.95	4.63	-0.26
BO 91	-5.63	-0.17	6.45	0.56	-4.52	-0.23	1.70	0.59	-1.96	-0.47	3.97	-0.29	1.24	0.51
CoJ 64	-4.39	-0.13	10.47	1.03	-8.05	-0.91	-3.91	-0.60	-1.13	0.01	7.01	0.61	-20.64**	-1.86**
Environment effects	9.18**	0.10	-18.40**	-2.07**	18.41**	2.63**	2.66	0.55	1.87	0.19	-13.70	-1.40		

* P < 0.05 and ** P < 0.01

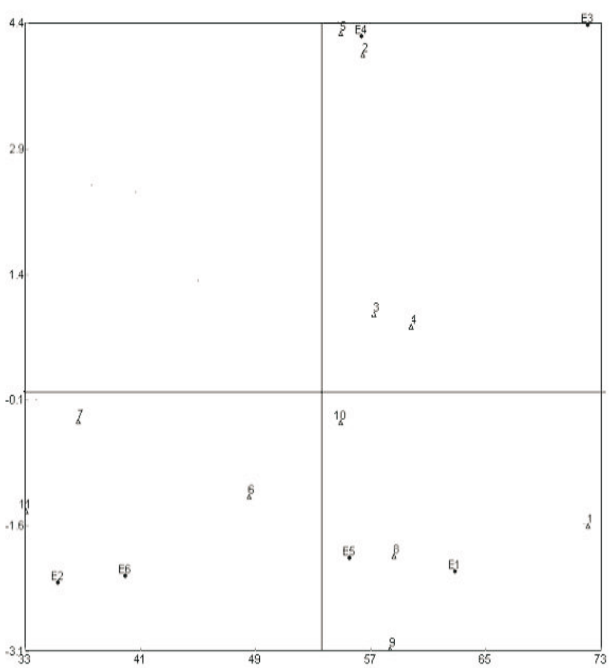

Fig. 1a.

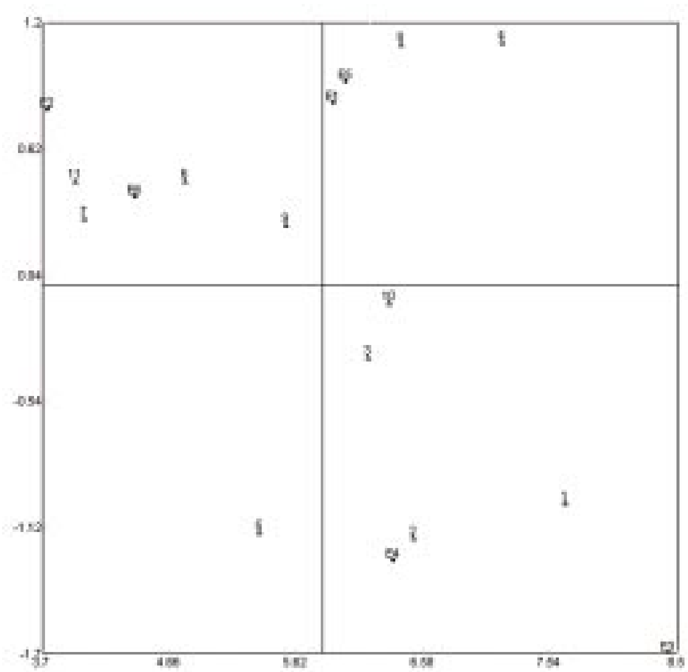

Fig. 1b.

Fig.1. AMMI-1 biplots for cane (a) and sugar yield (b) built for 11 sugarcane genotypes tested under six environments. Symbols are: 1-LG 03001, 2-LG 03002, 3-LG 03003, 4-LG 03004, 5-LG 03005, 6-LG 03006, 7-G 03007, 8-LG 03008, 9-LG 03009, 10-BO 91, and 11- CoJ 64.

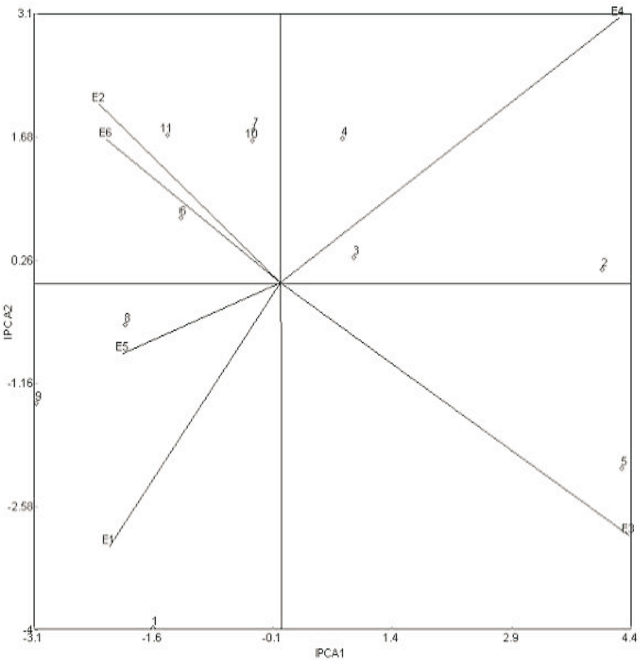

Fig. 2a.

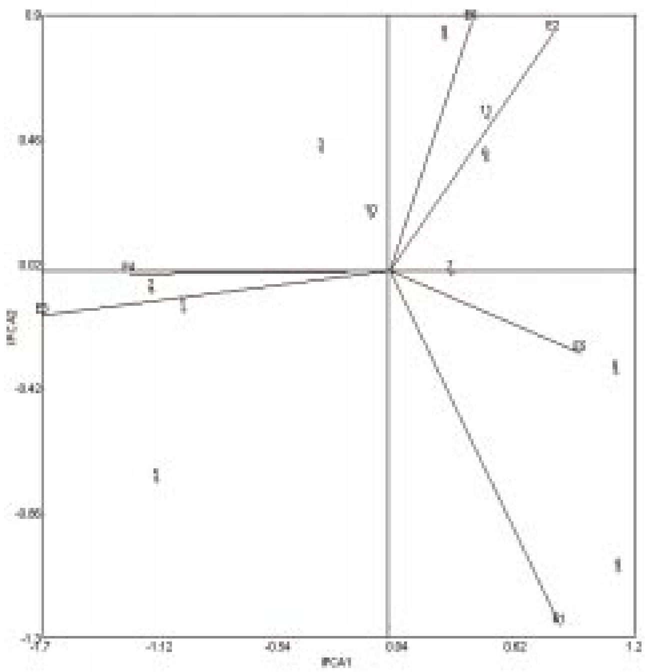

Fig. 2b.

Fig. 2. AMMI 2 biplot for cane (a) and sugar yield (b). Symbols are: 1-LG 03001, 2-LG 03002, 3-LG 03003, 4-LG 03004, 5-LG 03005, 6-LG 03006, 7-LG 03007, 8-LG 03008, 9- LG 03009, 10- BO 91 and 11- CoJ 64.

with small interaction were located near the origin e.g. LG 03003 for cane yield and LG 03007 and BO 91 for sugar yield. The genotypes that were far from the origin have positive response with those environments that were away from the origin but at the same time in the same direction with small angle (<90^o). The genotypes LG 03005 had shown positive response for cane yield with E_3, LG 03001 with E_1, LG 03008 and LG 03009 with E_5, LG 03006 and CoJ 64 with E_2 and E_6 and LG 03004 with E_4. For sugar yield, the genotypes LG 03001 and LG 03002 were positively responded with E_3, LG 03004 with E_1, LG 03008 with E_5, LG 03006 and CoJ 64 with E_2 and LG 03009 with E_6. For negative response, the genotype and environment vectors form angle between 90^o and 270^o, e.g. LG 03001 with E_2, E_4 and E_6 i.e. all represented to the moisture deficit condition. This means that LG 03001 has positive effects with E_1 while with other environments this genotype presents negative interaction for cane yield. Similarly, for sugar yield, LG 03001 and LG 03002 positively responded with E_3 and negative with other environments. Although, LG 03001 presented negative interaction, its mean yield in such environments was among the best which can be explained because of the fact that AMMI-2 biplot represents the G x E in part only and it does not include the main effects of genotypes. Thus, the biplot showed the best genotypes in each environment with respect to G x E but not with respect to the main effect of the genotypes.

Based on the analysis, it can be concluded that the studied environments represented significantly differential conditions for testing new genotypes for their adaptability and GEI. Further, genotype LG 03001 was specifically adapted to the normal growing condition, whereas, BO 91 had shown wider adaptation to all environments based on both cane and sugar yield.

References

1. **Blum A.** 1983. Breeding programme for improving crop resistance to water stress. *In:* Crop reactions to water and temperature stress in humid temperate climate, pp. 263-74. C.D. Paper Jr. and Kramer P.J. (eds).
2. **Lin C. S., Binns M. R. and Lefkovitch L. P.** 1986. Stability analysis: where do we stand? Crop Sci., **26**: 894-900.
3. **Becker H. C. and Leon J.** 1988. Stability analysis in plant breeding. Plant Breeding, **101**: 1-23.

4. **Kumar S., Singh J., Singh P. K. and Pandey D. K**. 2007. Stability of yield and its components in sugarcane (*Saccharum* spp. Hybrid complex). Indian J. agric. Sci., **77**: 220-3.

5. **Singh P. K., Kumar S. and Singh J**. 2000. Stability analysis for sugarcane genotypes grown under three different conditions. Indian J. Sugarcane Technol., **15** : 52-8.

6. **Crossa J., Gauch H. G. and Zobel R. W.** 1990. Additive main effects and multiplicative interaction analysis of two international maize cultivar trials. Crop Sci., **30**: 493-500.

7. **Queme J. L., Orzco H., Ovalle W., Soto G. and Melgar M**. 2001. AMMI analysis of sugarcane trials in Guatemala. Proceedings of International Society of Sugar Cane Technologists, **24**: 512-6.

8. **Quemé J. L., Orozco H., Ovalle W. and Melgar M.** 2005. Analysis of genotype-by-environment interaction for sugarcane based on the AMMI model. Sugar Cane Int., **23**: 21-4.

9. **Gauch H G and Zobel R W.** 1996. AMMI analysis of yield trial. *In:* Genotype by environment interaction, Pp. 85-122. Kang, M.S. and Gauch H.G. (eds.). Boca Raton, CRC Press.