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Research Article

Exploiting genotype x environment interaction in soybean breeding in Nigeria

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Abstract

Twenty early maturing soybean genotypes were evaluated in five locations in Nigeria to determine the influence of Genotype X Environment as it affect the selection of high yielding and stable varieties of soybean. In each location the trials were laid out in randomised complete block design with three replications. Out of the three models of GXE used, AMMI model proofed superior in explaining the interaction of the GXE. Four soybean genotypes (TGx1990-37, TGx1987-10F, TGx1989-19F and TGx1990-52F) were identified by the three analysis tools that were overall best in performance in relation to yield and stability. This suggests that for reliability and optimum result it is better to combine the result of the two or three analytical tools for yield and stability in the recommendation of genotypes to farmers. Of the five environments, Mokwa produced the least interaction effect followed by Yandev and may be most appropriate environments for soybean production and evaluation. Selection in these environments will be effective as the relative performance of these genotypes would be fairly stable.

Keywords: Genotype x Environment, Interaction, Soybean, Breeding, Nigeria

Introduction

Soybean constitutes an important component of the smallholder cropping systems in Africa and holds considerable potential for arresting soil fertility decline and enhancing household food and nutrition security. The contribution of soybean to the food security of rural households tends to be relatively more significant in Africa than elsewhere in the developing world. The dramatic increase in world soybean prices has influenced domestic prices in Africa, with the result that the production of soybean and other oilseeds has become potentially more rewarding to farmers relative to other food or cash crops.

In Nigeria, the cultivation of soybean is increasing in the savannas because it's a major cash crop widely used in food and feed (Brader 1998, Sanginga et al., 2002). The crop provides opportunity to diversify the cereal cropping systems in the savannas. Farmers have adopted new cultivars developed at IITA (Okogun et al., 2004) and NCRI that store well and unlike cowpea do not need chemical pest control. These varieties also nodulate freely with native rhizobia strains and take care of the proportion of their nitrogen (N) requirement through biological nitrogen fixation once the plants are established (Okogun et al 2004). However there is a gap between the soybean yields on farmer's fields (1.5 t/ha) and yields obtained in research stations. The theoretical limit of soybean productivity was suggested to be 8 tonnes/ha based on the amount of light energy available in the field (Specht, et al., 1999). However, world productivity during 2007 was 2.81 tonnes/ha. Even this has not been achieved in tropical countries like Nigeria, where low productivity is mainly due to the short growing periods available in guinea savannah, limited varietal stability, and narrow genetic base of soybean cultivars.

Increasing yields on farmers fields is a challenge that needs to be resolved through promotion of high yielding varieties, which are tolerant to biotic (Asian rust) and abiotic (notably drought and poor soil fertility) stresses. These improved varieties should also have end user preferred traits (e.g. big seed size, high protein content) to stimulate high levels of adoption by farmers.

Breeding programmes are intended to develop new varieties with superior agronomic performance compared to those in current production by farmers. Prior to release of the new varieties, they are evaluated in yield trials at several locations in multi-location trials. The variety trials provide important information that enables selection and recommendation of crop cultivars (Yan and Tinker, 2006; Yang et al., 2009). Comparisons are made with the performance of the commonly grown commercial varieties (checks). Genotype-by-environment interaction (GEI) is a major concern in plant breeding for two main reasons; first, it reduces progress from selection and second, it makes cultivar recommendation difficult because it is statistically impossible to interpret the main effects. GEI occurs in both short-term (3 to 4 years testing at a location) and long-term (several locations crop performance trials). The number of materials evaluated and the number of test environments required in multi-location trials affects the cost of plant breeding. However reduction in the number of test sites requires a thorough understanding of the genotype and GEI (Bernardo, 2002). A specific genotype does not always exhibit the same phenotypic characteristics under all environments and different genotypes respond differently to a specific environment.

Various techniques have been developed to reveal patterns of GxE interaction, such as joint regression (Finlay and Wilkinson, 1963; Perkins and Jinks, 1968), sum of squared deviations from regression (Eberhart and Russel, 1966), stability variance (Shukla, 1972), coefficient of determination (Pinthus, 1973), coefficient of variability (Francis and Kanneberg, 1978), and Type B genetic correlation (Burdon, 1977). These methods are commonly used to analyze multi-location environment trials data to reveal patterns of GE interaction. Alternatively, the additive main effects and multiplicative interaction (AMMI) model have led to more insight in the complicated patterns of genotypic responses to the environment (Gauch and Zobel, 1988; Zobel et al., 1988; Gauch, 1992; 2006). Yan et al. (2000) proposed another methodology known as GGE-biplot for graphical display of GE interaction pattern of Multi-environment trial (MET) data with many advantages. GGE biplot is an effective method based on principal component analysis (PCA) which fully explores MET data. It allows visual examination of the relationships among the test environments, genotypes and the GE interactions. The first two principle components (PC1 and 2) are used to produce a two dimensional graphical display of genotype by environment interaction (GGE-biplot). If a large portion of the variation is explained by these components, a rank-two matrix, represented by a GGE-biplot, is appropriate (Yan and Kang, 2003). In this study we have used G x E interaction of soybean grain yield to characterize genotypic responses to a set of contrasting environmental conditions.

Materials and Methods

Twenty early maturing soybean genotypes including three commercials checks were evaluated in five locations in Nigeria. Four of the locations are in the guinea savannah while one is in the derived savannah ecology of Nigeria (Table 1). The experimental design was a randomized complete block with three replications at each location. Plots were five rows of 3m length spaced 0.5 m apart. Planting was done using drilling method and the plant were later thinned down to a spacing of 5cm between plants within the rows. Accepted cultural practices were applied at each location. Data was taken on 5 plants per plots for plant height in cm and number of pods per plants. Days to 50% flowering was taken when half of each plot had flowered and days to maturity was taken when more than 75% of the plots have turned brown or dried and some leaves fallen off. 100 seed weight was measured by counting 100 seed from each harvested plots after threshing and weighed in grams. Grain weight per plot was taken after threshing the harvested pods from the net plots and weighed in kg. The leftover was weighed as fodder weight per plot in kg. Rust score was taken at the beginning of pod formation stage in all the location in percent using IITA chart.

Table 1: Five Locations and their ecologies for the Soybean Trials

Location	State	Ecology
Zaria	Kaduna	Northern Guinea. Savannah
Ibadan	Oyo	Derived Savannah
Minjibir	Kano	Northern Guinea savannah
Mokwa	Niger	Southern Guinea Savannah
Yandev	Benue	Southern Guinea Savannah

Statistical analysis

Analysis of variance procedure (Comstock and Moll, 1963) was adopted to test the significance of location, genotype, and first order interactions assuming the location effects as random and genotype effect as fixed.

The AMMI model used was: Yij = μ + gi + ej + ʎkϒikδjk + Ɛij N1

Where Yij is the grain yield of the i-th genotype in the j-th environment, μ is the grand mean, gi and ej are the genotype and environment deviation from the grand mean, respectively, ʎk is the eigen value of the principal component analysis (PCA) axis k, ϒik and δjk are the genotype and environment principal component scores for axis k, N is the number of principal components retained in the model, and Ɛij is the residual term.

GGE-biplot methodology, which is composed of 2 concepts, the biplot concept (Gabriel, 1971) and the GGE concept (Yan et al., 2000) was used to visually analyze the METs data. This methodology uses a biplot to show the factors (G and GE) that are important in genotype evaluation and that are also the source of variation in GEI analysis of METs data (Yan et al., 2001). The GGE-biplot shows the first 2 principal components derived from subjecting environment centred yield data (yield variation due to GGE) to singular value decomposition (Yan et al., 2000). In the current study, genotype-focused scaling was used in visualizing for genotypic comparison, with environment-focused scaling for environmental comparison. The statistical analysis was conducted using the Integrated Breeding Platform Breeding Management System version 2.1.

Results and Discussion

Significant differences were observed for all traits except plant height and number of pods per plants. Grain yield has been singled out as the most important trait in cereals and legumes. Soybean grain yield for the 20 genotypes ranged from 1055 to 1697kg/ha (Table 2). Ten genotype (TGx 1989-40F, TGx 1989-19F, TGx 1990-55F, TGx 1990-21F, TGx 1990-37F, TGx 1990-46F, TGx 1987-10F, TGx 1990-52F, TGx 1990-3F, TGx 1989-48F) gave higher grain yield than the grand mean yield (1382.3 kg/ha). Grain yield of environments ranged from 972.5 kg/ha in Mokwa to 1809.5 kg/ha in Zaria and was significant in all the five locations except Zaria (Table3). However, Zaria location also had the highest mean performance than other location. This is explained by the box plot (fig. 1). The soybean varieties also show wider variability in Zaria location. The box plot encloses observations between the 25th (lower quartiles) and 75th (upper quartiles), with the lines extending to the minimum and maximum of observed values. The large yield variation explained by environments indicated that the environments were diverse, with large differences between environmental means contributing most of the variation in grain yield.

Table 2: Combined mean performance of 20 soybean varieties across 5 locations in Nigeria

Variety	Days to 50% Flw	Days to Mat	Plant popl	Pod height (cm)	No Pods/ Plant	100 seed weight (g)	Fodder weight (kg)	Grain Yield (kg)	Rust score (%)
TGx 1989-40F	43	104	118.3	10.1	41.5	14.3	1301	1697	0.3
TGx 1989-19F	45	103	130.6	17.4	42.5	14.5	1163	1671	0.4
TGx 1990-55F	46	101	128.3	16.4	48.3	13.4	1493	1621	0.4
TGx 1990-21F	43	102	119.4	13.5	22.7	15.8	1041	1582	0.3
TGx 1990-37F	44	105	121.4	14.1	55.6	14.4	1141	1564	0.3
TGx 1990-46F	44	102	132.2	13.6	62.0	13.4	1268	1511	0.3
TGx 1987-10F	46	98	125.0	17.5	45.0	13.8	1102	1465	0.3
TGx 1990-52F	44	102	99.7	16.3	27.4	15.3	1106	1451	0.4
TGx 1990-3F	44	100	127.5	15.2	45.5	15.1	1307	1417	0.3
TGx 1989-48F	44	107	114.7	14.6	36.3	13.4	1513	1407	0.4
TGx 1990-38F	44	99	68.9	14.4	35.0	14.6	831	1351	0.4
TGx 1990-40F	44	99	119.2	17.7	42.8	13.9	1157	1323	0.3
TGx 1485-1D	44	106	132.9	15.5	42.1	12.0	1426	1323	57.8
TGx 1835-10E	43	95	143.3	16.8	57.8	12.6	957	1284	8.9
TGx 1990-57F	43	98	113.3	14.1	47.6	14.3	1096	1263	0.4
TGx 1989-41F	46	107	137.8	15.4	50.0	12.1	1302	1252	0.4
TGx 1990-18F	45	103	134.4	11.7	46.5	13.4	1117	1223	0.4
TGx 1989-21F	44	106	116.5	12.3	64.1	15.2	1123	1197	0.3
TGx 1990-6F	44	98	133.5	12.4	43.4	.	843	1167	0.5
TGx 1987-62F	48	97	135.8	14.2	62.4	12.3	1113	1055	0.4
Mean	44.4	101.5	123.2	14.7	45.9	13.8	1161.4	1382.3	3.7
SE	0.4	1.0	9.1	2.5	9.6	0.4	94.8	110.6	0.6
PROB	<.0001	<.0001	0.0001	0.8380	0.2458	<.0001	<.0001	0.0005	<.0001
CV%	2.4	2.4	17.8	30.1	36.4	9.3	24.1	30.6	27.1

Table 3: Mean Grain yield of Soybean Varieties across the five location

Variety	Ibadan	Minjibir	Mokwa	Yandev	Zaria	Mean
TGx 1989-40F	1428	1805	1167	1543	2540	1697
TGx 1989-19F	1633	1656	1200	1633	2235	1671
TGx 1990-55F	1718	1504	867	1380	2636	1621
TGx 1990-21F	1660	1471	1033	1147	2601	1582
TGx 1990-37F	1953	1418	1367	1147	1935	1564
TGx 1990-46F	1737	1815	883	1553	1565	1511
TGx 1987-10F	1683	1847	833	1273	1689	1465
TGx 1990-52F	1649	1542	900	1187	1975	1451
TGx 1990-3F	1597	1448	667	1440	1933	1417
TGx 1989-48F	2001	827	1283	1533	1390	1407
TGx 1990-38F	1402	1400	933	607	2412	1351
TGx 1990-40F	1797	1152	967	990	1712	1323
TGx 1485-1D	1054	1201	1483	807	2071	1323
TGx 1835-10E	1231	2145	533	740	1772	1284
TGx 1990-57F	1498	1584	733	880	1617	1263
TGx 1989-41F	1929	632	1233	1333	1132	1252
TGx 1990-18F	833	1536	800	840	2106	1223
TGx 1989-21F	1195	806	1133	1603	1247	1197
TGx 1990-6F	1280	1881	700	713	1260	1167
TGx 1987-62F	1278	1118	733	1247	899	1055
Mean	1537.0	1439.3	972.5	1179.8	1809.5	1382.3
SE	178.8	277.7	97.6	215.1	386.8	110.6
PROB	0.0018	0.0362	<.0001	0.0131	0.0920	0.0005
CV%	19.7	33.4	17.4	31.6	35.8	30.6

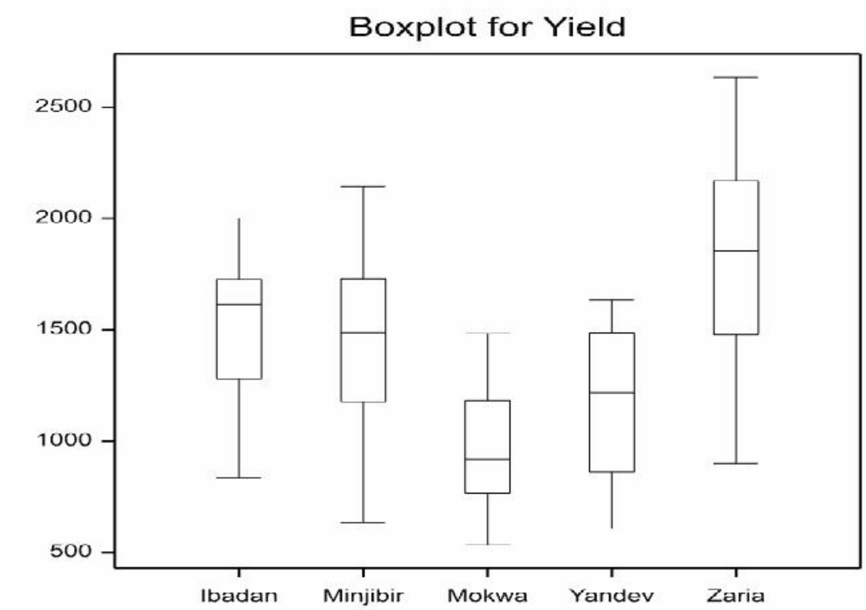


Fig 1: Box plot showing variability in Yield in different

According to Eberhart and Russell (1966), an ideal cultivar would have both a high average performance over a wide range of environments plus stability. Although genotypic main effect was not significant , environment main effect was highly significant (Table 4) which shows difference in genotypic performance across environment resulting in Genotype x Environment interaction. The existence of genotype x environment interaction (GEI) raised the need to identify stable and high yielding genotypes. The mean values for yield and regression coefficient (b), for 20 genotypes of soybean over five environments are presented in Table 5. Slope (b value) is the genotypic sensitivity to changes in the environmental quality; where values of b > 1 mean genotypes with a higher than average sensitivity, and less stable while b < 1 means genotypes that are less sensitive and more stable. The regression showed that TGx1989-19F had mean grain yield (1671kg/ha) greater than average mean 1382.3(kg/ha) and showed average genotypic sensitivity based on the regression coefficient (b=1) hence averagely stable. Five genotypes TGx1990-40F, TGx1990-55F, TGx1990-21F, TGx1990-52F and TGx1990-3F had more than average mean performance and above average sensitivity (i.e. below average stability, b>1, less stable). Four genotypes TGx1989-48F, TGx1990-46F, TGx1990-37F and TGx1987-10F had more than average mean performance and below average sensitivity (i.e. above average stability, b<1 more stable).

Table 4: Analysis of variance using F&W Regression Analysis

Table 4: Analysis of variance using F&W Regression Analysis

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Genotypes	19	3013015.3320	158579.7543	1.42	0.153
Environments	4	8782074.8736	2195518.7184	19.70	<0.001
Sensitivities	19	3468487.0523	182551.9501	1.64	0.078
Residual	57	6352680.6283	111450.5373		
Total	99	21616257.8862	218346.0393		

Table 5: Mean values for yield and regression coefficient (b), for 20 genotypes of soybean over five environments

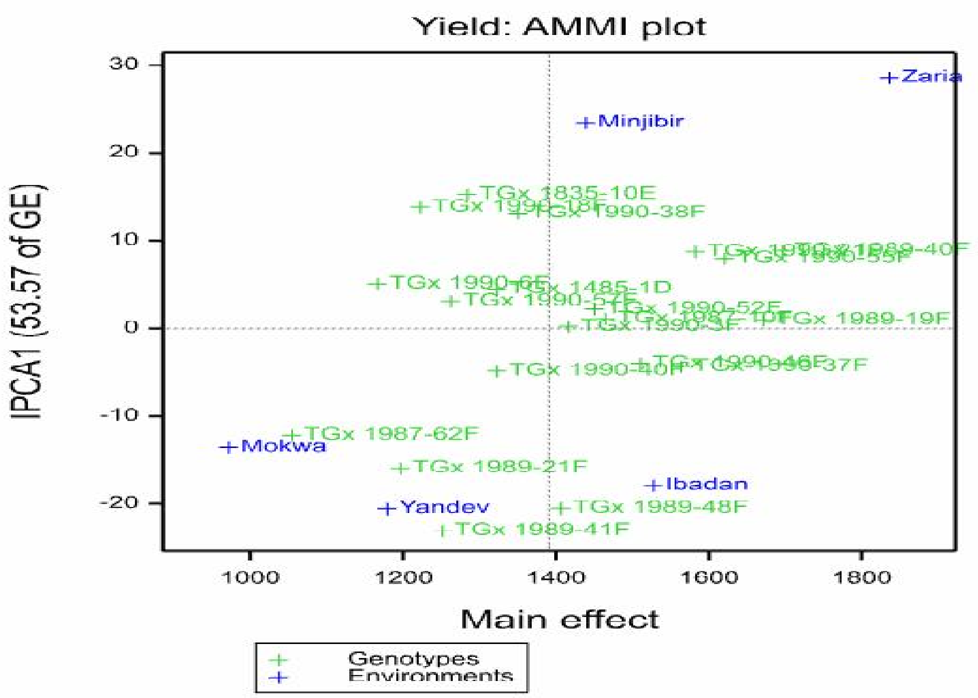
S/no	Genotype	Mean Grain Yield	Sensitivity (b value)	Dynamic stability (000)	Static stability (000)	Mean square Deviation (000)
1)	TGx 1989-41F	1252	–0.297	470.86	216.27	275.023
2)	TGx 1989-21F	1197	–0.235	449.20	81.12	99.787
3)	TGx 1989-48F	1407	–0.120	333.81	179.99	237.826
4)	TGx 1987-62F	1055	0.026	530.45	54.50	72.559
5)	TGx 1990-46F	1511	0.654	169.13	135.48	115.827
6)	TGx 1990-37F	1564	0.769	127.28	130.86	84.938
7)	TGx 1990-40F	1323	0.870	256.16	160.60	99.461
8)	TGx 1485-1D	1323	0.895	278.98	234.55	191.566
9)	TGx 1990-6F	1167	0.953	394.09	238.60	180.707
10)	TGx 1987-10F	1465	0.990	163.86	169.80	77.981
11)	TGx 1989-19F	1671	1.000	61.54	135.67	29.627
12)	TGx 1990-57F	1263	1.134	273.34	177.86	42.386
13)	TGx 1990-3F	1417	1.172	184.77	215.67	79.496
14)	TGx 1990-52F	1451	1.196	146.27	173.93	15.469
15)	TGx 1989-40F	1697	1.431	56.06	274.71	56.479
16)	TGx 1990-18F	1223	1.565	310.99	338.79	80.908
17)	TGx 1835-10E	1284	1.688	303.88	460.47	182.448
18)	TGx 1990-21F	1582	1.747	101.13	387.01	54.094
19)	TGx 1990-55F	1621	1.803	93.50	419.98	67.958
20)	TGx 1990-38F	1351	1.901	231.93	464.96	73.021
	G. Mean	**1382.3**				

Although TGx1989-40F does better than TGx1990-55F in the average performance, TGx1990-55F is superior to TGx1989-40F in the high-quality environments. This is because TGx1990-55F has a better ability to exploit improved environmental conditions, which is reflected in the higher genotypic sensitivity of the former ($b_{TGx1990-55F} = 1.803 > b_{TGx1989-40F} = 1.43$). However both genotypes has potential to respond to increase in environmental quality in a predictable way (dynamic stability). Most of the high yielding genotype have similar dynamic stability potential. High yielding genotypes like TGx1990-55F, TGx1990-3F and TGx1989-19-F also had high static stability (1.e. ability to give same performance across environments).

The AMMI Analysis of variance shows the environmental variance was significant and higher than both the genotype and GEI variance. The genotype variance was however higher than the GEI variance (Table 6). The result showed that the environment main effect (E) was the most important source of variation, due to its large contribution to the total sum of squares for yield. Variation due to genotype was larger than that due to GEI, meaning that differences among genotypes vary across environments. Similar observations were obtained by Kaya et al 2002 and Admassu et al 2008) in their studies. The presence of GEI was demonstrated by the AMMI model, when the interaction was partitioned among the first two Interaction Principal Component Axis (IPCA) as they were significant. The IPCA1 explained 53.57% of the interaction while IPCA2 explained 26.22%. (Fig. 2). They cumulatively captured 79.79% of the total GEI. This implied that the interaction of the 20 genotypes of soybean varieties with five environments was predicted by the first two principal components of genotypes and environments, which is in agreement with Guach and Zobel (1996).

Table 6: AMMI Analysis of variance for Genotypes and Environments

SOURCE	D.F.	S.S.	M.S.	V.R.	F pr
Genotypes	19	3013015	158580	1.23	0.2595
Environments	4	8782075	2195519	16.99	<0.001
GxE	76	9821168	129226		
IPCA 1	22	5261157	239143	4.10	<0.001
IPCA 2	20	2575576	128779	2.21	0.0204
Residuals	34	1984435	58366		



The differences among genotypes in terms of direction and magnitude along the X-axis (yield) and Y axis (IPCA 1 scores) are provided by AMMI biplot using the main effect and the first principal component scores of interactions(IPCA1) of both genotypes and environment (fig. 2). In the bi-plot, genotypes or environments that appear almost on a perpendicular line of the graph have similar mean grain yields and those that fall almost on a horizontal line have similar interaction (Crossa et al 1990). Hence the variability due to environments was greater than that due to genotype differences. Genotypes or environments on the right side of the midpoint of the perpendicular line have higher yields than those on the left side. The genotypes TGx1989-40F,TGx1989-19F, TGx1990-52F, TGx1990-40F, TGx1990 55F, TGx1990-37F and TGX 1990-3F were high yielding. In contrast TGx1987-62F, TGx189-21F, TGx198941F, TGx1990-6F and TGx1990-57F were low yielding.

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Genotypes or environments with large negative or positive IPCA1 scores have high interactions, while those with IPCA1 scores near zero (close to the horizontal line) have little interaction across environments (Egesi and Asiedu 2002) and are considered more stable than those further away from the line. In the biplot, TGx1990-3F, TGx1987-10F, TGx1989-19F and TGx1990-52F fell almost on a horizontal line near the zero point on IPCA1. This implies that these varieties showed high and stable yield. Genotypes TGx1989-40F, TGx1990-55F and TGx1990-21F were a little far away from the horizontal and implies that the genotypes are high yielding but relatively unstable

The genotypes TGx1990-52F, TGx1990-6F and TGx1485-1D were close to the horizontal but on the other side. This means that the genotypes are relatively stable but produce below average yield. The poorest of the genotypes due to instability and lowest yield were TGx1987-62F and TGx1989-21F. In terms of environment Mokwa and Yandev are most stable producing least interaction scores while Ibadan, Minjibir and Zaria in that order were unstable producing highest interaction scores.

The biplot of the best genotypes in each of the environments for grain yield is presented in Figure 3. The polygon view of the GGE-biplot explicitly displays ‘which-won-where’ i.e. (best genotype in each environment) and it is a summary of the GEI pattern of a multi-environment yield trial data. The polygon is formed by connecting the genotypes that are further away from the biplot origin such that all other genotypes are contained within the polygon. To each side of the polygon, a perpendicular line, starting from the origin is drawn and extended beyond the polygon so that the biplot is divided into several sectors, and the different environment were separated into different sectors. The genotype at the vertices of each sector is the best performer at environments included in that sector, provided that GGE is sufficiently approximated by PC1 and PC2. Hence, though there were seven sectors in all, three mega environments were identified. Ibadan, Mokwa and Yandev was one mega environment with TGx1990-37F(G5) and TGx1989-48F (G10) as winning or the best genotypes in this environment. The winning (best) genotype for the second mega-environment Zaria was TGx1989-40F(G1), while the last mega environment Minjibir has TGx1990-6F (G19) as the best. The remaining sectors have no environment within them and contain the following genotypes on their vertices TGx1989-19F(G2), TGx1989-41F(G16) and TGx1987-62F(G20). These vertices genotypes without environment in the sectors were not the highest yielding genotypes at any environment. However, genotypes within the polygon, particularly those located near the plot origin, were less responsive than the vertex genotypes.

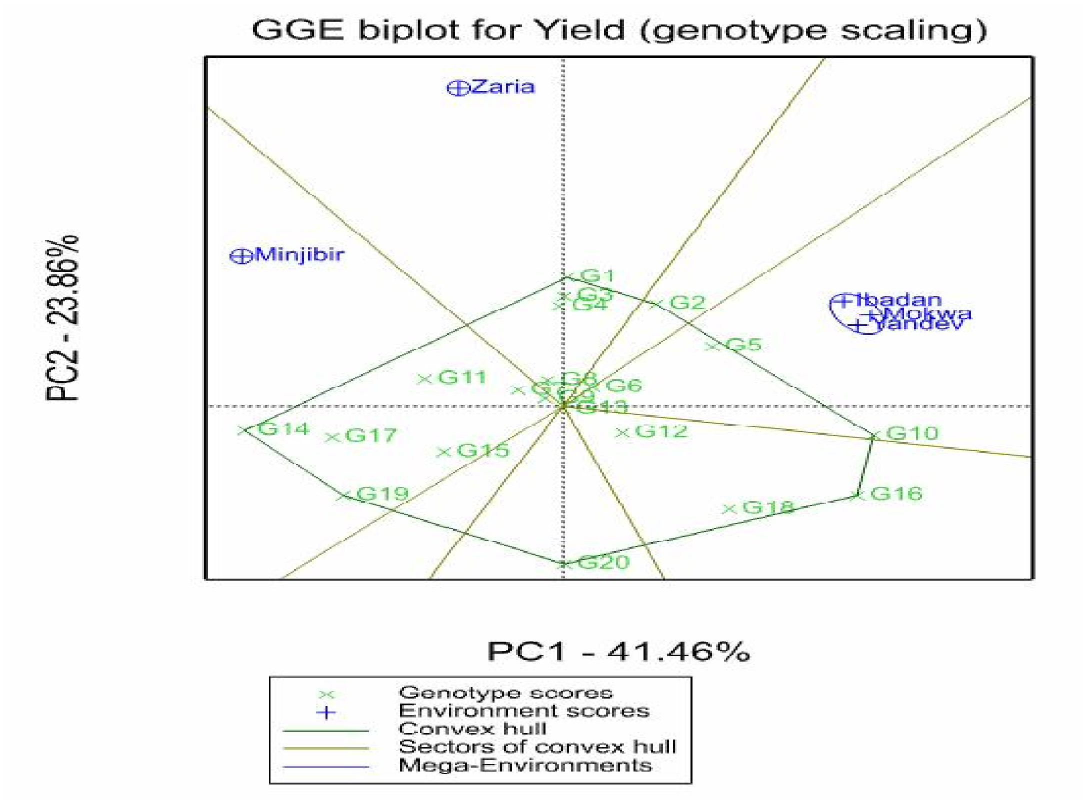

Fig 3: GGE biplot for best genotypes in different environments for Grain yield

Conclusion

Although AMMI and GGE biplots gave better expression of G X E, four soybean genotypes (TGx1990-37, TGx1987-10F, TGx1989-19F and TGx1990-52F) were identified by the three analysis tools that were overall best in performance in relation to yield and stability. This suggests that for reliability and optimum result it is better to combine the result of the two or three analytical tools for yield and stability in the recommendation of genotypes to farmers.

Genotypes with large interaction with the environment are unpredictable in performance and can only be grown in limited environments. Of the five environments, Mokwa produced the least interaction effect followed by Yandev and may be most appropriate environments for soybean production and evaluation. Selection in these environments will be effective as the relative performance of these genotypes would be fairly stable.

References

Bernardo R (2002). Breeding for quantitative traits in plants. Stemma Press, Minnesota, P. 369

Burdon RD (1977). Genetic correlation as a concept for studying genotype–environment interaction in forest tree breeding.Silvae Genet. 26:168-175

Comstock RE, Moll RH (1963).Genotype x Environment Interactions.Symposium on Statistical Genetics and Plant Breeding.National Academy Science National ResearchCouncil,Washington, D.C. pp. 164-196.

Finlay KW, Wilkinson GN (1963). The analysis of adaptation in a plant breeding programme. Aust. J. Agric. Res. 14:742-754.

Francis TR, Kannenberg LW (1978). Yield stability studies in short season maize. I. A. descriptive method for grouping genotypes. Can. J. Plant Sci. 58:1029-1034.

Gabriel KR (1971). The biplot graphic of matrices with application to principal component analysis. Biometrics 58:453-467.

Gauch HG, Zobel RW (1988). Predictive and postdictive success of statistical analyses of yield trials.Theor. Appl. Genet. 76:1-10.

Gauch HG (1992). Statistical analysis of regional yield trials: AMMI analysis of factorial designs. Elsevier, Amsterdam, The Netherlands, pp. 53-110.

Perkins JM, Jinks JL (1968). Environmental and genotype environmental components of variability III, Multiple lines and crosses. Heredity 23:339-354.

Pinthus JM (1973). Estimate of genotype value: A proposed method. Euphytica 22:121-123.

Shukla GK (1972). Some statistical aspects of partitioning genotype-environmental components of variability. Heredity 29:237-245

Specht, J. E., Hum, D. J., and Kumidini, S. V. 1999. Soybean yield potential - A genetic and physiological perspective. Crop Sci., 39: 1560-1570

Yan W, Tinker NA (2006). Biplot analysis of multi-environmental trial data: Principles and applications. Can. J. Plant Sci. 86:623-645

Yang R, Crossa J, Cornelius PL, Burgueno J (2009).Biplot analysis of genotype x environment interactions: Proceed with caution. Crop Sci. 49:1564-1576.

Zobel RW, Wright MJ, Gauch HG (1988). Statistical analysis of a yield trial.Agron. J.80:388-393.