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REVIEW ARTICLE

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Genotype X Environment Interactions for Bean Yield of Coffee Hybrids under Coffee Berry Disease Prone Environments in Southwestern Ethiopia

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ABSTRACT

Coffee (Coffea arabica L.) is the most important commercial crop in the national economy of Ethiopia. In the country, berry yields of coffee are considerably affected by genotype by environment interaction (GEI). The objective of this study was to investigate the GEI and stability for berry yield among selected coffee hybrids under coffee berry disease prone environments of Southwestern Ethiopia. Eight single cross hybrids and two standard checks were evaluated using randomized complete block design with three replications across eight environments (two sites and four years combination). The Additive Main Effects and Multiplicative Interaction (AMMI)) biplot model was used to assess the magnitude of GEI and stability of berry yield among test materials. Results from the AMMI analysis of variance revealed a significant contribution of the environmental effect on berry yield accounting to 72.10% of the total variation among hybrids. Genotypes and GEI contributed to 13.0% and 12.80% of the total variation of hybrids of this trait, respectively. With regards to the stability estimate Hybrid HC4 followed by HC1 had relatively moderate stability. These hybrids could be recommended for direct use in Gera and similar environments in southwestern Ethiopia.

Keywords: AMMI model, AMMI stability value, Berry yield, Coffea Arabica.

INTRODUCTION

Coffee is one of the leading commodities in the international trade. It provides a livelihood for some 125 million people around the world (Lashermes *et al*., 2011). Coffee (*Coffea arabica* L.) is the most important commercial crop in the national economy of Ethiopia. In Ethiopia, coffee is mainly grown in three altitude zones viz., the high altitude (over 1750 m above sea level), the medium altitude (between 1550 m and 1750m above sea level) and the low altitude (below1550 m above sea level (Bayetta *et al*., 2000).

However, production across these climatic ranges is seriously constrained by diseases, especially coffee berry disease (CBD) at highland (Eshetu, 2000). Crop variety may not produce uniform yields across these environments as result of the existence of Genotype by Environment (GE) interaction. Stability to resistance of any sort is one the most complex problems in the field of resistance breeding and the two type of resistance (vertical and horizontal) may not be sustainable due to fluctuation and continual changes in the population of pest and pathogen (Asante and Dixon, 2002). This complicates the selection of lines for release as commercial varieties and recommendations of cultivars for particular environments (Comstock and Moll, 1963; Asante and Dixon, 2002). Previous studies in coffee have also reported that GEI is greatly exacerbated by the outbreak of crop stresses such as drought or diseases thereby causing significant reduction in yield stability of genotypes (Mesifin and Bayetta, 1987; Wamatu *et al.,* 2003; Bertrand *et al*., 2010; Yonas *et al*., 2014) even in locally disparate environments. Efficient selection methods to discriminate between lines in a breeding programme depend on knowledge of the expected effects of environment and GEI (Wamatu *et al.,* 2003).

There is lack of information in the effect of GEI and stability of newly developed coffee hybrids when grown under coffee berry disease (CBD) prone environments. Moreover, a GEI estimates is usually applicable only to a specific population and a specific range of environments (Fins *et al*., 1992).

Different statistical or stability models including univariate and multivariate ones are available to estimate the magnitude of GEI (Annicchiarico, 2002). More recently, another model that has gained importance in investigating the role of genotype, environment and GEI effects in yield-trial experiments is the Additive Main Effects and Multiplicative Interaction (AMMI) (Gauch, 1992).

Multi environmental trials and subsequent data collection and analysis involving experimental hybrids are helpful to identify genotypes with high and stable yield performance and to select test environments (Kandus *et al*., 2010). Therefore, the objective of this study was to investigate the GEI for berry yield in coffee hybrids under CBD prone environments.

MATERIAL AND METHODS

A total of ten Experimental Arabica coffee F_1 hybrids along with two commercial check varieties 'Aba-Buna' (F_1 hybrid) and '74110' (pure line variety) (Table 1) were evaluated at two different CBD prone sites around Gera district in South-western Ethiopia for four consecutive cropping seasons. The sites were Gera Research Station and On-farm location around the station. Randomized complete block design (RCBD) with three replications was used. Each plot comprised of 16 trees and 2 m by 2 m spacing in 2500 trees ha^{-1} basis. Variation in growing micro-environments allows testing of the selected hybrids for GEI and their stability towards yield. Also the year differentiated in term of seasonal mean

distributions and variations in rainfall, minimum and maximum temperature, and relative humidity across cropping periods (Annex Figures 1a, 1b, 1c and 1d).

Table 1. Hybrid codes and hybrid definitions of ten coffee genotypes used in the study.

Hybrid name	Hybrid code	Hybrid Definition
HC-1	G1	Experimental F_1 Hybrid
HC-2	G2	Experimental F_1 Hybrid
HC-3	G3	Experimental F_1 Hybrid
HC-4	G4	Experimental F_1 Hybrid
HC-5	G5	Experimental F_1 Hybrid
HC-6	G6	Experimental F_1 Hybrid
HC-7	G7	Experimental F_1 Hybrid
HC-8	G8	Experimental F_1 Hybrid
Aba-Buna (HYCK	G9	Check F_1 Hybrid
74110 (VCK)	G10	Variety Check

Analysis of variance for each fertility environment and across environments was made for berry yield using the standard procedure as cited in Gomez and Gomez (1984). Homogeneity of residuals variance was determined by Bartlett's homogeneity test, before combing the data sets. Yield data were subjected to statistical analyses using proc GLM with MIXED procedure of SAS (SAS, 2008). AMMI analysis of berry yield was carried out to assess the relationship among hybrids and environments. Analysis combines, in a single model, additive components for the main effects of genotypes and environment as well as multiplicative components for interaction effects (Geberiel, 1971; Gauch, 1988; Gauch and Zobel, 1996).

The model is

$Y_{ij} = \mu + G_i + E_j + \sum_{k=1}^{n} l_k \gamma_{ik} a_{jk} + \rho ij + \varepsilon_{ij \text{ with GEij}}$ represented by $l_k \gamma_{ik} a_{jk} + \rho ij$.

Where: (i = 1, 2…….10: j = 1…….8); Y_{ij} = the performance of the i^{th} genotype in the j^{th} environment; μ= the grand mean; G_i = Additive effect of the i^{th} genotype (genotype mean minus the grand mean); E_j = Additive effect of the j^{th} environment (environment mean deviation).

The multiplicative parameters are:-

l_k= singular(eigenvalue) of n^{th} principal component axis; γ_{ik} and a_{jk} the genotype and environment scores (eigenvectors) for the n^{th} principal component axis; ρij the residual (remains if not all axes are used); ε_{ij} , the random error, which is the difference between Y_{ij} mean and the single observation for replicate r.

The AMMI stability value (ASV) was calculated according to the formula suggested by Purchase (1997) to measures the relative stability of each genotype in each environment and across environments. ASV is the distance of interaction principal component IPCA from coordinate point to the origin in a two dimensional plot of IPCA 1 against IPCA 2 scores in the AMMI model. Because the IPCA1 contributes more to the GEI sum of squares then a weighted value has to be estimated for each genotype and environment according to the relative contributions of the first two IPCAs. The following formula was used in the calculation of AMMI stability value (ASV).

ASV = $\{[(SSPCA1 / SSPCA2)\ (IPCA1score)]^2 + (IPCA2score)^2\}^{1/2}$; Where, SSPCA1 / SSPCA2

represents the weight assigned to the first interaction principal component score due to its high contributions in the GEI model. The larger the ASV value in either direction positive or negative the more specifically adapted the genotype to a certain environment. Smaller ASV indicates a more stable genotype across environments (Purchase, 1997).

RESULTS AND DISCUSSION

Analysis of variance

Separate analysis for individual environment was made and the F-test showed significant difference among the genotypes at each environment (data not shown). The residuals mean squares were homogenous across the individual environments mean berry yield thus the data were not transformed. Combined analysis of variances across environments (location–year combinations) resulted highly significant ($P < 0.01$) differences in genotype (G), environment (E) and the GEI effects. The partitioning of treatment sum squares indicated that the environment effect was a predominant source of variation with comparable GE and genotype effects (Table 2).

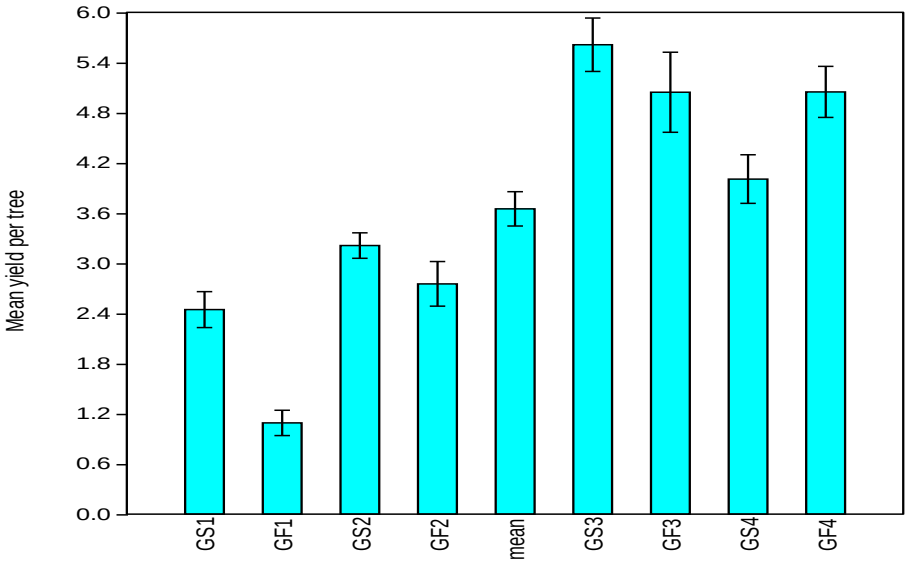


Figure 1. Berry yields for individual environment across hybrids.

Error bars represent standard errors.

GS1= Gera Research Station in 2011/12, GF1= Gera On-farm plot in 2011/12, GS2= Gera Research Station in 2012/13, GF2= Gera On-farm plot in 2012/13, GS3= Gera Research Station in 2013/14, GF3= Gera On-farm plot in 2013/14, GS4= Gera Research Station in 2014/15, GF4= Gera On-farm plot in 2014/15.

Environment

The mean performance of berry yield over environments indicated the relative performance of the hybrids tested across environments. The environment mean yield (kg tree^{-1}) ranged from 1.09±0.15 (GF1, Gera on-farm 2011/12) to 5.61± 0.32) (GS3, Gera station 2013/14) indicating seasonal differences among test environments (Figure 1). The variations within as well as between environments were mainly attributed to difference in rain fall followed by minimum temperature **(**Annex Figures 1a, 1b, 1c and 1d)**,** while maximum temperature and relative humidity (RH %) showed relatively lower variations. Difference due to coffee trees age across environments also contributed a lot in this regards. This result is in agreement

with many findings that show environmental factors have significant influence on the performance of genotypes (Gauch and Zobel, 1996; Wamatu *et al*., 2003; Yan and Tinker, 2005; Yonas and Bayetta, 2008; Meaza *et al.*, 2011; Lemi, 2016). This yield range reflected the different climatic conditions, disease incidence and crop bearing stages difference across environments (locations and years combination). A graph of genotype versus environment mean yield also showed the presence of GEI (Figure 2). The preliminary analysis of variance detected the presence of GEI and allowed to assess the magnitude of GEI among the coffee hybrids.

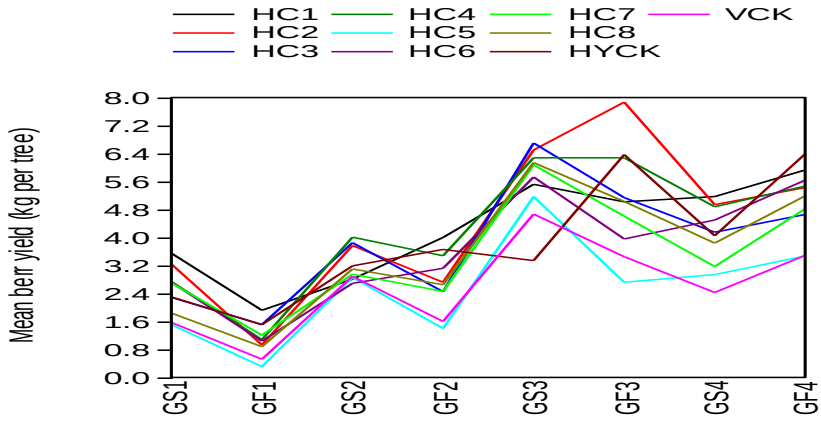


Figure 2. Plot of the ten genotypes *versus* the environments mean yield (kg per tree) to visually assess GEI. See code descriptions of environments in Fig. 1.

Table 2. Analysis of variance for the Additive Main Effect and Multiplicative Interaction (AMMI) model.

Source	Df	SS	MS	%SS[1]	%GEI
Model	95	702.2			
Genotypes(G)	9	91.5	10.169**	13.0	
Environments(E)	7	506.1	72.298**	72.1	
Reps within E	16	14.8	0.924*	2.10	
GEI	63	89.8	1.425**	12.8	
IPCA1	15	43.3	2.889**		*48.2*
IPCA2	13	29	2.227**		*32.3*
IPCA3	11	9.7	0.885*		*10.8*
IPCA4	9	3.6	0.396ns		*4.0*
IPCA Residuals	15	4.2	0.281		*4.7*
Error	144	62.8	0.436		

[1] % of model sum squares for environment, genotypes and GEI; %(italicized numbers) of GEI sum squares for IPCAs; * and ** Significant at the 0.05 and 0.01 probability levels, respectively

AMMI analysis of GE interaction

The AMMI analysis of variance for berry yield of the ten coffee genotypes tested in eight environments of Ethiopia is given in Table 2. Combined analysis of variance revealed that

genotypes, environment and genotype by environment interaction were found highly significant (P<0.01) (Table 2). The environment captured 72.1% of the total sum of square followed by the genotypes (13%). However, genotype by environment interaction captured 12% (Table 2). The large sum square of the environment implying that the environment was with higher differential in discriminating the performance of the genotype and caused most of the variation in berry yield. Meaza *et al.* (2011) reported similar result in study of AMMI in Ethiopia with 74 % of environmental influence which is comparable to the present study. Meaza *et al.* (2011) reported 8.7 and 15.7% were due to genotype and GEI, respectively, where the variation due to GEI is much higher than due to genotype in the present study.

Stability analysis by AMMI model

The AMMI model does not make provision for a quantitative stability measure, such a measure is essential in order to quantify and rank genotypes according to their yield stability, AMMI stability value (ASV) measure was proposed by Purchase (1997) to cope with this problem. ASV takes into account both IPCA1 and IPCA2 that justify most of the variation in the GEI; in this regard the genotypes with least ASV were considered the most stable. Accordingly, hybrids HC8 followed by HC4 and HC7 were found to be the most stable for their berry yield (Table 3). Hybrid check (HYCH), test hybrid HC2 and HC5 were unstable. Considering yield and ASV values hybrid HC4 and HC1 were superior in both terms over all environments.

Table 3. Mean yield (kg tree^{-1}), rank, IPCA 1 and IPCA 2 scores and AMMI stability values (ASV) of ten coffee genotypes tested across eight Gera environments.

Code	Hybrids	Yield	Rank	IPCAg[1]	IPCAg[2]	ASV	Rank
G1	HC1	4.24	3	-0.28	0.78	0.88	6
G2	HC2	4.42	1	-0.49	-1.22	1.43	9
G3	HC3	3.84	5	0.54	-0.37	0.89	7
G4	HC4	4.28	2	-0.17	-0.41	0.49	2
G5	HC5	2.55	10	0.80	0.23	1.21	8
G6	HC6	3.68	6	0.15	0.68	0.72	5
G7	HC7	3.50	8	0.37	0.02	0.55	3
G8	HC8	3.58	7	0.14	-0.18	0.27	1
G9	HYCK	3.85	4	-1.47	0.38	2.24	10
G10	VCK	2.58	9	0.42	0.09	0.64	4
	Mean	3.65					
LSD(0.05)		0.38					
C.V(%)		18.08					

AMMI biplot display

Using ANOVA, yield sum square was partitioned into genotype, environment and GEI. GEI was further partitioned by principal component analysis (Table 2). An AMMI biplot (Gabriel, 1971) was used to show both genotypes and environments simultaneously. The results of AMMI analysis indicated that the first three AMMI (AMMI1–AMMI3) were found to be highly significant (*P*<0.05 to 0.01) (Table 2) which led to the selection of the AMMI3 model. However, it is evident from Table 2 that the use of biplots to explain efficiently the interaction is very much justifiable (Zobel *et al*., 1988), since the first two PCA axes explain

80.5% of the total interaction variation. The first and second interaction principal components (IPCA 1 and 2) were highly significant ($p< 0.01$) for coffee berry yield. This was in general agreement with Wamatu *et al*. (2003), Meaza *et al.* (2011) and Lemi (2016).

The AMMI biplot was generated using the principal component scores to visualize the relationships between environments and hybrids. The first two principal components explained 80.5% of the total variation in genotype by environment interaction (GE) sums of squares (Table 2). The high yielding genotypes and environments were positioned on the right side of the biplots (Fig. 3). The AMMI2 biplot (Figure 4) showed that environments GS3 (Gera station 2013/14) and GF3 (Gera on-farm 2013/14) were the most discriminating for the hybrids followed by GF2 (Gera on-farm 2012/13) and GF4 (Gera on-farm 2014/15). The rest had a very small projection and with small angle closely related to those environments. Hybrids that had a small projection of vector for the environments indicating it performed well at that environment. For instance, the hybrid HC3 (G3) in Environments GS3 and GS2, and hybrid HC2 (G2) in Environment GF3 (Figures 3 and 4) performed well.

Genotypes placed near the plot origin were less responsive than genotypes far from it. Genotypes 2 (HC2) and genotype 4 (HC4) gave the highest mean yield (largest IPCA1 scores) but genotypes G4 (HC4) was more stable than genotypes G2 (HC2), because it has smaller absolute IPCA2 score.

Genotypes ID selections per environment

The AMMI analysis identified four best hybrids in terms of berry yield performance across eight environments. Hybrids HC1 (G1) was selected as number one in environments GF1, GS1, GS4 and GF2. It was also selected as second in GF4 and third in E3 (Table 4). Hybrid G3 was selected number one in environments GS3 and GS2. Other hybrid genotypes with multiple selections were G2, G4, G9, G6 and G7. All these hybrids with multiple selections of choices can be recommended for production in a wide range of environments as opposed to hybrids HC8 (G8) which had only one choice, limited to a single location or environment therefore could be recommended for cultivation and production in that specific environment (Table 4).

Table 4. First four AMMI genotype ID selections per environment.

Number	Environment	Mean	Score	1st	2nd	3rd	4th
7	GS3	5.612	1.3573	G3	G2	G4	G8
6	GS2	3.210	0.4491	G3	G4	G2	G9
1	GF1	1.090	0.2182	G1	G9	G7	G3
5	GS1	2.445	0.1457	G1	G2	G4	G7
8	GS4	4.005	-0.1182	G1	G4	G2	G6
2	GF2	2.755	-0.3558	G1	G9	G6	G4
4	GF4	5.049	-0.6144	G9	G1	G4	G6
3	GF3	5.042	-1.0818	G2	G9	G4	G3

See code descriptions of genotypes and environments in Table 1 and Fig. 1, respectively.

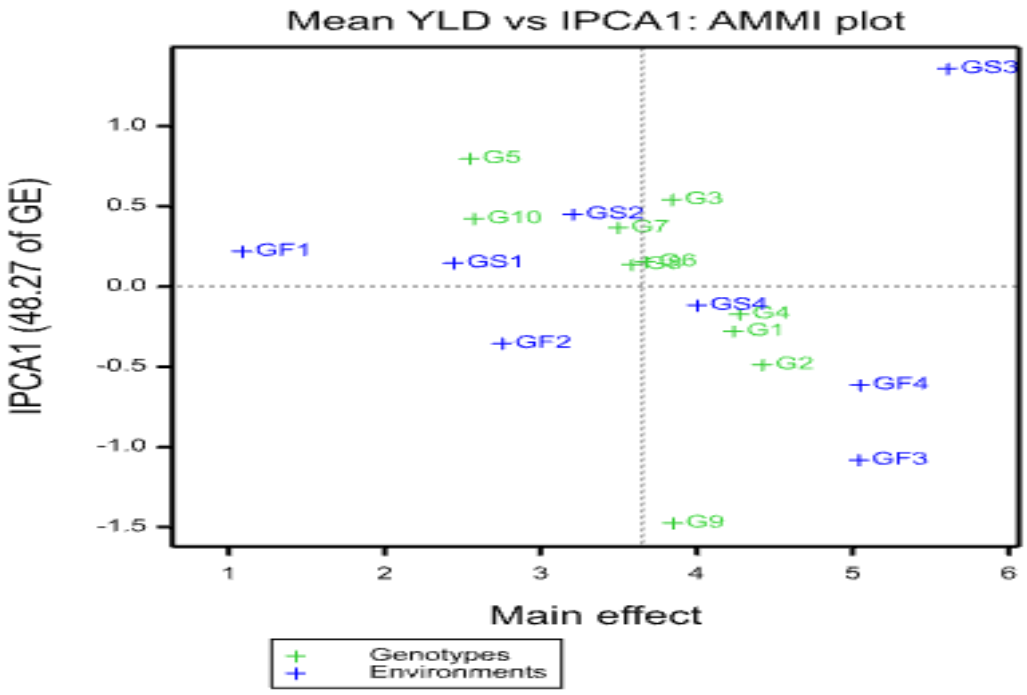


Figure 3. AMMI1 biplot with IPCA1 scores against means of genotypes and environments showing patterns of distribution of ten F1 hybrids (G1-G10) across eight environments. See code descriptions of genotypes and environments in Table 1 and Fig. 1, respectively.

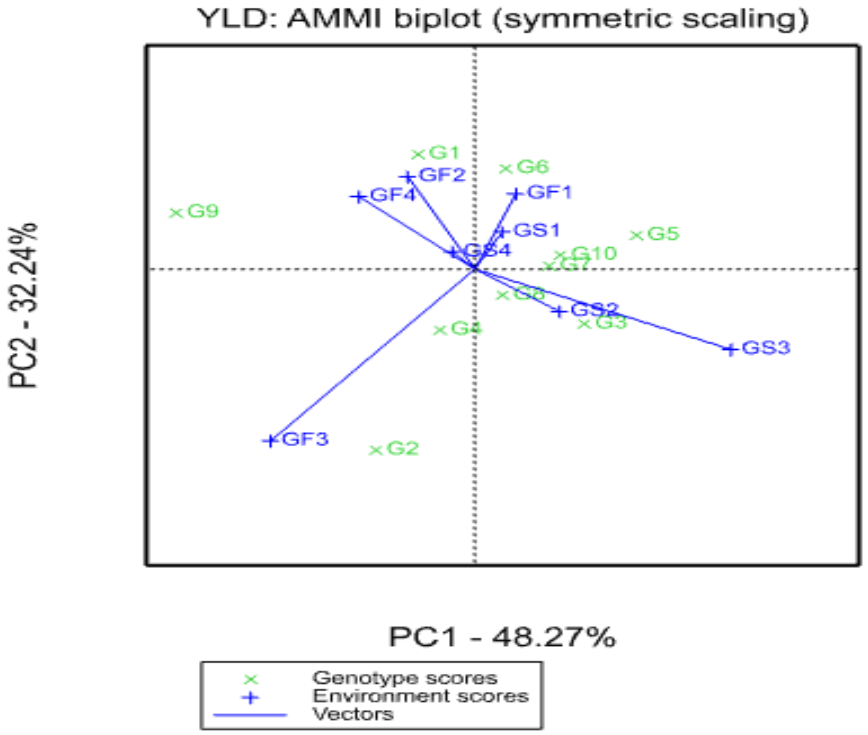
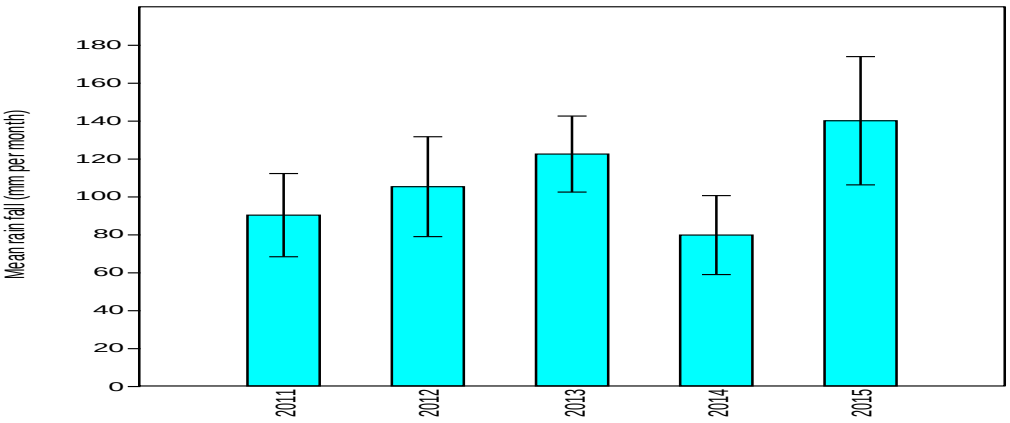
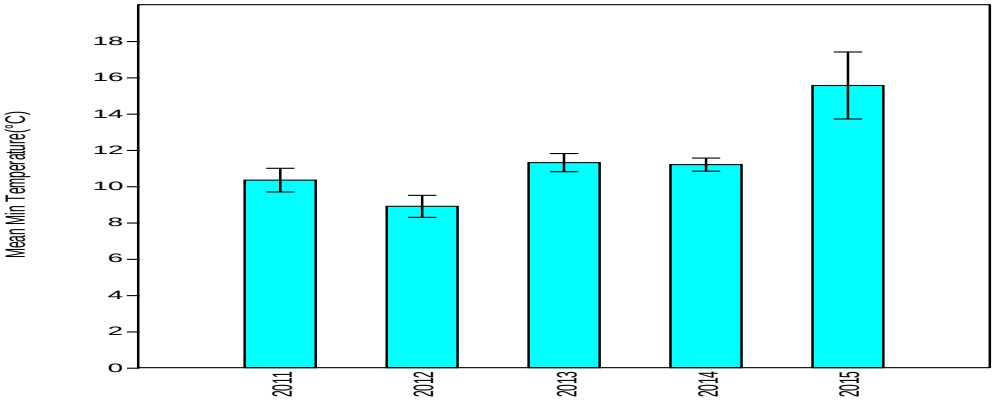


Figure 4. AMMI2 biplot for berry yield of ten coffee genotypes tested across eight highland environments of Southwest Ethiopia (2 sites, and 4 years). See code descriptions of genotypes and environments in Table 1 and Fig. 1, respectively.

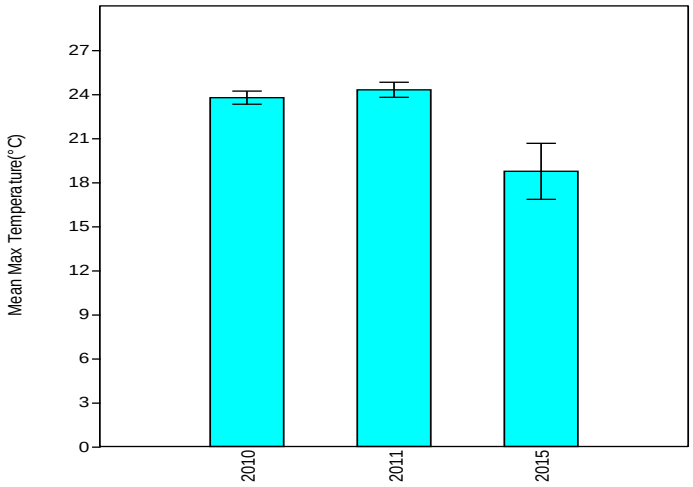
Annex 1. Gera Metrological data for Experimental Periods.



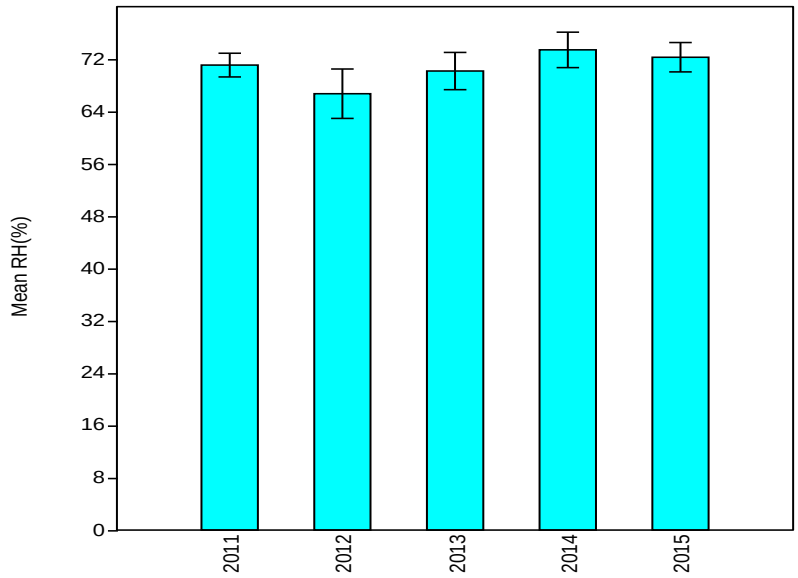
Annex Figure 1a. Rain fall (mm) distributions for individual environment across 12 months at Gera. Error bars represent standard errors. Source: Gera research Station



Annex Figure 1b. Minimum Temperature (^{o}C) distributions for individual environment across 10-12 months at Gera. Error bars represent standard errors. Source: Gera research Station.



Annex Figure 1c. Maximum Temperature (^{o}C) distributions for individual environment across 11-12 months at Gera. Error bars represent standard errors. Source: Gera research Station and Chira metrology station.



Annex Figure 1d. Relative humidity (RH %) distributions for individual environment across 9-12 months at Gera. Error bars represent standard errors. Source: Gera research Station.

CONCLUSION

Yield performance of genotypes is often confounded by GEI and therefore reduces selection efficiency and response. Using AMMI model the berry yield response of ten coffee hybrids clearly showed that some hybrids with higher berry yield across environments, displayed larger GEI, even within locally disparate environments at micro level. However, Hybrids HC4 and HC1 had relatively moderate stability. These hybrids could be recommended for direct use in Gera and similar environments in southwestern Ethiopia.

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