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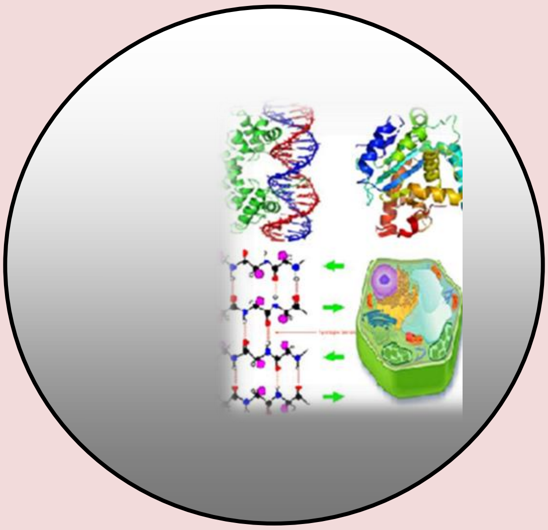

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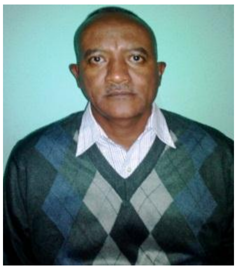

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RESEARCH PAPER

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Assessment of Genotype X Environment Interactions for Bean Yield in Coffee Hybrids using AMMI Analysis from Jimma-Tepi, Southwestern Ethiopia

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ABSTRACT

Coffee production is fundamental for over 80 developing countries including Ethiopia, for which it is the main foreign currency earner. In Ethiopia, 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 in mid- and lowland coffee growing agro-ecologies of Southwestern Ethiopia. Fifteen single cross hybrids and one standard check were evaluated using randomized complete block design with three replications across eight environments (two locations by four years combination). The Additive Main Effects and Multiplicative Interaction (AMMI) 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 84.30% of the total variation among hybrids. Genotypes and GEI contributed to 4.70% and 10.70% of the total variation of hybrids of this trait, respectively. GEI analysis for berry yield clearly showed that hybrids with higher berry yield across environments displayed larger GEI indicating breeding for high berry yield and stability of these yields across environments appears to be very problematic in Arabica coffee. Highest mean yield recorded for Hybrids HC7, HC5, HC4 at both locations and HC8 at Jimma. These hybrids could be recommended for specific adaptation.

Keywords: AMMI Model, AMMI stability value, Berry yield and Coffea Arabica.

INTRODUCTION

Coffee is undoubtedly the most valued of the stimulant crops. Coffee production is fundamental for over 80 countries including Ethiopia, for which it is the main foreign currency earner (Mishra and Slater, 2012). In Ethiopia, more recently, coffee accounted for over a third of export earnings and it is estimated that coffee forms a main source of livelihood to more than 20 million families (CSA, 2013). Jimma and Tepi which are representing mid- and lowland coffee growing agro-ecologies are the major one and in country wise well as regional wise.

Despite the significant importance of coffee in Ethiopia, its yield levels have remained low (0.634/ha) (CAS, 2016) relative to the global mean of 0.791 t ha^{-1}(Boansi and Crentsil, 2013), constrained by abiotic (erratic rainfall in distribution and intensity, soil property, *etc*.) and incidence of disease and pests. The biotic and abiotic factors are the main contributors for GEI (Annicchiarico, 2002; Rashidi *et al*., 2013) and coffee yields fluctuation from year to year and from location to location (Mesifin and Bayetta, 1987; Wamatu *et al.,* 2003). 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). 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 mid- and lowland coffee growing agro-ecologies. Moreover, a GEI estimate is usually applicable only to a specific population and a specific range of environments (Fins *et al*., 1992). Pooled analysis of variance over environments will determine the extent of genotype by environment interaction (Comstock & Robinson, 1952; Comstock & Moll, 1963; Holland, *et al*., 2003), but gives no estimates of the stability of a genotype, which is important for breeding decisions. Information concerning these parameters in coffee, especially in Ethiopia under mid- and lowland coffee growing agro-ecologies, is very scarce.

The measured yield of each cultivar in each test environment is a measure of an environment main effect (E), a genotype main effect (G), and the genotype × environment (GE) interaction (Yan and Tinker 2005). Obviously, E explains 80% or higher of the total yield variation; however, it is G and GE that are relevant to cultivar evaluation (Yan, 2002). Even in perennial crop like coffee, in most of the cases the proportion of E exceeds the stated one. 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 mid- and lowland coffee growing agro-ecologies in Ethiopia.

MATERIAL AND METHOD

Coffee multi-environment hybrid trials of 15 experimental F_1hybrids along one hybrid check (Table 1) were conducted at two different locations: Jimma with altitude of 1753m a.s.l and Tepi with 1220m a.s.l in Southwestern Ethiopia representing the midland and lowland humid coffee growing agro-ecologies, respectively. The four year which made the eight environments in combination with two locations were differentiated in term of seasonal mean, distributions and variations in rainfall, minimum and maximum temperature (Annex Figures 1a, 1b and 1c).

For all of the environments, a 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. The yield data set was balanced (all genotypes were present in each environment).

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).

Table 1. Hybrid codes and hybrid definitions of 16 coffee genotypes used in the study.

#	Code-name	Hybrid Definition
1	HC-1	Experimental F_1 Hybrid
2	HC-2	Experimental F_1 Hybrid
3	HC-3	Experimental F_1 Hybrid
4	HC-4	Experimental F_1 Hybrid
5	HC-5	Experimental F_1 Hybrid
6	HC-6	Experimental F_1Hybrid
7	HC-7	Experimental F_1 Hybrid
8	HC-8	Experimental F_1 Hybrid
9	HC-9	Experimental F_1 Hybrid
10	HC-10	Experimental F_1 Hybrid
11	HC-11	Experimental F_1 Hybrid
12	HC-12	Experimental F_1 Hybrid
13	HC-13	Experimental F_1 Hybrid
14	HC-14	Experimental F_1 Hybrid
15	HC-15	Experimental F_1 Hybrid
16	Aba-Buna (HYCK)	Check F_1 Hybrid

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

Analyses of variance and environments

The combined analysis variance result for bear yield of the eight environments showed a very high significant difference (p<0.01) of the environment, genotype and G×E interaction components. The environment mean yield (kg $tree^{-1}$) ranged from 0.76±0.11 (TE12, Tepi 2012/13) to 9.70± 0.32) (JE13, Jimma 2013/14) (Figure 1) indicating seasonal differences among test environments. This yield range reflected the different climatic conditions, disease incidence and crop bearing stages difference across environments (locations and years). The variations within as well as between environments were mainly attributed to difference in rain fall followed by minimum temperatures (Annex Figures 1a, 1b, and 1c)**,** while maximum temperatures relatively showed lower variations. Differences in trees age across environments were also contributed a lots to a variation in between environments. The difference in the rank of the genotypes in the various environments indicated the presence of GEIs, which was confirmed by the significant effect of the genotype by environment interaction in combined analysis (Table 2) and in interaction plot (Figure 2). The preliminary analysis of variance detected the presence of GEI and allowed to assess the magnitude of GEI among the coffee hybrids.

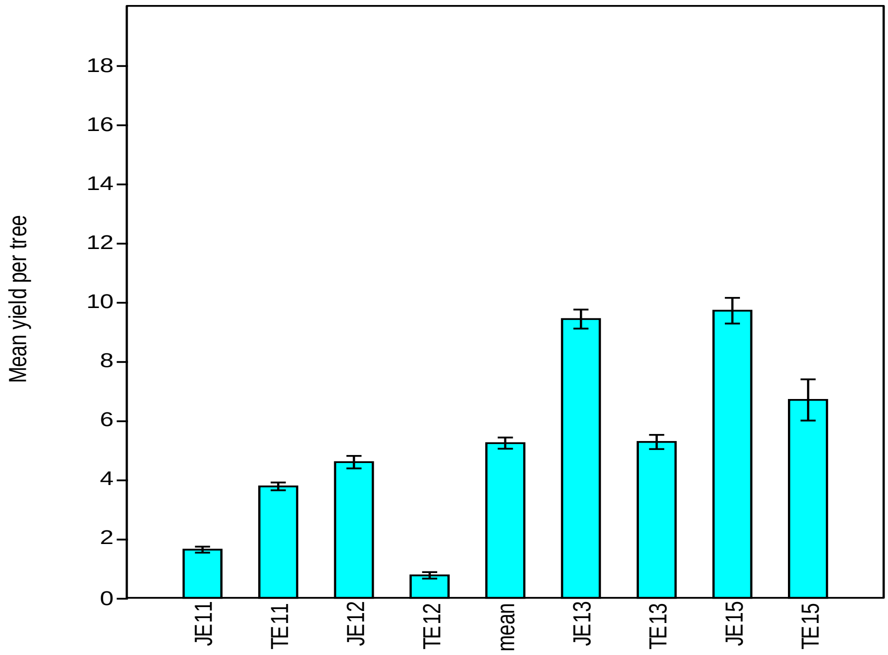


Figure 1. Berry yields (kg per tree) for individual environment across hybrids. *Error bars* represent standard errors.

JE11=Jimma 2011/12, JE12=Jimma 2012/13, JE13=Jimma 2013/14, JE15=Jimma 2015/16
TE11=Tepi 2011/12, TE12=Tepi 2012/13, TE13=Tepi 2013/14; TE15=Tepi 2015/16

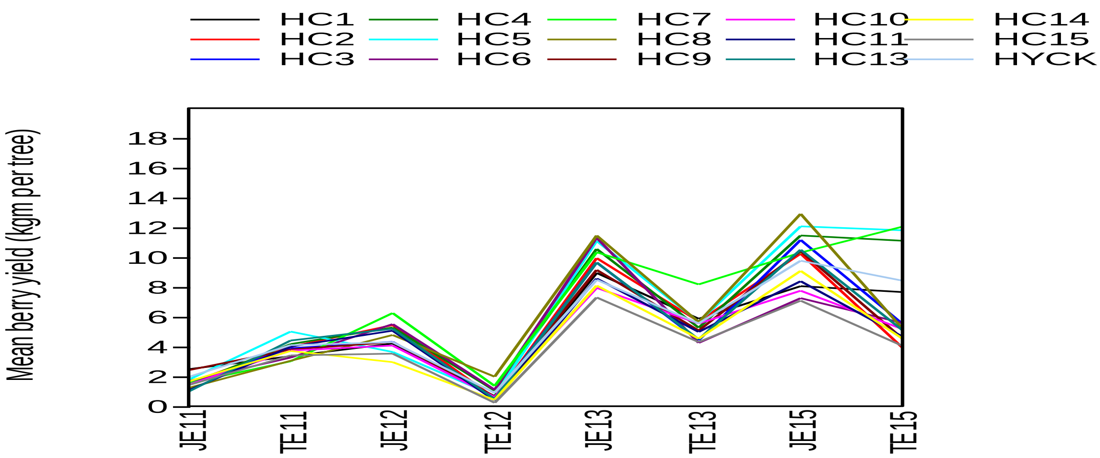


Figure 2. Plot of the 16 coffee hybrids *versus* the environments mean yield (kg per tree) to visually assess GEI. See code descriptions of environments in Fig. 1.

AMMI analysis of GE interaction

The AMMI analysis of variance for berry yield of the sixteen 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).

The environment captured 84.3% of the total sum of square followed by the genotypes captured 4.7%. However, genotype by environment interaction captured 10.7 % (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. This result is in agreement with many findings that show large proportion of the environment and the G×E interaction component in many crops (Gauch and Zobel, 1996; Wamatu *et al*., 2003; Yan and Tinker, 2005; Yonas and Bayetta, 2008; Lemi, 2016). 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 although it is slightly lower in respect to what has been reported in this study. Meaza *et al.* (2011) also reported 8.7 and 15.7% were due to genotype and GEI respectively, which is comparable to the present study.

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

Source	Df	SS	MS	% SS[1]	% GEI
Model	143	4282.13			
Genotypes(G)	15	203.4	13.56**	4.7	
Environments(E)	7	3608.8	515.55**	84.3	
Reps within E	16	10.5	0.65ns	0.2	
GEI	105	459.4	4.37**	10.7	
IPCA1	21	258.1	12.29**		*56.2*
IPCA2	19	104.8	5.52**		*22.8*
IPCA3	17	44.9	2.64**		*9.8*
IPCA4	15	27.7	1.85**		*6.0*
IPCA5	13	14	1.08**		*3.0*
IPCA6	11	6.1	0.56ns		*1.3*
IPCA Residuals	9	3.6	0.4		*0.8*
Error	240	100.4	0.42		

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

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 *et al*. (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 HC12 followed by HC3 and HC1 were found to be the most stable for their berry yield (Table 3). Hybrids HC7, HC5 and HC4 were unstable.

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

Hybrids	YLD	Rank	IPCAg[1]	IPCAg[2]	ASV	Rank
HC1	5.15	7	-0.32	0.77	1.10	3
HC2	5.17	6	0.90	-0.26	2.22	13
HC3	5.13	8	0.34	-0.70	1.08	2
HC4	6.30	3	-1.20	-0.45	2.99	14
HC5	6.47	2	-1.44	-0.72	3.61	15
HC6	5.00	11	0.41	0.51	1.12	5
HC7	6.63	1	-1.48	0.37	3.66	16
HC8	5.78	4	0.54	-1.37	1.91	12
HC9	5.05	10	0.68	-0.26	1.68	11
HC10	4.54	14	0.34	0.72	1.11	4
HC11	4.64	13	0.55	0.39	1.41	9
HC12	4.94	12	-0.36	0.43	0.98	1
HC13	5.11	9	0.51	-0.47	1.33	8
HC14	4.38	15	0.48	0.04	1.18	6
HC15	3.92	16	0.57	0.76	1.60	10
HYCK	5.44	5	-0.51	0.25	1.28	7
Mean	5.23					
LSD(0.05)	0.37					
C.V (%)	12.4					

AMMI Biplot Display

An AMMI biplot (Gabriel, 1971) was used to show both genotypes and environments simultaneously. The results of AMMI analysis indicated that the first five AMMI (AMMI1–AMMI5) were found to be highly significant ($P<0.01$) (Table 2) which led to the selection of the AMMI5 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 79.0% 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. From the biplot (Figure 3), environments are distributed from lower yielding in quadrants I (top left) to the higher yielding in quadrants II (top right) and III (bottom right) (Figure 1). The higher yielding environments classified according to the AMMI1 model were TE 13, JE13, TE 15 and JE15, whereas, the lower yielding environments are TE 11, TE 12, JE 11 and JE 12. As a result, TE12 is generally categorized under low yielding coffee environment as compared to the other two (TE15 and JE13), which were relatively categorized under high yielding environments. It is further noted that JE15 was the most favorable environment and TE12 the less favorable among the eight environments included in this study.

This situation is clearly indicated in Figure 3, where the two environmental variations are plotted far apart from the mean. The observed yield differences across the locations were due to many factors, like rain fall, high temperature and prevalence of coffee leaf rust at Tepi. The AMMI2 biplot (Figure 4) showed that environments JE15 (Jimma 2015/16) and TE15 (Tepi 2015/16) were the most discriminating for the hybrids followed by JE13 (Jimma 2013/14) and JE11 (Jimma 2011/12). The rest had a very small angle between them showing how closely they are. IPCA1 essentially captured the dissimilarity between TE15 and the other environments, while IPCA2 captured the remaining interaction components of the dissimilarity between JE15, JE13 and the other environments. Hybrids that had a small projection of vector for the environments indicating it performed well at that environment. For instance, the hybrid 7 in Environment TE15 and hybrid 8 in Environments JE13 and JE15 (Figures 3 and 4) performed well. Genotypes placed near the plot origin were less responsive than genotypes far from it. Hybrids HC5, HC7 and hybrid check (HYCK) gave the highest mean yield (largest IPCA1 scores) but hybrid check (HYCK) was more stable than the others two, because it placed near to origin (Figure 3). Experimental hybrids that combine both high yield and low ASV value could not be identified indicating breeding for high berry yield and stability of these yields across environments appears to be very problematic in Arabica coffee.

Table 4. Environments grouped by their winning genotypes, including the first 4 recommended cultivars for each environment, based on the AMMI2 estimates.

Environments		**Dominant cultivar**		**AMMI2 cultivar recommendations**			
Code	Yield (kgm/tree)		Yield (kgm/tree)	1st	2nd	3rd	4th
JE11	1.63	HC5	1.78	HC1	HC9	HC5	HYCK
TE11	3.77	HC5	5.01	HC5	HC13	HC4	HYCK
JE13	9.42	HC8	11.46	HC8	HC6	HC5	HC4
JE15	9.7	HC8	12.91	HC8	HC5	HC4	HC3
JE12	4.59	HC7	6.25	HC7	HC2	HC6	HC13
TE12	0.76	HC7	1.36	HC8	HC7	HC6	HC4
TE13	5.27	HC7	8.18	HC7	HC1	HC8	HYCK
TE15	6.69	HC7	12.05	HC7	HC5	HC4	HYCK
Mean	5.23						

Genotypes ID selections per environment

The AMMI analysis identified four best hybrids in terms of berry yield performance across eight environments. From Table 4 and Figure 3 it is possible to see that HC7 (Hybrid 7) was present in the top 4 rank in 4 out of 8 environments (being identified as dominant cultivar in 4 environments); followed by HC5 (Hybrid 5) that appeared in the top 4 rank in 5 of 8 environments, being the dominant cultivar in 2 environments; HC 8 (Hybrid 8) was the best in 3 environments and appeared in the top 4 rank in 4 of 8 environments. Other genotypes that, although were not dominant cultivars, but appeared consistently in the top 4 rank across 8 environments were: HC4 (hybrid 4), HYCK (hybrid check) and HC6 (hybrid 6), (5, 4 and 3 times inside the top 4 rank, respectively) while other hybrids exhibited rank differences (Table 4).

The difference in ranking of the AMMI selected hybrids in the different environments also implied differential yield performance as a result of the significant genotype by environment interaction. This is also referred to as crossover GEI (Yan and Kang, 2003).

See code descriptions of environments in Fig. 1.

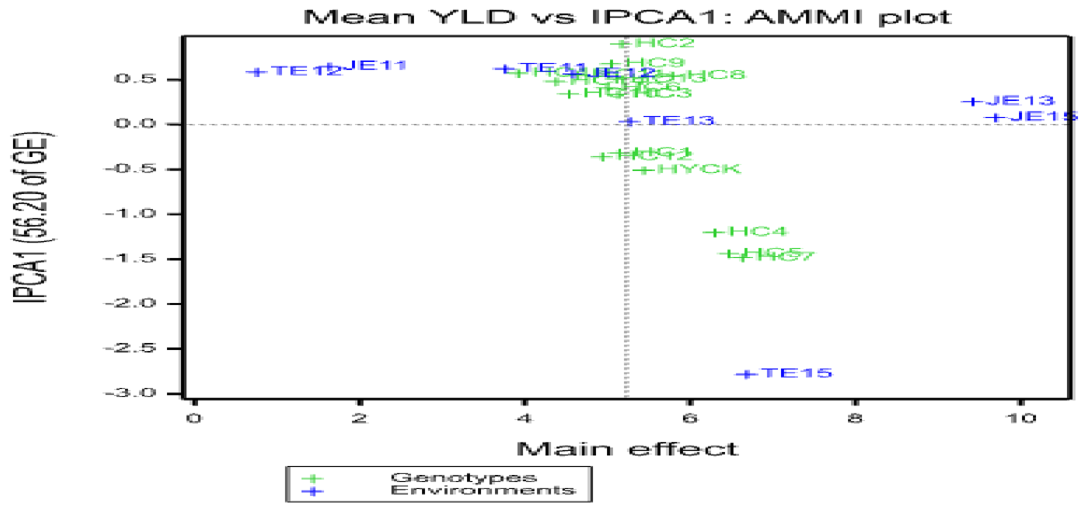


Figure 3. **AMMI1 biplot for berry yield of 16 coffee genotypes tested across eight Jimma-Tepi environments of Southwest Ethiopia (2 sites, and 4 years).**

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

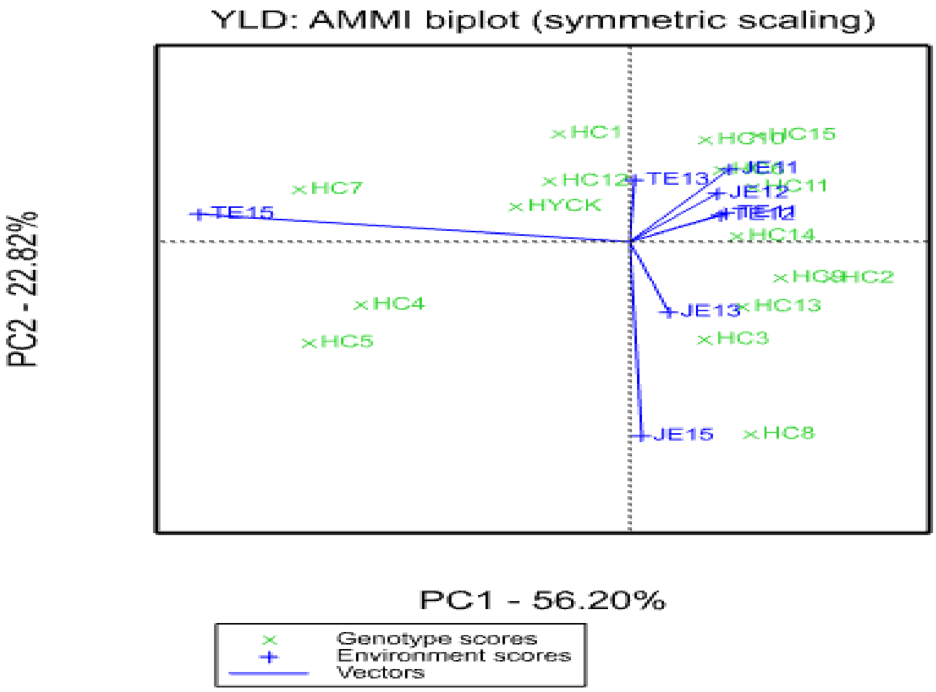
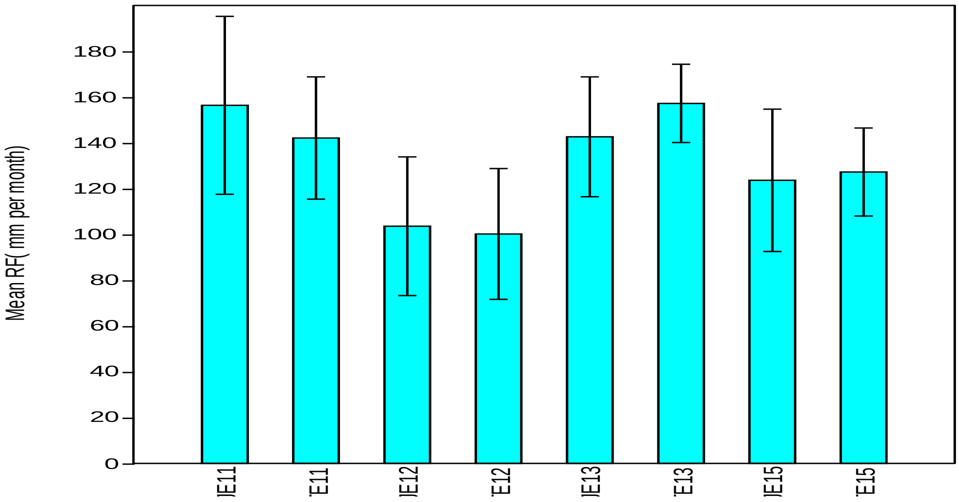


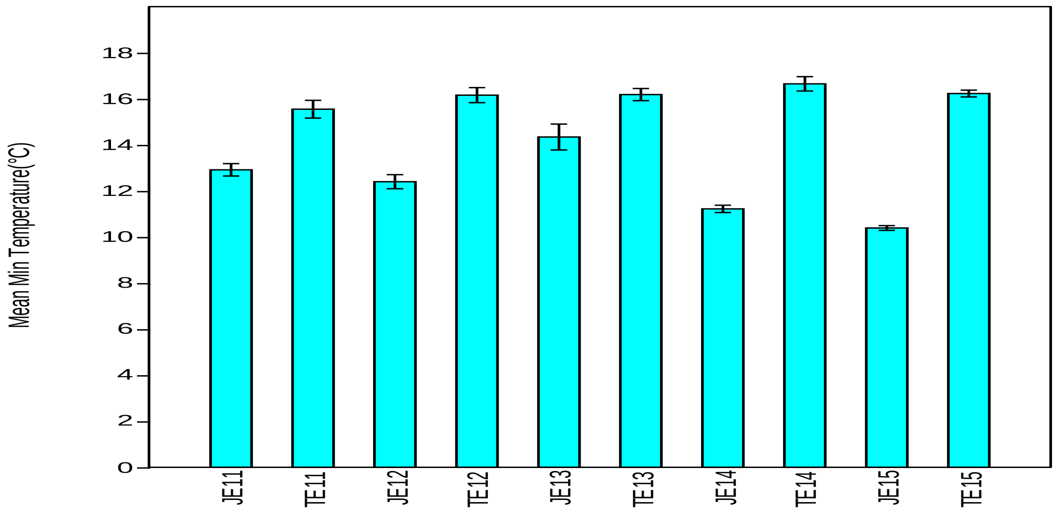
Figure 4. AMMI2 biplot for berry yield of 16 coffee genotypes tested across eight Jimma-Tepi environments of Southwest Ethiopia (2 locations, and 4 years). See code descriptions of genotypes and environments in Table 1 and Fig. 1, respectively.

Annex 1. Jimma and Tepi Metrological data for Experimental Periods.

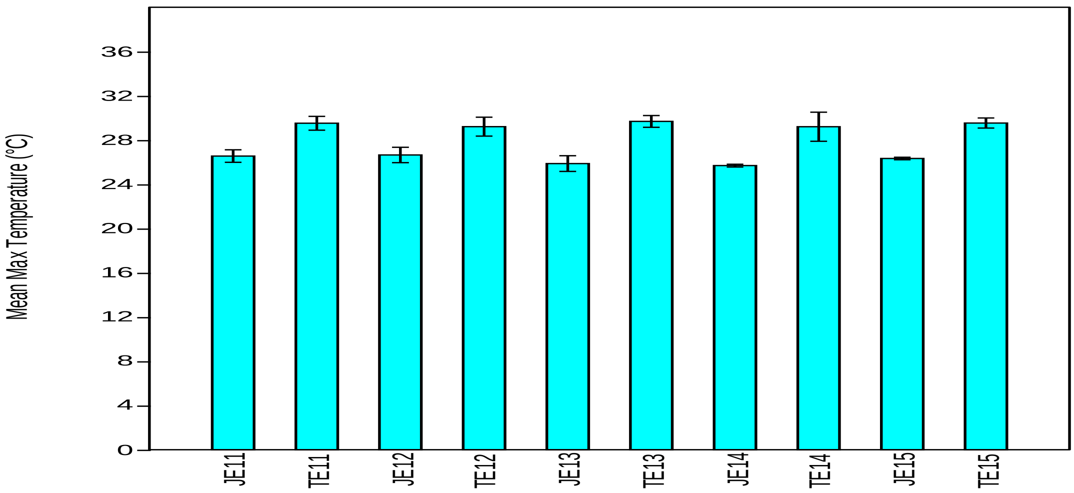


Annex Figure 1a. Rain fall (mm) distributions for individual environment across12 months at Jimma and Tepi. Error bars represent standard errors. Source: Jimma and Tepi research Stations and Tepi metrology station.

JE11=Jimma2011, TE11=Tepi2011; JE12=Jimma2012, TE12=Tepi2012, JE13=Jimma2013, TE13=Tepi2013; JE14=Jimma2014, TE14=Tepi2014, JE15=Jimma2015, TE15=Tepi2015



Annex Figure 1b. Minimum Temperature (^{o}c) distributions for individual environment across 9-12 months at Jimma and Tepi. Error bars represent standard errors. Source: Jimma and Tepi research Stations and Tepi metrology stations. See code descriptions of environments in Annex Figure 1a.



Annex Figure 1c. Maximum Temperature (°C) distributions for individual environment across 9-12 months at Jimma and Tepi. Error bars represent standard errors. Source: Jimma and Tepi research Stations and Tepi metrology stations. See code descriptions of environments in Annex Figure 1a.

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 16 coffee hybrids clearly showed that some hybrids with higher berry yield across environments, displayed larger GEI indicating breeding for high berry yield and stability of these yields across environments appears to be very problematic in Arabica coffee. However, Hybrid HC7, HC5, HC4 and HC8 had highest mean yield across some environments. This hybrid could be recommended for specific adaptation.

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