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By

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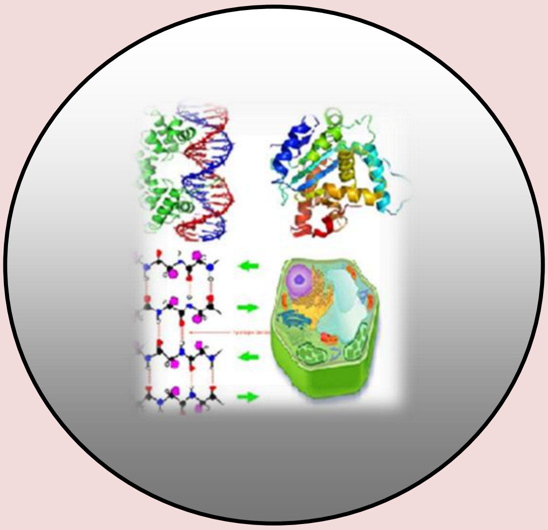

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RESEARCH PAPER

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GGE Biplot to Evaluate Arabica Coffee (*Coffee arabica* L.) Hybrids for Genotype × Environment Interaction and Yield Stability in Mid-Lowland Agro-Ecologies, Southwestern Ethiopia

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ABSTRACT

The genotype × environment interaction influences greatly the success of breeding strategy in a perennial crop like coffee (Coffea arabica L.). Sixteen improved arabica coffee hybrids were evaluated in eight environments (two locations and four years combination) in replicated trials. Genotype main effects and genotype × environment interaction (GGE) biplot analysis was employed. GGE biplot analysis revealed that the hybrids that performed well at Jimma environment is: 'HC8' and Tepi environment is: 'HC7'. The stable hybrid that performed well across locations and over the years for bean yield is: 'HC5' and 'HC4'. Therefore, 'HC5' and 'HC4'can be recommended for production in both locations. The GGE analysis delineated the test environments into two mega-environments mainly focusing on the two productive years (2013 and 2015) which can be useful for targeted evaluation of genotypes and in culling unstable genotypes. Jimma site during 2015 (JE15) and Tepi site during 2015 (TE15) was the most suitable environment in discriminating the coffee hybrids.

Keywords: Bean Yield, Genotype × Environment Interaction, GGE biplot and Arabica coffee.

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). 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 genotype × environment interaction (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). Efficient selection methods to discriminate between lines in a breeding programme depend on knowledge of the expected effects of GEI (Wamatu et al., 2003). The GEI also influences greatly the success of breeding strategy in a perennial crop like coffee (*Coffea arabica* L.).

Usually a large number of genotypes are tested across a number of sites and years, and it is often difficult to determine the pattern of genotypic response across locations over years without the help of graphical display of the data (Yan et al., 2001). GGE biplot analysis provides solution to the above problem as it displays the two-way data and allows visualization of the interrelationship among environments, genotypes, interactions between genotypes and environments facilitate grouping of mega environments, and rank genotypes using mean yields and stability (Cooper et al., 1997, Gauch and Zobel, 1997, Yan, 2001). Use of such utility of GGE biplot in exploitation of positive effect of GEI not yet been experienced in coffee Multiple-Environment Trials (MET).

In an attempt to develop superior hybrid cultivars, candidate F_1 hybrids were developed from diverse parental origins after systematic evaluation and selection using agronomic traits, disease and quality parameters (Behailu et al., 2008). To determine G x E interactions and the yield stability associated with each of these hybrids, the best performing and stable F_1 hybrids should now be ranked and selected across representative test environments for direct production or as testers for future hybridization programs targeting the mid-lowland coffee growing agro-ecologies of Southwestern Ethiopia. Therefore, the objectives of this study were to determine G x E interaction and yield stability of single-cross hybrids recently developed from Harar, Sidamo and Southwestern Ethiopian coffee parental origins and to identify promising genotypes and representative test environments using GGE biplot.

MATERIALS AND METHODS

Description of study sites and germplasm

The study was conducted for four cropping seasons at two locations providing a total of eight environments in Southwestern Ethiopia (Table 1). The study sites represent the mid-lowland coffee growing agro-ecologies of Southwestern Ethiopia. Agro-climatic and geographic descriptions of the study sites are presented in Table 1.
The study used 15 experimental F_1 hybrids derived from parental lines originated from three germplasm sources, namely Harar, Sidamo and Southwestern Ethiopian coffee's (Table 2). One standard check, single cross commercial hybrid, Aba-Buna (here after referred as HYCK) was included as comparative control.

Experimental design and field management

The Hybrids were established in a Randomized Block Design (RBD) with three replications and established in July, 2008 at both locations with comprising of sixteen coffee trees of each genotype in each plot. Recommended cultural practices were followed. Berry yield obtained converting plot berry yields to a tree basis (kg tree^{-1}).

Table 1. Descriptions of the study locations for experimental periods.

Environment code	Site	Season	Geographic position			Annual rainfall^a (mm)	Temperature (C^0)		Soil type
			Longitude	Latitude	Altitude (m.a.s.l.)		Min.	Max.	
JE11	Jimma	2011	$7^0$40'N	$36^0$47'E	1753	1876.8	12.9	26.6	Chromic Nitosol, Cambisoi
JE12	Jimma	2012				1243.2	12.4	26.7	
JE13	Jimma	2013				1711.7	14.3	25.9	
JE15	Jimma	2015				1483.9 (1572)	10.4 (11.6)	26.3 (26.3)	
TE11	Tepi	2011	$7^0$11'N	$35^0$25'E	1220	1705.6	15.6	29.5	Dystric Nitosol
TE12	Tepi	2012				1202.6	16.2	29.2	
TE13	Tepi	2013				1886.9	16.2	29.7	
TE15	Tepi	2015				1527.4 (1594)	16.2 (15.7)	29.5 (29.9)	

m.a.s.l. meters above sea level, a Long term mean weather data is shown in parenthesis.

Table 2. The Germplasm composition of Arabica coffee hybrids used in the study.

#	Germplasm Composition*	Hybrid Code-name
1	SW x Harrar	HC-1
2	SW x Harrar	HC-2
3	SW x Harrar	HC-3
4	SW x Harrar	HC-4
5	SW x Harrar	HC-5
6	SW x SW	HC-6
7	SW x Harrar	HC-7
8	SW x SW	HC-8
9	SW x Sidama	HC-9
10	SW x Sidama	HC-10
11	SW x Sidama	HC-11
12	SW x Sidama	HC-12
13	SW x SW	HC-13
14	SW X SW	HC-14
15	SW x Sidamo	HC-15
16	SW x SW (hybrid, check)	Aba-Buna (HYCK)

*SW = South-Western Ethiopian coffee type, HC = Hybrid coffee, HYCK = hybrid check

Data analysis

Bean yield data were subjected to combined analysis of variance using PROC GLM procedure in SAS 9.3 (SAS, 2002) to test the significance of G x E interaction prior to subsequent analyses. The hybrids were treated as the fixed factor, while environments, replications within environments were random factors.

The variation due to genotypes and G x E for bean yield was examined using GGE biplot based on the principal component analysis (PCA) of environment centered data (Yan et al., 2000). The GGE biplots were generated using Gen Stat Release 16 statistical software (GENSTAT, 2013) using the model based on singular value decomposition (SVD) of the first two principal components (Yan, 2002).

The association of genotype x environment as represented by the which-won-where pattern (Gauch and Zobel, 1997, Yan, 2002), relationships among test environments (Cooper *et al*., 1997) and genotypes (Yan, 2001) were visualized using their respective GGE biplots. An average environment coordinate (AEC) was drawn on the genotype-focused biplot to visualize the mean and stability of the hybrids (Yan and Kang, 2003). Furthermore, ideal environments and hybrids were identified using the AEC.

RESULTS

Climatic conditions of test environments

The soil, climatic, and biological conditions of the study sites vary considerably. Preliminary climatic data over the seasons showed an erratic distribution in total rainfall and temperatures received across the study sites (Table 1). Particularly, there were maximum drop of rainfall at both sites and rise of temperature at Jimma site in 2012 when compared to the long term means (Table 1).

Analysis of variance

Combined analysis of variance revealed that genotypes, environment and genotype by environment interaction were found highly significant ($P<0.01$) for bean yield (Table 3). The result indicated variability in performance among the hybrids and their differential response to the varying environments. Hybrid genotypes HC7 and HC5 were high yielding with yield of 6.63 kg/tree which is equivalent to 27.6 qt/ha on 2500 tree/ ha basis and 6.47 kg/ tree, respectively. These two genotypes showed significant yield advantage of 21.9 % and 19.0 % over standard hybrid check, respectively (data not shown). However, in the presence of significant G x E interaction (GEI) mean performance *per se* is not a reliable to selecting superior genotype for diverse environments (Kang and Magari, 1996). Thus, it is important to further characterize the nature of G×E interaction effects using GGE biplot to identify stable and high yielding genotypes.

Table 3. Combined analysis of variance (ANOVA) for berry yield at Jimma-Tepi environments.

Source of variation	DF	SS	MS
Environment(E)	7	3608.88	515.555**
Rep(E)	16	10.47	0.654
Genotype(G)	15	203.4	13.560**
GEIs	105	459.37	4.375**
Error	240	100.43	0.418
Total	383	4382.56	

*, ** Significant at p< 0.05 and p<0.01 levels, respectively

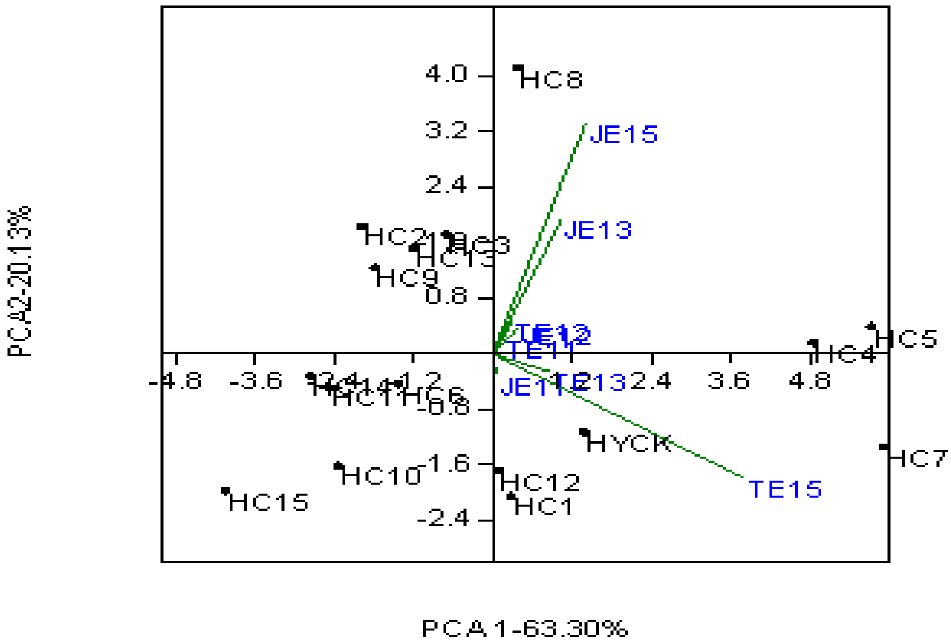

Figure 1. GGE Biplot constructed based on environment-focused singular-value partitioning showing relationships of the test environments and their discriminating ability. Code descriptions of environments and genotypes are as given in Tables 1 and 2, respectively.

GGE biplot analysis

The GGE biplot was a utilized to investigate the GEI in this study. The GGE biplots for berry yield of fifteen selected coffee hybrids and hybrid check variety evaluated in eight environments are shown in Figures 1, 2, 3 and 4. The GGE biplot accounted 83.43 % of the total phenotypic variation. The first principal component explained 63.30 % while the second explained 20.13 %.

Figure 1 shows the length of vectors of each environment and their cosine angles among them and it is referred to as the vector view of the GGE biplot. According to Yan and Kang (2003), the length of the vector, which approximates the standard deviation (SD) within each test environment, is a measure of the environment's ability to discriminate the hybrids. Accordingly, the vector that represents the sites, Jimma (JE15) and Tepi (TE15), during 2015 in Figure 1 had longest vectors, however their cosine angle between them was significantly high indicating that they are negatively strongly correlated and had high discriminating ability about the genotypes differently. The Jimma site in 2013 (JE13) had the next longest vector and its cosine angle with the same site in 2015 (JE15) was significantly small indicating that they are positively strongly correlated and had high discriminating ability about the genotypes. Either of these two environments can be used in evaluation studies because they have ability to discriminate the genotype and they give more and similar information about them. Other environments JE11, JE12, TE11, TE12 and TE13 were the least discriminating environments because of their shortest vectors.

In Figures 2 and 3 the concentric circles located on the average environment coordinate (AEC) axes assisted breeders to visualize the stability of environments and genotypes in yield performance according to Yan and Kang (2003). Environments that fall onto the center of the innermost concentric smallest circle are considered ideal while those located closer to it (innermost circle) are considered desirable and discriminating (Naroui et al., 2013). In the present study, the Tepi site in 2015 (TE15) followed by Jimma site in 2015 (JE15) and in 2015 (JE13) were considered ideal or representative because they were located in the smaller innermost concentric circle (Figure 2) suggesting that it was close to an ideal environment for further evaluation of yield performance in coffee. In contrast, other environments JE11, TE11, JE12, TE12 and TE13 located far away from the concentric innermost circle hence were considered undesirable. These environments were neither representative nor discriminating (Figure 2). They were the low yielding environments that coffee trees found at their earliest bearing stages. On the other hand, in Figure 3 hybrids HC4 followed by HC5 and HC7 were considered closed to ideal because were located in the smaller innermost concentric circle on the AEC abscissa with an arrow pointing to it. Hybrid HC4 and HC5 having above average performances more closed to AEC axis suggesting that they are most stable hybrids. Such genotypes are considered to be desirable and can be used as reference genotypes or hybrids for evaluating. Other genotypes such as HC15 and HC10 were undesirable (Figure 3).

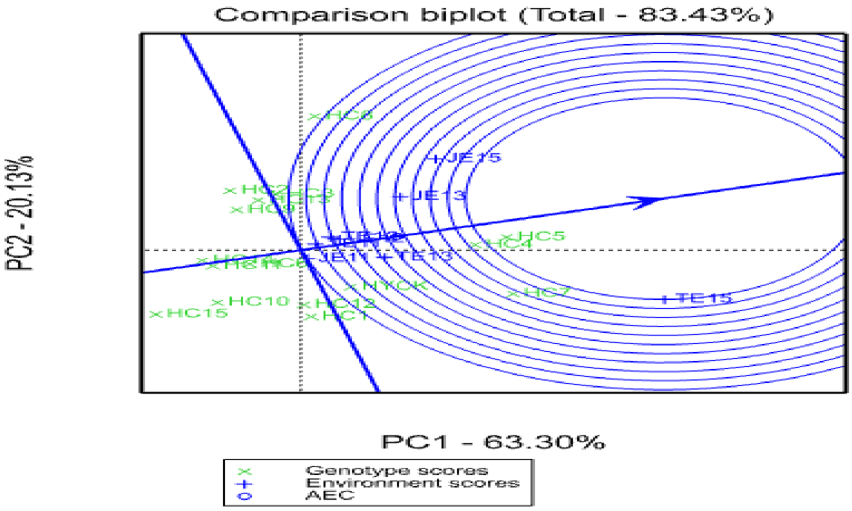

Figure 2. GGE Biplot showing ranking of environments based on ideal test environments or representativeness, constructed based on environment-centered and environment-focused singular-value partitioning. Code descriptions of environments and genotypes are as given in Tables 1 and 2, respectively.

Figure 4 presents the won where pattern view of the GGE biplot. This biplot is important it is used to indicate the most performing genotypes (superior) in each of the possible mega environments identified. The vertices of the irregular polygon drawn on the GGE biplot represent the yield potential of the wining genotypes (Yan *et al*., 2007). Hybrids HC8, HC5 and HC7 were considered superior because they were located at the vertices of the polygon and therefore, among the most responsive genotypes to environments in their respective directions compared to other hybrids. The hybrid HC8 was also very close to the environments JE15 and JE13, HC5 close to TE11 and TE15, and HC7 close to TE13 and TE15 suggesting that they adapted well to these environments (Figure 4). Apart from identifying the best hybrid in a given test environment, the polygon view also divides the test environments into two mega- environments. From Figure 4, two mega-environments are visible: JE13, JE15, JE12, TE12 and TE11 in the hybrid 8 and hybrid 5 sector or niche (group I), and the JE11, TE13 and TE15 in the hybrid 7 sector (group II). However, only two (2013 and 2015) of the four production seasons or years consistently represented their site in each of the delineated mega- environment.

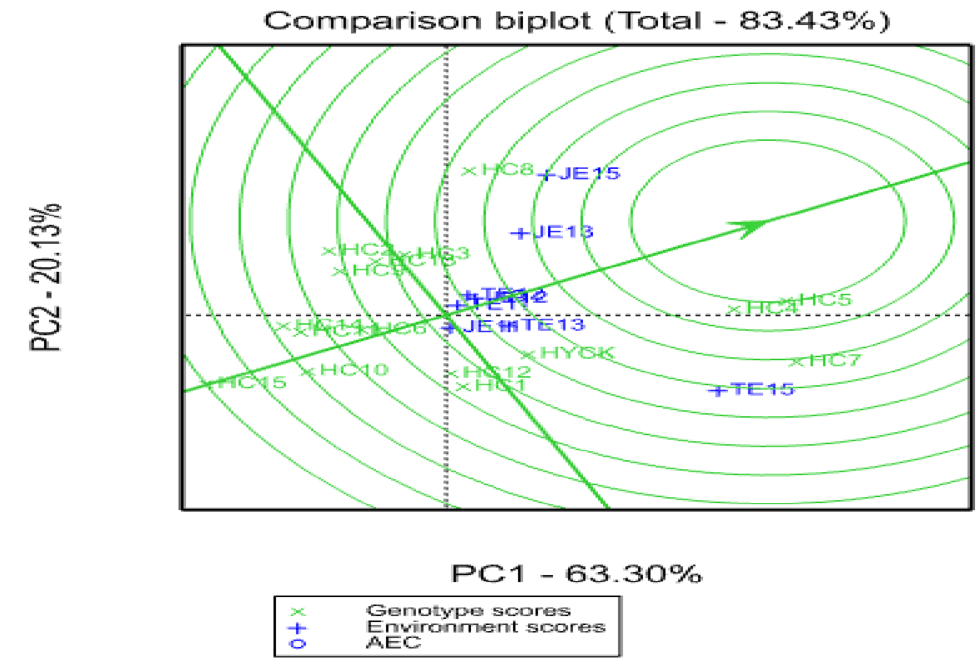

Figure 3. GGE biplot showing genotypes based on ideal genotype, constructed based on environment-centred and genotype focused singular-value partitioning. Code descriptions of environments and genotypes are as given in Tables 1 and 2, respectively.

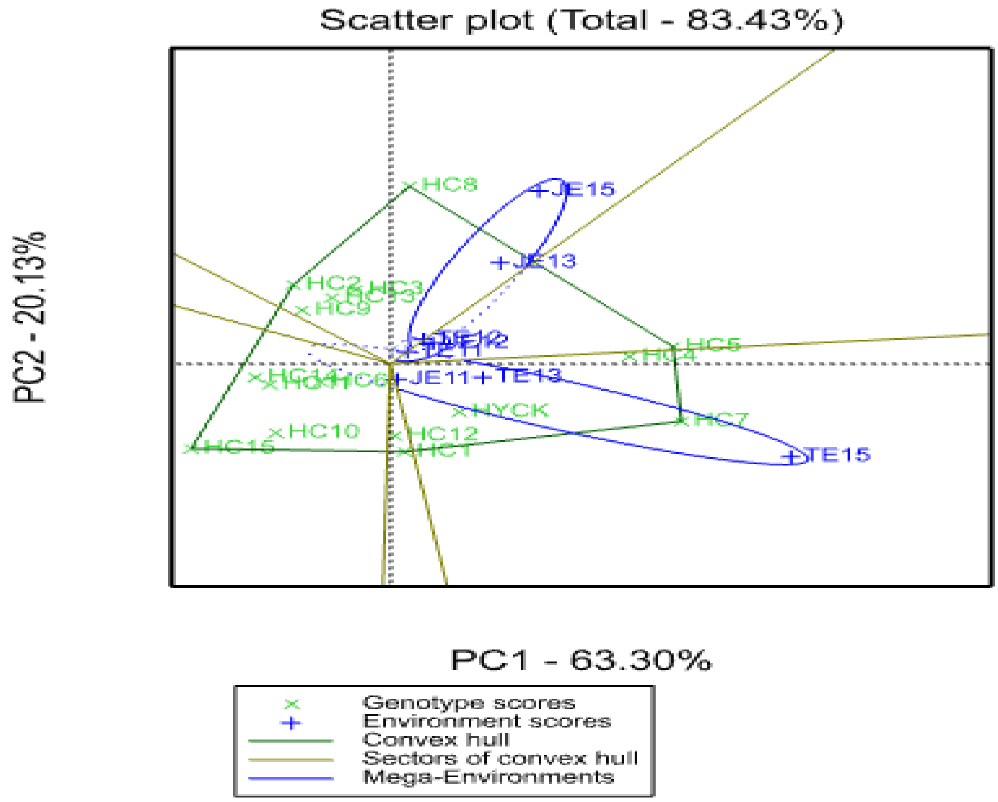

Figure 4. The polygon view of the GGE biplot analysis showing the won where pattern for selecting superior genotypes, constructed based on environment-centred and symmetrical singular-value partitioning. Code descriptions of environments and genotypes are as given in Tables 1 and 2, respectively.

DISCUSSION

The large sum of squares for environments in the combined analysis of variance indicated that the environments were diverse (Table 3). This provided large differences among environmental means resulting in significant yield variations among the experimental hybrids. This suggested that environmental conditions accounted for most of the total variation. A large contribution of the environment affecting yield stability was reported in several studies (Wamatu et al., 2003, Yan and Tinker, 2005 Yonas and Bayetta, 2008, Meaza et al., 2011, Lemi, 2016). However, it is G and GE that are relevant to cultivar evaluation (Yan, 2002).

In the GGE biplot analyses, useful information was extracted from the different biplot graphs. The total percentage variation (83.43 %) explained in Figure 1 to Figure 4 which is sufficient to explain the GGE (Yan, 2002). From the GGE biplot (Figure 1), it was possible to visualize the interrelationships among the environments, their discrimination power and representativeness to select superior test environments for a given mega-environment. Yan (2001) defined an "ideal" test environment, which is a virtual environment that has the longest vector of all test environments (most discriminating) and is located on the AEC abscissa (most representative). Accordingly, the vector that represents the sites, Jimma (JE15) and Tepi (TE15), during 2015 in Figure 1 had longest vectors, however their cosine angle between them was significantly high indicating that they are negatively strongly correlated and had high discriminating ability about the genotypes differently. Such strong negative correlation of this type causes significant crossover in performance of genotypes and therefore affect areas of recommendation for cultivation and production of the developed genotypes (Yan and Tinker, 2006). Figure 2 also verified these two environments as ideal because they were located in the smaller innermost concentric circle, however their wider angles with AEC axis (Figure 1) will raise questions in their representativeness. Under such condition these types of environments cannot be used in selecting superior genotypes, but are useful in culling unstable genotypes (Yan et al., 2007). While, other environments (JE11, JE12, TE11, TE12 and TE13) with short vectors gives little information about the performance of the genotypes under study thus should not be used in evaluation studies. This can be further explained as these environments are the seasons/years in which the coffee trees were found at their earliest crop bearing stages to express their full yielding potential. Figure 3 indicated an ideal cultivar. According to Yan and Kang (2003), the main focus in Figure 3 was genotype and the genotype-focused scaling. This helped to identify the best hybrids, and thus hybrids HC4 followed by HC5 and HC7 was found the best for being close to the ideal cultivar both in mean yield and stability performances. The superiority of G x E interaction in relation to genotype (G) in present study suggests the existence of different mega-environments. This further visualized in polygon view of GGE biplot (Figure 4). Figure 4 suggests the existence of two mega-environments for four cropping years at Jimma and Tepi locations in southwestern Ethiopia, designated as niches of hybrid HC8 and HC7, respectively. According to Yan *et al*. (2007) the which-won-where or crossover patterns should be repeatable across years to divide the target environment into sub-regions or mega-environments, otherwise the GEI cannot be exploited but the superior and stable genotypes can be selected based on their average performance across target environments. In line with this truth, in our case, although the two sites tried to differentiate the genotypes, they were not consistent across four years that the Jimma site is not separated from Tepi site in all of four years. This makes it, on one side doubtful to conclude that the two sites represent different mega- environments. However, on other side considering the two productive seasons (2013 and 2015) alone where coffee trees found at their full crop bearing stages for yield evaluation as well as coffee is being a perennial crop, the two sites were clearly placed separately in different mega-environments at the niches of hybrid HC8 and HC7 (Figure 4) which is justifiable to accept the differentiation of the target environment into two mega-environments. Moreover, the present study recognized that in perennial crop like coffee, the actual environment effects (climate variables) were confounded with the age difference of coffee trees across the experimental periods. As result it founds difficult to correctly characterize and spell out its real effects and thus suitable statistical techniques that can handle this deviation is suggested to be employed in future GEI studies in coffee. Nevertheless, the study indicates the possibility of identifying suitable and stable improved coffee hybrids under diverse environmental conditions by applying a GGE biplot.

CONCLUSION

Using GGE biplot the hybrids that performed well at Jimma environment is: 'HC8' and Tepi environment is: 'HC7'. The stable hybrid that performed well across locations and over the years for bean yield is: 'HC5' and 'HC4'. Therefore, 'HC5' and 'HC4'can be recommended for production in both locations.

The GGE analysis delineated the test environments into two mega-environments mainly focusing on the two productive years (2013 and 2015) which can be useful for targeted evaluation of genotypes and in culling unstable genotypes. The two mega-environments are Jima, which is a medium cool coffee growing environment, and Tepi which is a warm coffee growing environment as the second mega-environment. However, these divisions should be confirmed after inclusion of multiple locations and traits. Further, the present study suggests that in perennial crop like coffee for proper identification of sites/ environments and selection of genotypes on the basis of their ideal and representativeness prior consideration of the growing stage of coffee trees in relation to trait of interest is crucial.

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