International Journal of Multidisciplinary Research and Growth Evaluation

International Journal of Multidisciplinary Research and Growth Evaluation
ISSN: 2582-7138
Received: 10-08-2020; Accepted: 14-09-2020
www.allmultidisciplinaryjournal.com
Volume 1; Issue 4; September-October 2020; Page No. 13-18

Genetic variation, heritability and genotype x environment interaction of yield and various agronomic traits of hybrid coffee (*Coffea arabica* L.) genotypes grown under Jimma-Tepi environments in South-western Ethiopia

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Abstract
An experiment to partition the component of variation in selected hybrid of Arabica coffee was conducted at two different locations in South-western region of Ethiopia. Genetic variation, genotype × environment interaction of 15 quantitative morphological characters, was studied in fifteen Arabica coffee hybrids including two standard checks. The hybrids were evaluated at three to four environments (location-by-year combinations). The randomized complete block design was used in each environment. Data were collected on an individual tree basis for all traits except for yield, measured on a plot basis and converted to individual tree basis for statistical analysis. Results attained by this study showed that moderate genetic variation was detected only for four agro-morphological traits of hybrid coffee genotypes, the remaining traits had shown low genetic variation. Some of the traits were under strong influence of environment than genetic as revealed by high range of variation across environments than genotypes. The traits that had a low ratio of σ^2ge/σ^2g also showed a moderate value for heritability. For traits, stem girth, canopy diameter, length of primary branches and reaction to coffee leaf rust incidence, with a low G x E interaction and moderate heritability, selection can be done at any of the environments within Mid-lowland coffee agro-ecology in early breeding stages with high selection efficiency. Thus, these traits can be confirmed at the breeding site.

Keywords: Agronomic traits, Arabica coffee, Genotype x environment, Genetic variability and Heritability

Introduction

Coffee is the most important cash crop for a number of sub-Saharan Africa countries including Ethiopa with more than half of their foreign exchange earnings comes from its products (Phirii *et al*., 2010) [20]. Mid- and lowland coffee growing agro-ecologies of Jimma and Tepi areas are the major coffee producing one & in country wise as well as regional wise in Southwest Ethiopia. The three major coffee state farms, namely Limu, Tepi and Bebeka are also found in these agro-ecologies and so their demand for improved technologies, like improved varieties is also greater (Behailu *et al*., 2008) [1]. These climates are highly conducive for coffee plant & berry development, however, coffee leaf rust (CLR) and coffee berry disease (CBD) are also the major production constraints (Eshetu, 1997; Eshetu *et al*., 2000) and mainly, the former at both environments and the later at only in mid environment as result the average yield of these areas don't exceed the national average of 0.634 t/ha clean coffee (CSA, 2016). However there is a possibility to identify high yielding, disease resistant and good quality genotypes in these environments (Behailu *et al*., 2008) [1].

The current coffee variety development program is also follows separate breeding strategy on these climates from highland counterpart. In this regard use of hybrid coffee is well known to contribute towards higher productivity and stability of performance under a wide range of environmental conditions (Bertrand, 2010) [2]. As the hybrid coffee gains commercial acceptance, the need for genetic information to assist its improvement becomes more apparent. Genetic variability in Arabica coffee has been studied by several workers (e.g., Dharmaraj and Gopal, 1986; Yigzaw, 2005; Mistro, *et al*., 2008; Petek, *et al*., 2008; Olika, *et al*., 2011, Fekadu *et al*., 2019) [7, 25, 19, 16, 17, 13]. Significant differences were observed among genotypes for most characters, and high phenotypic and genetic coefficients of variation for, plant height, and plant vigor were reported. Other characters, viz canopy diameter, internode length on primaries, stem girth and number of primary branch were reported to have high phenotypic and genetic coefficients of variation as well (Walyaro and Van der Vossen, 1979; Walyaro, 1983; Yonas and

Tarekegn, 2015). However, most of the above studies were run in a single environment and there is also little information on how those agronomic traits interact with the environment, e.g., genotype by environmental (G x E) interactions. Heritability and the effect of G x E interaction estimates are also usually applicable only to a specific trait, population and a specific range of tested environments. Estimating genetic variance under only one environment may lead to biased genetic variance estimates (Dudley and Moll, 1969). Pooled analysis of variance over environments will determine the extent of G x E interaction as well as heritability estimates to predict average performance of a given genotype and genetic worth of a particular trait in a given set of environments (Comstock and Robinson, 1952; Comstock and Moll, 1963; Holland, *et al*., 2003).

Information concerning these parameters in Arabica coffee, especially in Ethiopia, is very scarce. Therefore, the objectives of this study were to: (1) determine the extent of variation in yield and other related characters in a group of seventeen hybrids coffee genotypes; (2) determine the heritable components of the overall variability with the help of suitable genetic parameters; and (3) determine the relative contribution/magnitude of G x E interaction to the variation in various agronomic traits of seventeen coffee genotypes across Jimma-Tepi environments.

Materials and Methods

Field experiments

The study was conducted in two different locations in South-western region of Ethiopia, namely at Jimma Agricultural Research Center (JARC) and Tepi National Spice Research Center (TNSRC). The Jimma site represents the midland and Tepi represent lowland humid coffee growing agro-ecologies.

Fifteen F_1 hybrids along two commercial check varieties were evaluated in this study (Table 1). The experimental material was laid out 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 and observations were made on 15 agro-morphological (growth and yield related) parameters including stress parameter (reaction to coffee leaf rust) for two seasons (2014 and 2015) except for yield related parameters one season were used at Tepi due to the sensitivity of the experimental materials for biennial bearing habit these parameters were not available. The coffee data collection techniques for 14 agro-morphological (growth and yield related) characters as described by Fekadu *et al*. (2019) [13] were adopted. While, coffee leaf rust incidence (CLR, %), assessed visually in the field on individual tree, infected leaves per tree was estimated by calculating the percent of the infected leaves on sample branches during August to October; at which coffee berries reach their full maturity stage before harvesting time.

Table 1: Description of the coffee hybrids and commercial checks used for the study

#	Code-name	Germplasm Composition*	Cross categories†
1	HC-1	SW X Harrar	CBD res x Harrar +HY
2	HC-2	SW X Harrar	CBD res x Harrar +HY
3	HC-3	SW X Harrar	CBD res x Harrar +HY
4	HC-4	SW X Harrar	CBD res x Harrar +HY
5	HC-5	SWX Harrar	CBD res x Harrar +HY
6	HC-6	SW X SW	CBD res x CBD res +Q
7	HC-7	SW X Harrar	CBD res x Harrar +HY
8	HC-8	SW X SW	CBD res +Q xCBD res +Q
9	HC-9	SWX Sidama	CBD res x Sidama +HY
10	HC-10	SWX Sidama	CBD res x Sidama +HY
11	HC-11	SWx Sidama	CBD res x Sidama +HY
12	HC-12	SWx Sidama	CBD res x Sidama +HY
13	HC-13	SW X SW	CBD res x high yielder
14	HC-14	SW X SW	CBD res x high yielder
15	HC-15	SWx Sidamo	CBD res x Sidama +HY
16	Hybrid check (Aba-Buna)	SW X SW	CBD res x high yielder
17	Variety check- Desu (at Jimma)	SW	HY + wide adaptable
18	Variety check- Geisha (at Tepi)	Introduced variety	Lowland adaptable + rust resistance

*SW=South-western Ethiopian coffee type; Harrar= Harrar coffee type ; Sidamo= Sidamo coffee type

†CBD res = CBD resistant

Data analysis

All data were tested for the homogeneity of trial variance errors using Bartlett's test before statistical analysis was proceeded. In cases of non-homogeneity, data were transformed to meet requirements of significant test. Accordingly, coffee leaf rust (CLR) percent incidences were transformed by arcsine.

Analysis of variance was performed with the MIXED procedure of SAS version 9.2 (SAS, 2008). For the purposes of estimating hybrid means and comparing check entries with experimental hybrids, checks were considered fixed effects. Environment and replications were considered random effects. To estimate genetic components of variance, the genotypes were considered random effects and variance components for genotypes and genotype x environment interaction were estimated with the SAS MIXED procedure.

Heritability on a plot basis and its approximate standard error for each trait across environments were estimated as: $h^2_{bs=}$ (σ^2g)/ [σ2g + σ^2ge + σ^2e] using SAS Proc MIXED model of SAS after Holland et al. (2003), where σ^2g is the estimate of genotypic variance, σ^2ge is the estimate of genotype x environment variance, σ^2e is the estimate of error variance, and e is the number of environments. Data were being balanced in present study for which the REML based variance component estimates were comparable with ANOVA (Shaw, 1987), for this reason the genotypic mean, phenotypic and genetic variances from REML analysis were used to estimate phenotypic and genotypic coefficient of variation according to the formula given by Burton (1952). The magnitude of the G x E interaction relative to the genetic variance was determined from REML variance component estimates of each trait using the ratio σ^2ge/σ^2g.

Results and Discussion
Phenotypic variation
Phenotypic variations for 15 quantitative traits of coffea Arabica were estimated and are presented in Tables 2. Relatively low range of variability ranges were observed across genotypes (1.87 % for percent fruit bearing primary branches to 15.54% for bean yield) than across environments (2.04% for canopy diameter to 71.51% for number of secondary branches). Higher ranges occurred across environments than cultivars for most of traits, especially high ranges recorded for number of secondary branches (71.51%), number of berries per bearing node (45.71%), percent of fruit bearing nodes (43.85), coffee leaf rust (CLR) incidence (44.19%) and internode length on the main stem (20.23%). However, none of ranges in agronomic as well as yield characters showed larger across genotypes than across environments indicating more of the existing variations were under control of environment than genetic.

There was significant phenotypic differences (P <0.05 to P <0.01) among the genotypes in seven out of fifteen the traits studied viz. plant height, stem girth, canopy diameter, internode length on the main stem, CLR percent incidence, length of primary branches and berry yield (Table 3), confirming the existence of variability among the genotypes for these significant characters offering a better scope for further improvement of the crop.

There was also significant to highly significant differences (P <0.01) among environments for all agronomic and yield characters except for canopy diameter (Table 3). This is attributable to microclimate differences (like shade) might occurred between two sites, especially at early growth stages of the coffee trees, apart from this, these repeatedly measured growth and yield characters were also subjected to the time related environment differences that cause changes in their size. Similarly, large environmental influences on growth and yield traits have been reported by various authors (Walyaro, 1983; Yonas and Tarekegn, 2015; Fekadu *et al*., 2019) [13, 29].

Table 2: Variability ranges of genotypes and environment mean values for yield and agronomic traits of seventeen coffee hybrids and checks evaluated at Jimma-Tepi environments

Traits	Ranges				Mean	CV (%)
	Genotype n=10	CV%	Environment n=3-4	CV%	n= 51,68	
	Growth traits					
PH	292.04-340.92	5.01	290.13-339.43	6.53	318.14	8.85
Girth	6.39-7.73	5.31	6.02-7.79	10.80	6.87	11.23
NPB	66.09-78.69	5.37	56.08-80.41	15.24	71.39	16.26
SNN	39.39-46.60	4.27	34.71-49.27	14.22	40.86	14.56
CD	182.84-218.59	5.62	195.61-205.35	2.04	199.70	6.62
ILS	6.33-7.87	6.58	6.01-9.11	20.23	7.03	20.06
LPB	79.58-101.59	7.70	82.08-97.53	9.30	88.21	11.70
BNN	18.11-22.68	5.68	18.44-24.58	15.54	20.90	15.97
ILB	3.79-4.74	5.90	4.02-4.69	7.88	4.33	11.37
SB	5.19-7.69	10.48	2.04-11.49	71.51	6.62	60.90
	Yield and yield related traits					
BP	80.13-85.32	1.87	74.15-96.13	13.61	83.49	11.55
BN	57.88-67.08	4.04	34.04-87.29	43.85	60.72	36.70
BeNo	15.42-19.26	5.99	8.22-22.92	45.71	17.13	38.79
YLD	4.85-8.60	15.54	4.14-9.23	42.18	6.27	40.94
	Stress parameter					
CLR[1]	24.10-48.71 (16.67-56.46)	13.74	19.30-56.86 (10.92-70.11)	44.19	41.36 (43.66)	42.46

[1]Figures in parenthesis indicate original value

PH, plant height (cm); GIRTH, stem girth (cm); NPB, number of primary branches per tree;

SNN, number of main stem nodes; CD, canopy diameter (cm); ILS, internode length on the main stem (cm); LPB, length of primary branches (cm); BNN, number of primary branch nodes; ILB, internode length of primary branches (cm); SB, number of secondary branches per primary branch; BP, percent fruit bearing primary branches per tree (%); BN, percent fruit bearing nodes per primary branch (%); BeNo, number of berries in two heavily bearing nodes per primary branch; YLD, berry yield (kg $tree^{-1}$); CLR, percent coffee leaf rust incidence (%).

Table 3: Mean Squares for various agronomic traits in some Arabica coffee hybrids and commercial check varieties evaluated at Jimma-Tepi environments

Traits		Source of variation				CV (%)
	Environment (E)	Reps(E)	Genotypes (G)	G x E	Error	
Growth traits						
PH	22023.41*	5494.56**	3051.93**	924.97	410.01	6.36
Girth	28.07**	1.05**	1.66**	0.21**	0.10	4.66
NPB	6036.34**	727.68**	176.09	128.11*	85.37	12.94
SNN	1924.95**	232.82**	40.81	31.72	23.51	11.22
CD	847.35	498.03**	1509.19**	176.24	127.57	5.65
ILS	103.08**	4.03**	2.57**	1.03**	0.39	8.87
Stress parameter						

CLR	17036.60**	1004.38**	387.51**	97.64**	34.04	14.1
DF	3	8	16	48	128	
Growth traits						
LPB	3428.99*	658.38**	414.87**	77.57	52.74	8.23
BNN	538.20**	37.87**	12.72	12.24**	4.28	2.07
ILB	5.94**	0.11	0.59	0.47**	0.12	7.83
SB	1142.31**	39.53**	4.31	2.60*	1.5	18.52
Yield and yield related traits						
BP	6580.25**	129.44**	22.03	13.72	35.65	7.15
BN	36155.93**	86.14*	54.02	41.22	36.64	9.97
BeNo	3125.39**	30.49**	9.46	6.76**	3.09	10.26
YLD	356.42**	0.30	8.54*	4.32**	0.30	8.8
DF	2	6	16	32	96	

* and ** Significant at the 0.05 and 0.01 probability levels, respectively

PH, plant height (cm); GIRTH, stem girth (cm); NPB, number of primary branches per tree;
SNN, number of main stem nodes; CD, canopy diameter (cm); ILS, internode length on the main stem (cm); CLR, percent coffee leaf rust incidence (%); LPB, length of primary branches (cm); BNN, number of primary branch nodes; ILB, internode length of primary branches (cm); SB, number of secondary branches per primary branch; BP, percent fruit bearing primary branches per tree (%); BN, percent fruit bearing nodes per primary branch (%); BeNo, number of berries in two heavily bearing nodes per primary branch; YLD, berry yield (kg $tree^{-1}$)

Genetic variation and heritability

The magnitude of phenotypic variation does not reveal the relative amount of genetic and non-genetic components of variation. These were ascertained with the help of genetic parameters such as genotypic coefficient of variation and heritability estimates. Generally, low genotypic coefficient of variation (GCV %) was observed among the hybrids and commercial check varieties for all characters evaluated. The traits berry yield and CLR percent incidence , however, had relatively highest GCV compared with the others with respective value of 10.93% and 11.88% (Table 4) indicating the relative importance of these characters for improvement of these hybrid coffees. Moreover, trait berry yield also showed higher GCV than environmental coefficient of variation (CV %) emphasizing the dominant genetic over environmental control of these traits in coffee in our experiment, while other traits exhibited least GCV. The low GCV of these traits corroborated with higher range values across environments than cultivars in Table 2. The result was partly contradictory to Dharmaraj and Gopal (1986) [7] who reported that high GCV for percent of fruit bearing nodes and number of berries per bearing node. Percent coffee leaf rust incidence had highest genotypic coefficient of variation (GCV), though correspondingly largest environmentally determined variation (CV %) was observed. On an average, the higher magnitude of GCV was recorded for coffee leaf rust incidence (11.88) and berry yield (10.50) suggesting sufficient variability is available and thus exhibited scope for genetic improvement through selection for these two traits.

The heritability value derived from a genotypes evaluated over number of environment would increase the accuracy of the estimates of each trait (Falconer and Mackay, 1996). Heritability estimates among the traits across all environments ranged from 0.03 for number of main stem nodes and percent fruit bearing primary branches per tree to 0.46 for stem girth (Table 4). A moderate heritability (0.30±0.11 and 0.46±0.11) and genetic advance expressed as percentage of mean (13.31 and 24.48) was estimated for CLR percent incidence and stem girth, respectively (Table 4). An exhibited low estimate of h^2_{bs} for other traits could be explained by high proportion of error variance (ranged from 45.83% for internodes length of primary branches (ILB) to 96.95% for percent fruit bearing primary branch per tree, apart from those characters that influenced by genotype-environment interaction. The progress in selection would be high for traits with moderate to high heritability estimates and lower for traits with low heritability estimates according to Panse (1957).

The plant vigor traits (plant stem girth and canopy diameter) and length of primary branches had moderate broad sense heritabilities with a range from 0.38 to 0.46. Stem girth had the highest observed heritability (0.46±0.11) across the environments. However, high magnitudes of heritability (>0.50) for above traits were reported by various investigators (Walyaro, 1983; Yigzaw, 2005; Petek, *et al*., 2008; Yonas and Tarekegn, 2015, Fekadu et al., 2019) [25, 19, 13, 28]. On other study Olika, *et al*. (2011) [17] reported lower heritability estimates for canopy diameter, stem girth and length of primary branches. This suggests that heritability estimates are influenced in part by the environment and population under study.

Table 4: Variance components, genotypic and phenotypic coefficients of variation, genetic advance, heritability (its standard error) and ratio of genotype*environment interaction variance to genetic variance estimates of yield and other agronomic traits of, fifteen F1 hybrids and two commercial check varieties evaluated at Jimma-Tepi environments

Traits	σ^2G	σ^2GE	σ^2e	h^2_{bs} plot –basis	PCV (%)	GCV (%)	GA (%)	σ^2GE/σ^2G
Growth traits								
PH	177.25	171.65	410	0.23(0.10)	8.66	4.19	4.10	0.97
GIRTH	0.12	0.03	0.10	0.46(0.11)	7.28	5.04	6.90	0.25
NPB	4.00	14.25	85.35	0.04(0.05)	14.26	2.80	1.18	3.56
SNN	0.76	2.74	23.51	0.03(0.05)	12.721	2.13	0.79	3.61
CD	111.12	16.01	127.7	0.44(0.10)	7.99	5.28	7.25	0.14
ILS	0.13	0.21	0.39	0.18(0.09)	12.16	5.13	4.51	1.62
LPB	37.48	8.27	52.74	0.38(0.11)	11.25	6.94	8.81	0.22

BNN	0.05	2.65	4.28	0.10(0.09)	12.64	1.07	2.60	53.00
ILB	0.01	0.12	0.11	0.05(0.11)	11.33	2.31	1.17	12.00
SB	0.19	0.37	1.50	0.09(0.08)	21.68	6.58	4.02	1.95
Yield and yield related traits								
BP[1]	0.92		29.26	0.03(0.08)	6.48	0.33	0.40	
BN	1.42	1.53	36.64	0.04(0.06)	10.35	1.96	0.85	1.08
BeNo	0.30	1.22	3.09	0.07(0.08)	12.53	3.20	1.81	4.07
YLD	0.47	1.34	0.30	0.22(0.15)	23.17	10.93	10.50	2.85
Stress parameter								
CLR	24.15	21.2	34.04	0.30(0.11)	21.54	11.88	13.31	0.88

PH, plant height (cm); GIRTH, stem girth (cm); NPB, number of primary branches per tree; SNN, number of main stem nodes; CD, canopy diameter (cm); ILS, internode length on the main stem (cm); LPB, length of primary branches (cm); BNN, number of primary branch nodes; ILB, internode length of primary branches (cm); SB, number of secondary branches per primary branch; BP, percent fruit bearing primary branches per tree (%); BN, percent fruit bearing nodes per primary branch (%); BeNo, number of berries in two heavily bearing nodes per primary branch; YLD, berry yield (kg tree^{-1}); CLR, percent coffee leaf rust incidence (%)
[1]Unable to calculate σ^2GE, and associated genetic parameters due to negative variance components.

Genotype by environment interaction

The Genotype x environment interaction (GEI) term was significant for nine out of fifteen traits (Tables 3), viz. stem girth, number of primary branches per tree, internode length on the main stem, CLR percent incidence, number of primary branch nodes, internode length of primary branches, number of secondary branches, number of berries bearing nodes and berry yield, five of which other than stem girth, internode length on the main stem, berry yield and CLR percent incidence, were in a trait complex (with non- significant genotypic difference) and requires information about the causes of these GEIs before the breeder can embark on enhancing these traits. The σ^2 ge/σ^2g ratio was also larger than 1 for seven out of nine traits with significant genotype by environment interactions (Tables 4). These unfavorable variance component ratios are reflected in heritability estimates of lower than 0.30 for most of traits, and also relative to GEI effects except for those traits that had weak genetic component (Table 3) with much environmental variation (Tables 2 and Tables 3). Therefore, the selection program aimed at improvement of these characters in present test materials would not be a better strategy. However, the moderate heritability estimates (h^2_{bs} = 0.30-0.46) with low GEI (σ^2ge/σ^2g = 0.14- 0.88) exhibited by three growth traits (stem girth, canopy diameter and length of primary branches) and stress parameter (reaction to coffee leaf rust) indicated that breeding based at one site/environment would be efficient for improving these characters in other sites/environments. On the other hand, for traits with low heritabilities (h^2_{bs} < 0.30) individual selection will not be effective but progeny testing would increase the accuracy of the selection. The h^2_{bs} estimates of most of the same traits in similar study reported by Fekadu *et al*. (2019) [13] were higher than the present study. For example growth traits heritability estimates in hybrids of the previous study for plant height, stem girth, and canopy diameter were 0.55, 0.71 and 0.75 but low in hybrids of the present study with respective order 0.23, 0.46 and 0.44. These confirm that parameters should be estimated for each population and environment, it could be risk to make decision based on heritability estimated derived from other population (Dudley and Moll, 1969; Fins *et al*., 1992).

Generally, for plant vigor traits (stem girth and canopy diameter), length of primary branches and reaction to coffee leaf rust incidence with low G x E interaction and moderate heritability 0.30 for reaction to coffee leaf rust incidence to 0.46 for stem girth, selection can be done at any environments within mid-lowland coffee agro-ecologies in early breeding stages with high selection efficiency. Thus these traits can be confirmed at the breeding site/research station. Besides having moderate heritability, these four morphological traits can be directly measured and selected in the field. Therefore, it would be gainful to select for high yielding genotypes indirectly through these traits.

Conclusion

Significant genotypic variation was observed for seven out of fifteen agro-morphological traits among the fifteen hybrids along with two check varieties. Four of significant traits have showed moderate heritability estimates while in others low estimates were observed. Traits with moderate heritability estimates should respond to phenotypic selection. Low GEI was also observed for these heritable traits. As result selection at only one environment would serve the other environments. Thus, these traits can be confirmed at the breeding site.

Acknowledgement

This work was co-financed by the Ethiopian Institute of Agricultural Research (EIAR) and Jimma University (JU). Thanks to Jima Agricultural Research Center (JARC) for providing the experimental materials, and Jima and Tepi Coffee Breeding Section for their management of the experimental sites.

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