Biplot evaluation and identification of mega-environments for durum wheat production in the highlands of Amhara Regional State

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ABSTRACT

Environmental changes affect both crop growth and yield due to significant genotype by environment interactions (GEI). The selection of suitable breeding and testing locations is vital to the success of a plant breeding program. In our study, the GGE biplot program was used to analyze the yield and GEI data from a four-year durum wheat trial in the northwestern part of the Amhara Regional State, Ethiopia. The trial involved 21 durum wheat varieties and 39 environments across thirteen durum wheat-producing areas of Amhara. The result of the combined analysis for variance showed a highly significant mean square (p>0.001) for location x genotype, location, and genotypes. Environment (location, year, and location x year) had the highest impact on yield, accounting for 87.13% of the yield variability. The main components (PC1 and PC2) accounted for only 56.22% of the total variation of the grain yield. The low proportion explained by the biplot is an indication of complexity between the genotypes and the genotype-environment interaction. After the study, we were able to divide the Amhara region durum wheat testing location into four mega-environments. 1) Adet, Mota and Bichena; 2) Wonbeerema, Debere Tabor, and Debre Elias; 3) Geregera, Bassoliben, and Gaint, and 4) Enewari and Simada. From this study, for reasonable discrimination of large number of durum wheat genotypes, only four ideal test environments (Mota, Debre Tabor, Gaint, and Mehalmeda) maybe deployed thus saving time and resources.

1. INTRODUCTION

Environmental changes affect both crop growth and yield due to significant genotype by environment interactions (Giauffret et al 2000; Rao et al 2011). The most reliable way to evaluate the performance of a variety is to grow it in multiple environments for several years (Signor et al 2001). The selection of suitable breeding and testing locations is vital to the success of a plant breeding program. Besides, an ideal test location is not only used to discriminate the genetic difference between genotypes, but also to know the target environments for which the selected genotypes are best adapted (Badu-Apraku et al 2013; Yan et al 2011). When evaluating the stability and adaptability of a variety, it is important to examine the genotype-environment (GE) interaction and assess its growth in different environments and ecological regions. Some varieties are well adapted to the specific ecological areas; that is, they show similarities in development potential and constraints under specific environments, or where the same group of varieties forms the best combination year after year (Gauch and Zobel 1997; Oliveira et al 2014; Yan and Holland 2010).

An additive main effect and multiplicative interaction (AMMI) model is commonly used to analyze GE interaction during yield trials. Understanding the GE interaction is very important to assess the adaptability and stability of a variety. AMMI can detect the GE interaction in a multidimensional space and present the interaction using a biplot. AMMI has been used to analyze planting environments in wheat (Crossa et al 1991) and other crops. However, AMMI biplot is not a true biplot and its application has been inadequate (Gauch et al 2008). In contrast, the genotype main effect plus genotype-environment interaction (GGE) biplot model utilizes multi-region data for environmental evaluation and provides a better graphical illustration (Yan and Holland 2010). The GGE biplot can facilitate a better understanding of complex GE interaction in multi-environment trials of breeding lines and agronomic experiments. GGE biplot has been used to identify the performance of varieties under multiple stress environments, ideal variety, mega-environment, and core testing sites (Akinwale et al 2014). It has also been successfully used in sugarcane trials (Glaz and Kang 2008; Ramburan et al 2012).

In a GGE biplot, an environmental discrimination power is approximately equal to the vector length of that environment, representativeness is approximately equal to the cosine of the angle between the environment vector and the average environment vector, and the desirability index is approximately equal to the projection of the environment vector onto the average environment vector axis (Yan and Holland 2010). A GGE biplot can effectively analyze the GE interaction, identify the best variety for a specific ecological region, evaluate the test environments, and evaluate the desirability of a test environment based on its representativeness and discrimination power on genotypic differences (Xu et al 2014). A good understanding of the target environment and the test locations is a prerequisite for effective and meaningful genotype evaluation (Bellon 2001). In our study, the GGE biplot program was used to analyze yield and GE interaction data from a four-year durum wheat experiment in the highlands of Amhara Regional State, Ethiopia. The experiment involved 21 durum wheat varieties and 39 environments in 13 durum wheat-producing locations. The main objectives of this study were to provide the basis and support for selecting the best durum wheat mega environments to select representative test location in each mega-environment and suggest appropriate breeding strategy for each mega-environment in the

highlands of Amhara Regional State.

2. MATERIALS AND METHODS

This experiment was carried out in different durum wheat growing areas in the highlands of Amhara Regional State during the main growing season in 2014, 2015, 2016, and 2017.

2.1. Description of Test Environments and Experimental Conditions

The four-year test was conducted in 13 locations (Table 1). The geographical coordinates and descriptions of the selected parameters of the testing sites/locations are presented in Table 1. The field experiment was designed in the randomized complete block design (RCBD), with three replications at each site each year. The plot size of each experimental unit was 1.2m x 2.5m (3m2) that contained a total of six rows while the harvestable was four (0.8m x 2.5m = 2m2). Planting was carried out by hand drilling in rows 20 cm apart at a seed rate of 150 kg ha-1 between the end of June and early August (Debre Tabor at the end of June Adet and Gaint on early July Mota, Debre Elias, Bassoliben, Gozamin, Bichena, and Geregera on mid-July Wonberema and Enewari on end-July and at Mehal Meda on early August). Nitrogen and phosphorus fertilizer was applied in the form of urea and diammonium phosphate (DAP), with the recommended rate for each location. Half of the total nitrogen and all phosphorus were applied at the time of planting while the remaining nitrogen was applied at the time of tillering. Two to three interculture and hand weeding were carried out to keep the plots free of weeds.

Table 1: Descriptions of some selected parameters of the test locations

Location	Latitude	Longitude	Altitude	Year	Average Max T (°c)	Average MinT (°c)	Total RF (mm)
Adet	11^016'N	37^029'E	2240	2014	25.12	11.91	1011.9
				2015	25.94	12.30	1088.2
				2016	25.21	11.92	962.8
				2017	23.30	12.18	1029.5
Mota	11^005'N	37^052'E	2487	2014	22.76	10.29	1231.2
				2015	24.10	10.44	1402.6
				2016	23.48	9.76	1189.9
				2017	24.01	10.67	1425.5
Wonberema	10^039'N	36^058'E	2062	2014	28.1	10.9	1176.40
				2015	26.6	11.4	1268.10
				2016	26.1	7.3	1516.55
				2017	24.8	NA	1422.40
Debre Elias	10^018'N	37^029'E	2230	2014	22.4	12.5	2063.30
				2015	20.7	13.1	1825.70
				2016	NA	NA	NA
				2017	22.4	13.1	2466.00
Debre Tabor	11^051'N	38^01'E	2706	2014	22.1	9.8	1525.0
				2015	21.9	10.1	1134.4
				2016	21.1	9.8	1327.5
				2017	21.5	10.4	1127.5
Bassoliben	10^008N	37^044	2325	2014	NA	NA	1298.3
				2015	NA	NA	NA
				2016	22.5	17.2	1612.3
				2017	16.7	9.0	1572.5
Gaint	11^050'N	38^021E	2937	2014	17.3	8.2	919.50
				2015	19.2	9.3	1243.20
				2016	17.7	8.7	1037.20
				2017	18.2	8.8	779.10
Simada	11^030'N	38^015E	2170	2014	22.7	6.9	1055.4
				2015	23.8	9.3	444.1
				2016	23.4	11.6	1145.8
				2017	23.0	11.4	901.4
Gozamin	10^033N	37^073	2476	2014	21.29	11.02	1133.3
				2015	22.21	11.82	957.2
				2016	21.68	11.07	1115.9
				2017	21.41	11.27	1178.8
Geregera	11^040'N	38^048'E	2879	2014-17	NA	NA	NA
Bichena	10^025'N	38^013'E	2514	2014	21.51	10.49	895.4
				2015	22.50	10.87	799.7
				2016	NA	NA	NA
				2017	24.98	11.10	1245.3
Enewari	9^053'N	39^008'E	2657	2014-17	NA	NA	NA
Mehal Meda	10^018'N	39^04'E	3090	2014-17	NA	NA	NA

Note: NA = data not available; unit of the altitude in meters above sea level; Max T = average maximum temperature of the year; Min T = average minimum temperature of the year; RF = total rainfall of the year

Description of Genotypes

In this study, 21 durum wheat varieties released by different research centers in the country were tested. Description of some selected parameters of these varieties is presented in Table 2.

Table 2: Description of some selected parameters of the tested durum wheat varieties

Code	Variety	Pedigree	Year of release	DH	DM	Grain yield (Qt/ha)	Altitude range
1	Asasa	DZ 2085	1997	NA	NA	NA	NA
2	Denbi	AJAIA/BUASHEN	2009	68	113	40-56	1800-2650
3	FLAKIT	EN-25	2007	74	140	21.5	2400-3000
4	Ginchi	DZ-1050	2000	NA	NA	NA	NA
5	Hitosa	CHEN/ALTAR-84	2009	67	113	40-60	1800-2650
6	kokate	DZ-2016-1BZR-10 205-OAK-2AK(23)	2005	68-72	110-120	30-50	1900-2800
7	Lelisso	DZ-1605	2002	65	139	32.7	2300-2800
8	Malefia	CD 191-076 AR-3AP-OAP 2AP-OAP-ALTAR 84 /stn	2005	73	139	27.12	2400-3000
9	Megenagna	DZ-2023	2004	56-72	99-128	20-40	1900-2800
10	Mettaya	DZ-2212	2004	65-75	113-139	21-35	2000-2800
11	Mosobo	DZ-2178	2004	60-72	102-132	20-40	1900-2800
12	Mukiye	STJ13//BCR/LKS4/3/TER-3	2012	61	111	40-56	1800-2700
13	Mangudo	ICAJIHAN 22	2012	63	117	43-50	1800-2700
14	OBSA	ALTAR 84 ALTO-1/AJAYA	2006	71	131	68	2300-2600
15	Oda	DZ 2227	2004	72	137	38.53	2300-2600
16	Quami	CD-75533-A	1996	NA	NA	NA	NA
17	Selam	DZ-1666-2	2004	60-75	107-135	22-36	1900-2800
18	Tate	CD94523	2009	69	135	42-59	2300-2600
19	TOLTU	4/B/R9096#21001(980 SN Patho)	2010	60-68	125-135	44-60	2300-2600
20	Ude	CD 95294-2Y	2002	63-80	111-132	35	NA
21	Yerer	CD 94026-4Y	2002	65-80	109-134	37	NA

Data Collection

Data on plant height (average height of five plants measured from the ground to the tip of the spike excluding the own (cm)), spike length (average length of five spikes containing grains (cm)), days to heading (when the spikes of 50% of the plants are fully visible), days to maturity (the date by which 90% of the plot is ready for harvest) and grain yield (gm/plot) were collected from harvestable rows of each plot, but only the grain yield data are used. The grain moisture content was adjusted to 12.5%.

Statistical Analysis

The data set thus generated, composed of yield data from 21 genotypes across thirty-nine environments was subjected to GGEbiplot analysis using the GenStat 18th edition statistical package (VSN International 2015). The first two principal components (PC1 and PC2) used in the

construction of the GGEbiplot were derived from subjecting environment-centered grain yield means for each location, averaged over the four seasons, to a singular value.

3. RESULTS AND DISCUSSION

3.1. Environment and Genotype x Environment Variation

The mean grain yield of genotypes across locations is presented in Table 3. Analysis of variance was performed for the yield data, the result of the combined analysis of variance showed that the effect of different genotypes, locations, years, location x genotype, year x genotype, and location x year were all highly significant (Table 4). Based on the percentage effect of each variant over the total effect (sum of squares), the relative contribution of various factors on grain yield variability was compared. Environment (Location, Year, and location x year) had the highest impact on yield, accounting for 87.13% of the yield variability (Table 4). This result is in agreement with the findings of (Luo et al 2015). The next was the genotype environment (GE) interaction (genotype x location), accounting for 5.51%. The genotype alone accounted for the least variability (0.95%). Within the environment, changes in location, year, and year x location accounted for 38.7%, 12.21%, and 36.21% of the variance in production, respectively (Table 4).

The genotype by environment interaction accounted for more variation than the main effect of the genotype (Witcombe et al 1996). In this study, GGE biplot analysis showed that the test environments had the highest effect (87.3%) on durum wheat yield than either genotype or GE interaction alone. The Location x-year interaction had the greatest effect among the interactive parameters, whereas Genotype x Year had the least effect. The impact of each factor on durum wheat yield variability could be ordered from high to low as: Location (38.7%) > Location x Year (36.21%) > Year (12.21%) > Location x Genotype (5.51%) > Location x year x Genotype (5.46%) > Genotype (0.95%) > Year x Genotype (0.65%). The effect of GE interaction was far greater than the genotype alone, and some durum wheat varieties may only adapt to certain specific areas. Therefore, as long as the ecological conditions allow it is advisable to increase the number of genotypes in durum wheat genotype evaluation. The GE interaction effect needs to be seen under consideration when recommending a certain variety for production in a specific location (Bellon 2001).

Table 3: Four years mean grain yield (ton ha^{-1}) of twenty-one durum wheat genotypes tested at thirteen locations in the Amhara Region

Genotypes	Test environments												
	AD	BL	BI	DE	DT	EN	GA	GG	GO	MM	MO	SM	WO
Assasa	3.38	1.67	4.08	2.19	3.75	5.24	4.84	1.97	3.12	3.92	2.32	2.11	2.25
Denbi	3.70	1.93	4.41	1.99	3.10	4.81	4.97	2.25	3.65	4.20	2.71	1.96	2.69
Flakit	3.65	1.48	4.03	1.76	3.29	5.08	5.34	2.12	3.99	4.42	2.73	1.99	2.60
Ginchi	3.96	1.43	3.65	2.53	4.18	5.44	3.93	2.23	2.95	3.50	3.18	3.18	3.59
Hitosa	4.56	1.89	3.87	2.41	3.76	4.29	5.16	2.12	2.95	3.82	2.89	3.60	3.72
Kokit	3.96	1.56	4.07	2.13	3.78	4.46	4.72	1.83	4.14	3.14	3.25	3.62	3.53
Leliso	3.44	1.56	3.71	2.14	3.67	5.13	4.44	2.17	3.69	3.57	3.31	3.73	3.77
Malefia	3.11	2.08	2.91	2.84	3.87	4.62	5.53	2.38	3.44	3.99	2.12	3.13	2.77
Megegna	4.46	1.75	3.75	2.70	4.31	5.04	3.91	1.90	3.23	3.17	2.94	3.53	4.07
Metaya	4.07	1.62	4.12	2.66	3.85	5.27	4.34	2.12	3.75	3.57	3.75	3.71	3.88
Mossobo	4.22	1.50	4.59	2.38	3.90	5.11	5.24	1.94	3.70	3.27	3.53	3.93	3.60
Mukuya	4.23	1.62	3.65	1.30	3.19	5.30	5.71	2.20	4.15	4.06	3.23	3.98	3.22
Mungdo	3.82	1.45	3.94	1.82	3.16	4.75	4.98	2.39	3.36	3.96	2.67	3.41	3.02
Obsa	3.93	1.56	3.75	1.97	2.94	5.00	5.37	2.36	3.57	4.15	3.01	3.83	3.21
Oda	3.24	1.54	3.62	2.14	3.90	4.91	5.04	2.15	3.72	3.17	3.25	3.16	3.35
Quamy	2.99	1.64	3.55	2.60	3.88	4.77	4.41	2.29	3.21	2.97	2.78	3.23	3.53
Selam	4.03	1.68	4.11	2.69	4.24	5.29	4.73	2.23	3.45	3.69	3.59	3.21	3.71
Tate	4.34	1.85	3.77	1.98	3.53	4.93	5.03	2.48	3.57	3.97	3.11	3.72	3.81
Toltu	3.92	1.19	3.65	1.60	2.78	4.79	5.16	2.39	3.69	4.04	3.25	3.71	3.16
Ude	3.63	1.40	4.11	2.04	4.04	4.78	4.73	1.62	3.52	4.11	3.30	3.20	2.96
Yerer	3.15	1.15	4.09	1.32	2.55	5.42	3.90	1.99	3.11	3.90	3.27	3.82	2.89

Note: AD=Adet, BL= Baso Liben, BI=Bichena, DE= Debre Elias, DT= Debre Tabor, EN= Enewari, GA= Gaint, GG= Geregera, GO=Gozamin, MM=Mehal Meda, MO= Mota, SM= Simada, WO= Wonberema

Table 4: Combined analysis of variance over locations and years for grain yield of durum wheat genotypes

Source of variation	DF	SS	MS	F	Size of explained variation (%)
Environments (E)	38	3872.96	101.92	234.53**	87.13
Genotypes (G)	20	42.01	2.10	4.83**	0.95
G*E	760	516.61	0.68	1.56**	11.62
REP	2	13.57	6.79	15.61**	0.31
Total	820	4445.16			
G	20	42.01	2.10	4.83**	0.95
Location (L)	12	1720.36	143.36	329.90**	38.70
REP	2	13.57	6.79	15.61	0.31
Year (Y)	3	542.80	180.93	416.35**	12.21
L*G	240	244.89	1.02	2.35**	5.51
Y*G	60	28.89	0.48	1.11**	0.65
L*Y	23	1609.80	69.99	161.06**	36.21
L*Y*G	460	242.83	0.53	1.21	5.46
Total	820	4445.16			

Note: * = p<0.05; ** = p<0.01

Mega-Environment Analysis

The polygon view of the GGE biplot shows which genotype is best for which environment is presented in Figure 1. The visualization of the 'which-won-where' pattern of multi environment trial data is important for studying the possible existence of different mega-environments in a region (Gauch and Zobel 1997; Mohammadi et al 2011). The main components (PC1 and PC2) accounted for only 56.22% of the total variation of the grain yield. The low proportion explained by the biplot is an indication of complexity among the genotypes and the genotype-environment interaction. For the effective evaluation of genotypes, further classification of the test locations into mega environments is crucial. The genotypes in the vertices were the highest yielder in these environments. These biplot sectors and environment grouping in relation to genotype performance revealed that the genotype Mettaya (G10) was the best genotype (vertex genotype) for Adet, Mota, and Bichena; Yerer (G21) was the best for Enewari and Simada; Megenagna (G9) was the best for Wonberema, Debre Tabor, and Debre Elias; Malefia (G8) was the best for Geregera, Bassoliben, and Gaint. This result suggests there are clusters of mega-environments. The GGE biplot can identify test regions with good discrimination power will help improve the accuracy and efficiency of regional trials (Glaz and Kang 2008). If all varieties gave low yields without any significant difference within a test location, it is mostly due to human management error or natural disasters (Luo et al 2015). An important advantage of GGE biplot is to identify redundant testing locations, and if the redundant locations are removed, precision and important information about the variety will not be misplaced (Witcombe et al 1996). Therefore, to estimate the representativeness and discrimination power of a test location, it is crucial to conduct a long-term experiment and analyze the data collected from year to year to minimize factors related to human management error or natural disasters.
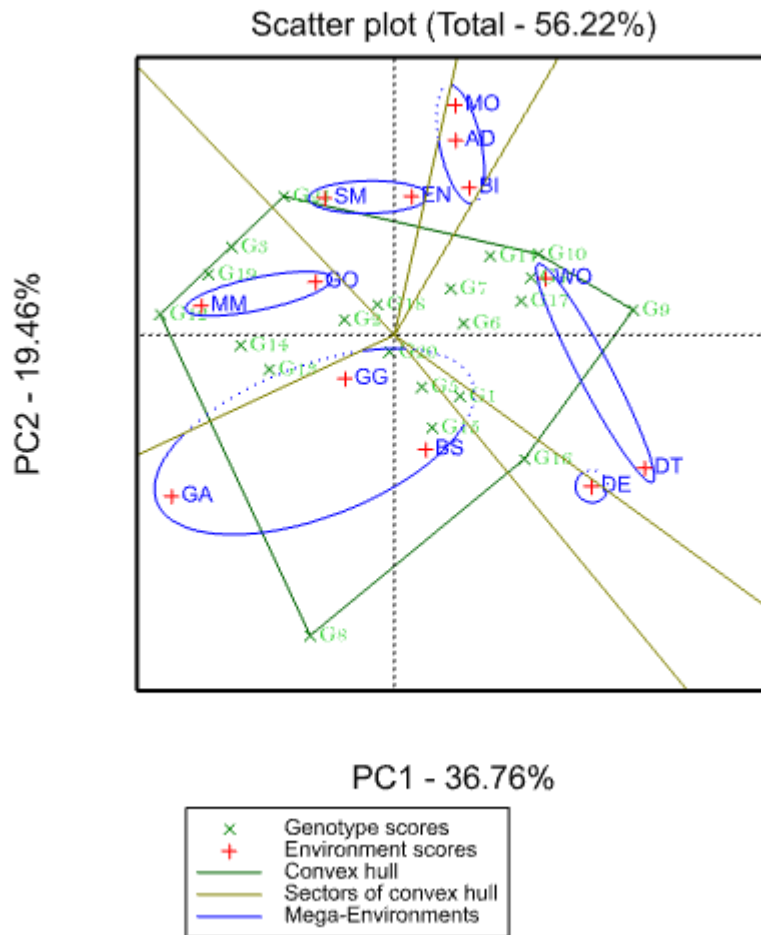
Figure 1. Polygon view of the genotype main effect and genotype by environment interaction (GGE) biplot of 21 durum wheat varieties evaluated at 13 locations

Discrimination power and representativeness

The discrimination power of a test environment (location) in a GGE biplot is proportional to the length of the environment vector, which is the line connecting the origin and the test environment point (Yan and Holland 2010). The length of the vector approximates the standard deviation (the discriminating ability) of the test location while the cosine of the angle between two vectors is equivalent to the correlation coefficient between the two locations. Figure 2A, Mota (MO), Debre Tabore (DT), Gaint (GA), and Debre Elias (DE) displayed the highest discriminating power; Geregera had the least discriminating ability. Based on the interrelationship between locations, four different mega-environments could be

identified for durum wheat production in the highlands of Amhara Regional State. Geregera (GG) and Gozamin (GO) had short vectors and therefore did not correlate with those locations with long vectors. Mota had an angle greater than 900 with Debre Tabor, Gaint, and Mehalmeda, indicating that Mota was negatively correlated with those locations. Mota had an acute angle with Adet, Bichena, and Enewari, indicating that they had a positive correlation with it.

According to previous studies, a desirable location for a variety can be identified by comparing the discrimination power and representativeness of all the locations tested (Witcombe et al 1996; Yan et al 2010) used GGE biplot to analyze the mega-environments and test locations for oat in Quebec. They revealed that the

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Quebec oat-growing regions can be successfully divided into two different mega-environments (Bellon 2001). Our study divides the Amhara region durum wheat testing location into four mega-environments. 1) Adet, Mota and Bichena; 2) Wonbeerema, Debere Tabor, and Debre Elias; 3) Geregera, Bassoliben, and Gaint, and 4) Enewari and Simada. An appropriate adjustment to test environments and evaluation criteria is always necessary to define ecological zones more accurately and to further improve the effectiveness of a variety of trials (Bellon 2001).
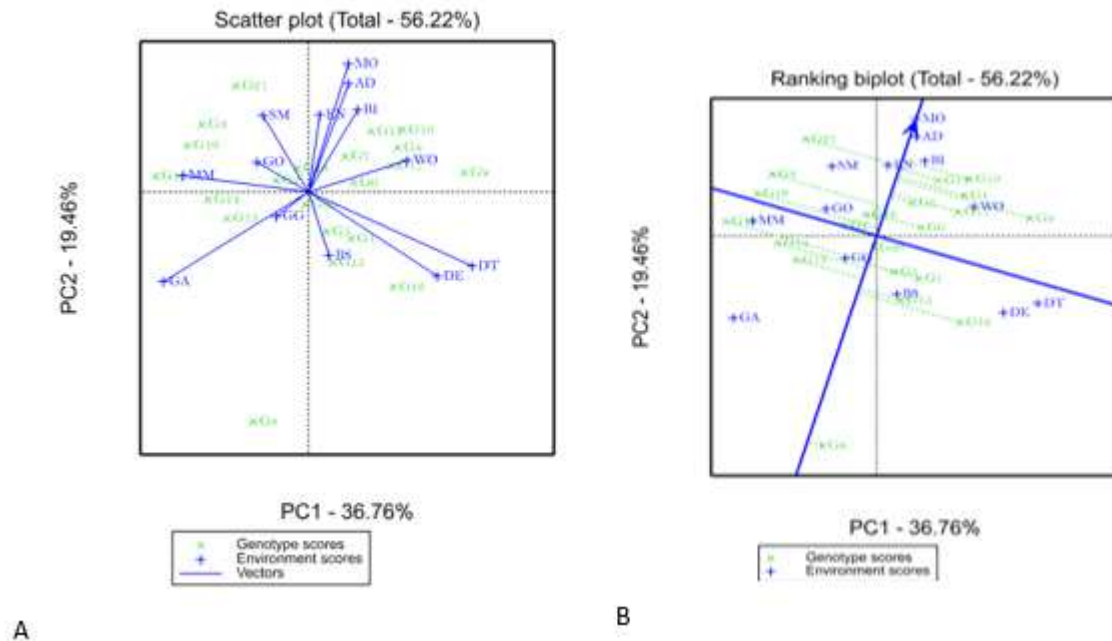
Figure 2. Environment Vector Plot (A) Ranking Plot for genotypes based on environment (B) of 21 durum wheat varieties evaluated at 13 locations

The representativeness of a test environment (location) refers to the consistency of a target environment when compared with other environments or the average of all test environments (Badu-Apraku et al 2013; Yan et al 2011). In a GGE biplot, the representativeness of a target environment is shown by the angle between the test environment vector and the average environment coordination (AEC) (Yan et al 2011). AEC abscissa is a single-arrowed line passing through the biplot origin and the average of all environments (Hossain et al 2018) (Figure 2b). The smaller the angle between the environments, the stronger the representativeness of the environment (Sánchez-Martn et al 2014).
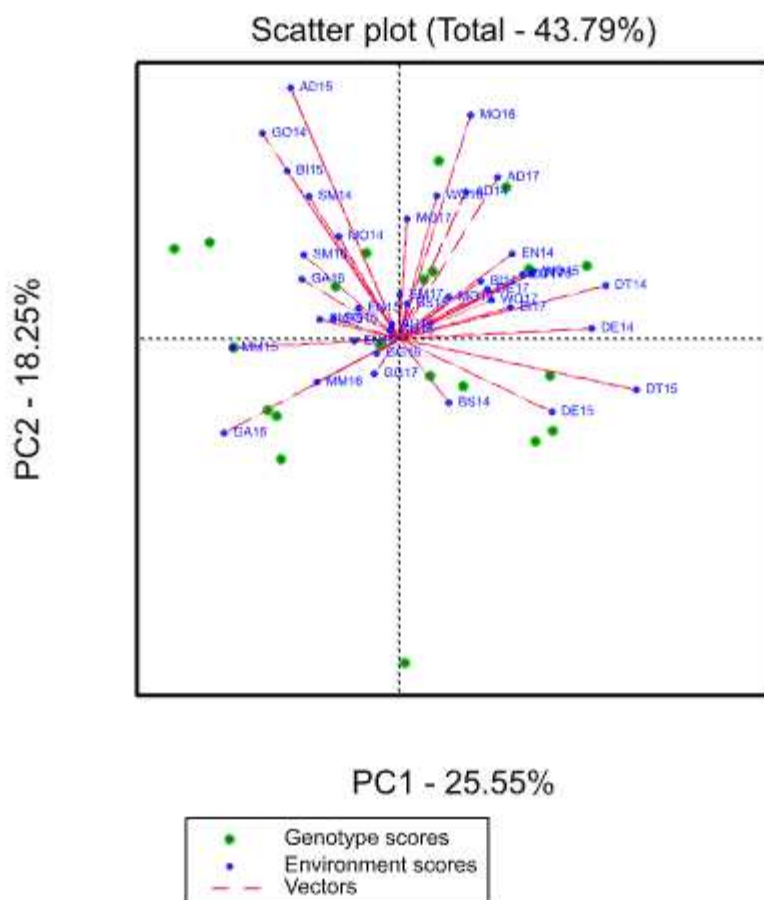
Test environment evaluation.

Figure 3. Environment vector plot of 39 environments across thirteen locations

The repeatability and representativeness for the test sites of durum wheat genotypes in the highlands of the Amhara Regional State are presented in Figure 3. The biplot explained 43.79% of the total variation of yield in the environments. Debre Tabor had the highest repeatability, since DT 14, DT15, DT16, and DT17 had the smallest angle among their vectors. Adet, Debre Elias, Mota, and Wonberema had also angles less than 900 among their respective vectors indicating they displayed high repeatability. Bichena, Enewari, and Gozamen had an angle greater than 900 among their respective vectors, indicating they were unrepeatable. Large angles among the respective vectors of Bichena, Enewari, and Gozamen imply they were uncorrelated positively. GO16, AD16, and EN16 had the shortest vector, indicating they were uncorrelated with any of the other test environments (Figure 3).

4. CONCLUSIONS

The advantage of identifying a mega environment is we can restrict it to fewer test centers thus saving resources and energy. Mega-environment analysis effectively discriminated the genotypes over the environment. The evaluation of test environments revealed the nature of mega-environment and ideal test environments among the environments evaluated. Among the interactive factors, the location x year interaction showed the greatest effect, and the genotype x year showed the least impact on durum wheat yields. Based on the GGE biplots, Debre Tabor, Adet, Debre Elias, Mota, and Wonberrema had the highest repeatability.

While Bochena, Enewari, and Gozamen are unrepeatable. Based on the overall grain yield result, G11 (Mosobo) and G10 (Mettaya) had shown high grain yield and stability. The yield of Mossobo (G11), Mettaya (G10), Selam (G17), Tate (G18), Felakit (G3), Denbi (G2), Megenagna (G9) and Leliso (G7) was higher than average. The study divides the Amhara region durum wheat testing location into four mega-environments. From this study, for reasonable discrimination of a large number of durum wheat genotypes, only four ideal test environments (Mota, Debre Tabor, Gaint, and Mehalmeda) maybe deployed thus saving time and resources.

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