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REGULAR ARTICLE

GGE biplot analysis of genotype-by-environment interaction and grain yield stability of bread wheat genotypes in South Tigray, Ethiopia

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ABSTRACT

Studying genotype-by-environment interaction and determining representative testing environments are important for releasing new varieties. Nineteen bread wheat varieties were thus evaluated to study their adaptability and stability in seven environments of south Tigray. The experiment was carried out in a randomized complete block design with two replicates in three locations in 2011 and two locations in 2012 and 2013. Genotype, environment and genotype-by-environment interaction had significant effects on grain yield. The environment accounted for 78.3%, while the genotype-by-environment interaction for 14.7% of the variation in grain yield. Based on the polygon view of the GGE biplot, three mega-environments were detected with different winning genotypes (paven-76, Mada-Walabu and ET-13A2), which are therefore to be regarded as specifically adapted. Considering simultaneously mean yield and stability, the best genotypes were Dinkinesh, Gasay, Alidoro, Kakaba and Dand'a, which therefore can be regarded as adapted to a wide range of environments.

Key Words: *GGE; genotype; environment; genotype-by-environment interaction.*

INTRODUCTION

Wheat is one of the major cereal crops in the Ethiopian highlands (between 6° and 16° N and 35° and 42° E, at altitudes ranging from 1500 to 3200 m a.s.l.; White et al. 2001), particularly in the southeastern, central and northwestern regions of the country. The most common wheat species cultivated there are bread wheat (*Triticum aestivum* L.) and durum wheat (*Triticum durum* Desf.) (Tesemma and Belay 1991).

During 18 years, wheat production area in Ethiopia showed a 121% increase, increasing from 0.769 million ha in 1995 (CSA 1998) to 1.7 million ha in 2013 (CSA 2013). At the same time, grain yield showed only a modest increase of 18%. A possible reason is poor wheat productivity in Ethiopia, with an average yield of 2.3 t ha^{-1}, that is 24% and 48% below the African and world averages, respectively.

In Ethiopia, wheat ranks 4th after teff, maize and sorghum in cropped area; 4th after maize, teff and sorghum in total grain production; and 2nd after maize in yield, accounting for more than 15% of total cereal production (CSA 2013). However, the national mean wheat yield (2.3 t ha^{-1}) is far below the average yield obtained in experimental plots in the country (>5 t ha^{-1}). This gap (over 2.7 t ha^{-1}), i.e., the difference between research plot yield and farmer's field yield, could be due to genotype-by-environment interaction, which makes most cultivars achieve high yields only in good environmental conditions. Hence, the genotype-by-environment interaction is probably the main cause of why traditional plant breeding failed to support resource-poor farmers, especially in marginal and fragile environments (Ceccarelli et al. 2006).

In Tigray, wheat ranks 3rd after sorghum and maize in productivity and production area (CSA 2013). The average yield in the study area is 1.8 t ha^{-1}, which is 0.5 t ha^{-1} below the national average. Again, such low yielding could be due to genotype-by-environment interaction. Hintsa and Abay (2013) found significant genotype-by-environment interaction in Tigray and emphasized the need of specific adaptation in the region. To improve yielding in Ethiopia and its Tigray region, improved varieties should be released. They should be, however, tested in various agro-ecological environments within the region. This study aimed thus to assess the adaptability and yield stability of nationally released bread wheat varieties under the environmental conditions of the Tigray region.

MATERIAL AND METHODS

The experiments were conducted during the main cropping season, in three locations in 2011 and two locations in 2012 and 2013. Nineteen bread wheat varieties (Table 1) were studied in experiments arranged as a randomized complete block design (RCBD) with two replicates. Depending on weather, the varieties were planted from mid-June to the first week of July and harvested 120-145 days after planting (Table 2). Plots were 2.5 m long and had six rows, with spacing of 0.2 m between rows and 0.5 m between plots. Distance between blocks was 1.5 m. A seed rate was 150 kg ha^{-1}. The following fertilizers were applied: 62 kg N ha^{-1} and 46 kg P_2O_5 ha-1, applied at planting, and 23 kg P_2O_5 ha^{-1}, applied after 40 days. Grain yield was recorded from four central rows in each plot.

Different approaches are used to quantify the genotype-by-environment interaction and recommend the best genotypes for target environments. Examples include joint regression (Eberhart and Russel 1966), stability variance index (Shukla 1972), coefficient of variation (Francis and Annenberg 1978), additive main effect and multiplicative interaction (AMMI) analysis (Gauch and Zobel 1988), and GGE biplot (Yan et al. 2002). The last method is based on data visualization and proved to be helpful in: (i) detection of the genotype-by-environment interaction pattern, (ii) classification of mega environments, (iii) simultaneous selection of genotypes based on stability and mean yield, and (iv) characterization of testing environments based on their discriminating ability and representativeness (Yan et al. 2000). We will, thus, use this method to analyze the data.

First, the combined analysis of variance was performed, with all effects fixed. The GGE biplot was built according to the formula given by Yan et al. (2000):

$$y_{ij} - \mu - \beta_j = \lambda_1 \xi_{1i} \eta_{1j} + \lambda_2 \xi_{2i} \eta_{2j} + \varepsilon_{ij}$$

where y_{ij} is the mean for the i-th genotype in the j-th environment, μ is the overall mean, β_j is the effect for the j-th environment, λ_1 and λ_2 are the singular values of the first and second principal components (PC1 and PC2), ξ_{1i} and ξ_{2i} are the eigenvectors for the i-th genotype for PC1 and PC2, η_{1j} and η_{2j} are the eigenvectors for the j-th environment for PC1 and PC2 and ε_{ij} is the residual error term. The analysis was performed by using Genstat 13 (Payne 2009).

Table 1. Bread wheat genotypes evaluated in the seven environments.

Variety	Code	Year of release	Maturity (days)	Adaptation altitude (m a.s.l.)	Source centre
Senkegna	G1	2005	105-125	1900-2800	ADARC/ARARI
Mada-Walabu	G2	2000	100-125	2300-2800	SARI/OARI
Tossa	G3	2004	134-143	2400-3000	SRARC/ARARI
Digelu	G4	2005	100-120	2000-2600	KARI/EIAR
paven-76	G5	1982	120-135	750-2500	KARI/EIAR
Kakaba	G6	2010	90-120	1500-2200	KARI/EIAR
Tussie	G7	1997	125-130	2000-2500	KARI/EIAR
Hawi	G8	2000	105-125	1800-2200	KARI/EIAR
ETBW-5496	G9	2011	-	2200-2600	KARI/EIAR
ET-13A2	G10	1981	127-149	2200-2900	KARI/EIAR
Kulkulu	G11	-	-	-	Haramaya University
K6295-4A	G12	1980	128-131	1900-2400	KARI/EIAR
Dinkinesh	G13	2007	145	2400-3000	SRARC/ARARI
Gasay	G14	2007	118-127	1890-2800	ADARC/ARARI
Danda,a	G15	2010	110-145	2000-2600	KARI/EIAR
Alidoro	G16	2007	118-180	2800-3100	HARC/EIAR
Tay	G17	2005	104-130	1900-2800	ADARC/ARARI
ETBW-5483	G18	2011	-	1800-2400	KARI/EIAR
Sofumar	G19	2000	125-150	2300-2800	SARI/OARI

Table 2. Environments used in the study and their main characteristics.

Code	Environment	Year	Longitude (E)	Latitude (N)	Altitude (m.a.s.l.)	Rainfall mm/year	Soil type
E1	A/gara	2011	39°33′	12°31′	2490	949.4	Sandy loam
E2	A/gara	2012	39°33′	12°31	2490	1271.6	Sandy loam
E3	A/gara	2013	39°33′	12°31′	2490	1052.4	Sandy loam
E4	Atsella	2011	39°56′	12°91′	2465	456.7	Clay loam
E5	Atsella	2012	39°56′	12°91′	2465	351.0	Clay loam
E6	Atsella	2013	39°56′	12°91′	2465	734.3	Clay loam
E7	Mekhan	2011	39°32′	12°44′	2423	485.0	Loam

Source: Agriculture Bureau of Tigray (2013)

RESULTS AND DISCUSSION

COMBINED ANALYSIS FOR INDIVIDUAL ENVIRONMENTS

Environment A/gara gave the highest yield in all three consecutive years. This could be due to high rainfall and uniform rain distribution during the growing seasons. Atsella was the lowest yielding environment in the three years probably because of the low rainfall and its bad distribution during the growing seasons (Table 3).

The genotype and environment main effects were significant ($P < 0.001$), as was the genotype-by-environment interaction ($P < 0.0476$) (Table 4). The environment explained 78.3% of sums of squares, followed by the genotype-by-environment interaction (14.6%) and genotype (7%) (Table 4). The effect of the environment was 12.4% and 5.9 % times greater than the effects of genotype and genotype-by-environment interaction, respectively. Hence, the environment caused most of the variation in grain yield of bread wheat genotypes. Similar large environmental effects have been reported for Tigray, which calls for specific adaptation and breeding programs for the region (Abay and Bjornstand 2009, Hinsta et al. 2011, Hinsta and Abay 2013, Gebremedhin et al. 2014).

Table 3. Yield response of 19 genotypes across 7 environments.

Variety	A/gara			Atsella			Mekhan
	2011	2012	2013	2011	2012	2013	2011
Senkegna	58.7	33.2	54.2	36.5	11.0	23.4	26.3
Mada-Walabu	62.8	44.4	53.6	49.1	11.0	25.1	41.6
Tossa	60.3	52.1	62.9	33.4	18.8	25.7	46.8
Digelu	57.8	53.5	51.0	42.8	32.0	27.0	27.5
paven-76	58.3	57.4	41.1	49.3	26.8	26.8	35.0
Kakaba	58.1	51.9	47.9	38.1	17.8	30.0	45.7
Tussie	49.1	48.9	43.8	42.8	16.7	31.8	38.1
Hawi	46.5	41.7	42.9	42.8	14.7	34.0	41.0
ETBW-5496	49.2	40.6	44.1	35.3	13.7	25.4	28.8
ET-13A2	38.0	43.2	39.9	28.3	10.5	35.2	26.0
Kulkulu	45.3	33.2	43.9	22.7	14.5	27.3	34.7
K6295-4A	41.3	32.1	44.1	35.9	10.8	28.6	29.6
Dinkinesh	60.3	47.6	52.6	36.1	24.7	25.7	33.5
Gasay	60.7	48.6	50.9	36.0	15.4	37.4	38.0
Danda'a	59.0	44.1	46.7	43.2	11.1	38.6	37.7
Alidoro	59.5	37.4	44.7	36.3	17.6	30.8	40.8
Tay	58.3	41.0	56.6	37.6	11.6	31.3	36.0
ETBW-5483	61.5	37.3	47.8	46.4	12.7	30.0	29.1
Sofumar	65.3	39.9	45.4	37.3	12.8	30.4	26.4

Table 4. Combined analysis of variance for 19 bread wheat genotypes across seven environments.

Source	df	SS	MS	% SS explained
Genotypes	18	3408	189.3**	7.06
Environments	6	37763	6293.8**	78.29
GxE Interactions	108	7071	65.5*	14.65
Blocks within Environments	7	854	122	
Error	126	6059	48.1	

POLYGON VIEW OF THE GGE BIPLOT

The polygon view of the GGE-biplot analysis helps one detect cross-over and non-cross-over genotype-by-environment interaction and possible mega environments in multilocation yield trials (Yan et al. 2007). G10 (ET-13A2), G1 (Senkegna), G2 (Mada-Walabu), G3 (Tossa) and G5 (paven-76) were vertex genotypes (Figure 1). They are best in the environment lying within their respective sector in the polygon view of the GGE-biplot (Yan and Tinker 2006); thus these genotypes are considered specifically adapted. Genotypes close to the origin of axes have wider adaptation (Abay and Bjornstand 2009).

The environments fall into three quadrants while the genotypes into four quadrants (Fig 1). G5 (paven-76) performed well in E5 (Atsella, 2012) and E2 (A/gara, 2012) and was moderately adapted to E7 (Mekhan, 2011) and E4 (Atsella, 2011). Paven-76 performed well in environments with relatively low rainfall, but also in environments with higher rainfall and more uniform distribution. Vertex genotype G2 (Mada-Walabu) performed well in E1 (A/gara, 2011) and E3 (A/gara 2013), thus being adapted to high rainfall. Genotype G10 (ET-13A2) was best adapted to E6 (Atsella, 2013). Two vertex genotypes, G1 (Senkegna) and G3 (Tossa), had the highest yield in none of the environments (Fig. 1).

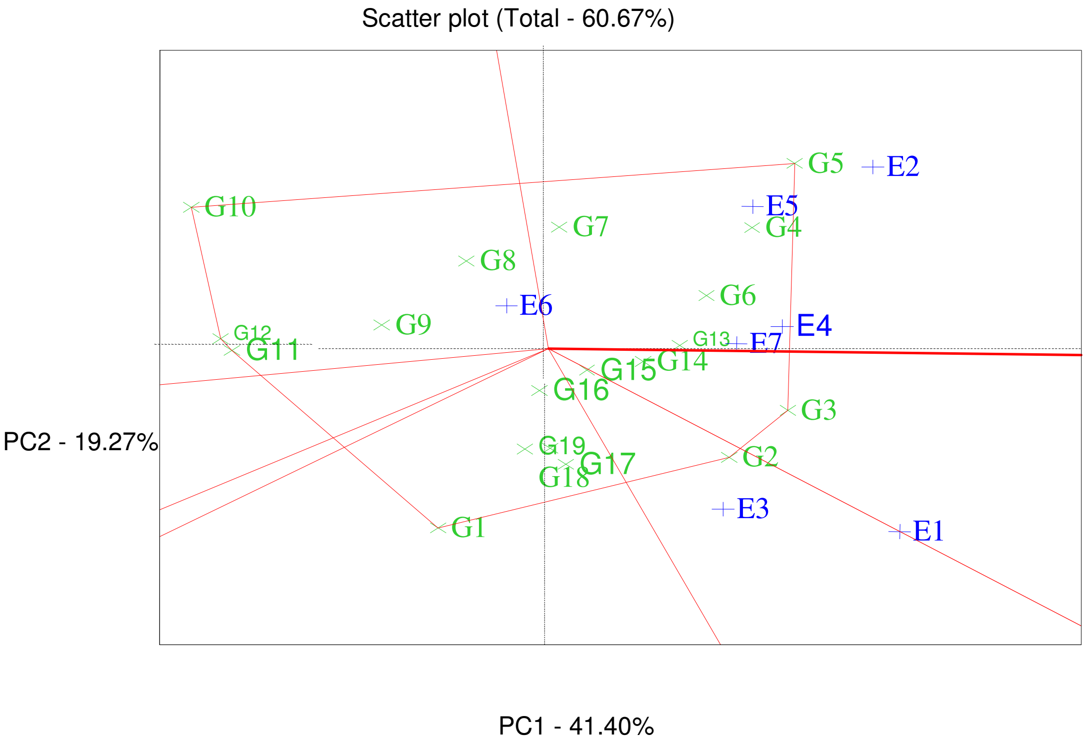

Figure 1. Polygon view of the GGE biplot using symmetrical scaling of 19 bread wheat genotypes across seven environments. The genotypes are abbreviated as G1, G2, …, G19 and the environments as E1, E2, …, E7 (See Tables 2 and 3).

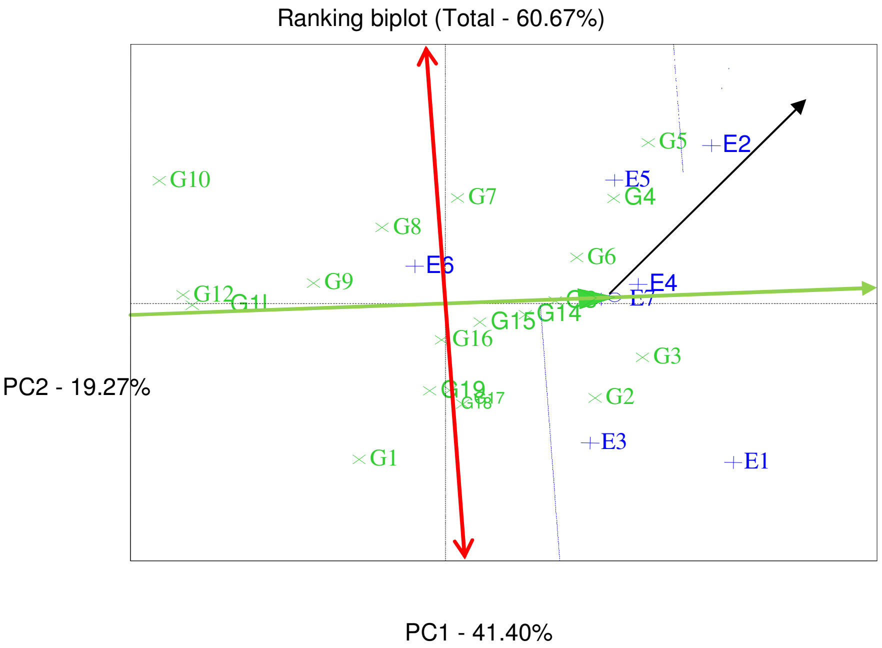

Figure 2. GGE biplot with scaling focused on genotypes, for mean grain yield and stability of 19 bread wheat genotypes tested across seven environments. The genotypes are abbreviated as G1, G2, …, G19 and environments as E1, E2, …, E7 (see Tables 2 and 3).

MEAN GRAIN YIELD AND ITS STABILITY

The best genotype can be defined as the one with the highest yield and stability across environments. In the GGE biplot, genotypes with high PC1 scores have high mean yield, and those with low PC2 scores have stable yield across environments (Yan and Tinker, 2006). The average environment abscissa is represented in Figure 2 by a single head arrow pointing towards higher yield across environments. The average environment ordinate (AOE) is represented as a double-headed arrow and points towards lower stability in both directions (Yan and Hunt, 2001).

Genotypes G1 (Senkegna), G10 (ET-13A2), G8 (Hawii), G9 (ETBW-5496), G11 (Kulkulu) and G12 (K6295-4A) had mean grain yield lower than the grand mean. The genotypes that yielded higher than the grand mean were G2 (Mada-Walabu), G3 (Tossa), G4 (Digelu), G5 (paven-7), G6 (Kakaba), G7 (Tussie), G13 (Dinkinesh), G14 (Gasay), G15 (Danda'a), G16 (Alidoro), G17 (Tay), G18 (ETBW-5483) and G19 (Sofumar) (Figure 2).

The most stable genotypes were G11 (Kulkulu), G12 (K6295-4A), G16 (Alidoro), G15 (Danda'a), G14 (Gasay), G13 (Dinkinesh), G6 (Kakaba) and G3 (Tossa) because they showed the shortest distance from the average environment abscissa. G18 (ETBW-5483), G2 (Mada-Walabu), G1 (Senkegna) and G5 (paven-76) had a large contribution to the genotype-by-environment interaction; they were unstable across environments, having the longest distance from the average environment abscissa.

Considering simultaneously yield and stability, G13 (Dinkinesh), G14 (Gasay), G15 (Danda'a), G16 (Alidoro), G6 (Kakaba) and G3 (Tossa) showed the best performances (Figure 2), suggesting their adaptation to a wide range of environments (Annicchiarico 1997). Also in studies by Mohamed et al. (2013) and Farshadfar et al. (2012) the highest-yielding wheat genotypes were stable, a desirable situation for plant breeders.

EVALUATION OF GENOTYPES BASED ON THE IDEAL GENOTYPE

An ideal genotype has the highest mean grain yield and is stable across environments (Farshadfar et al. 2012). The ideal genotype is located in the first concentric circle in the biplot. Desirable genotypes are those located close to the ideal genotype. Thus, starting from the middle concentric circle pointed with arrow concentric circles was drawn to help visualize the distance between genotypes and the ideal genotype (Yan and Tinker 2006).

The ideal genotype can be used as a benchmark for selection. Genotypes that are far away from the ideal genotype can be rejected in early breeding cycles while genotypes that are close to it can be considered in further tests (Yan and Kang 2003). Placed near to the first concentric circle, genotypes G3 (Tossa), G4 (Digelu), G6 (Kakaba) and G13 (Dinkinesh) can be thus used as benchmarks for evaluation of bread wheat genotypes. G5 (Paven-76), G14 (Gasay), G15 (Danda'a), G16 (Alidoro) G2 (Mada-Walabu) and G17 (Tay) were located near the ideal genotype, thus being desirable genotypes. Undesirable genotypes were those distant from the first concentric circle, namely, G10 (ET-13A2), G11 (Kulkulu), G12 (K6295-4A) (Figure 3). Our results confirm those by Sharma et al. (2010), who found outstanding genotypes near to the ideal genotype in wheat for five consecutive years, and those by Mulugeta et al. (2011), who found an ideal genotype of potato in the first concentric circle.

EVALUATION OF ENVIRONMENTS BASED ON THE IDEAL ENVIRONMENT

The ideal environment is representative and has the highest discriminating power (Yan and Tinker 2006). Similarly to the ideal genotype, the ideal environment is located in the first concentric circle in the environment-focused biplot, and desirable environments are close to the ideal environment. Nearest to the first concentric circle, Environment E4 (Atsella, 2011) was close to the ideal environment (Figure 4); therefore, it should be regarded as the most suitable to select widely adapted genotypes.

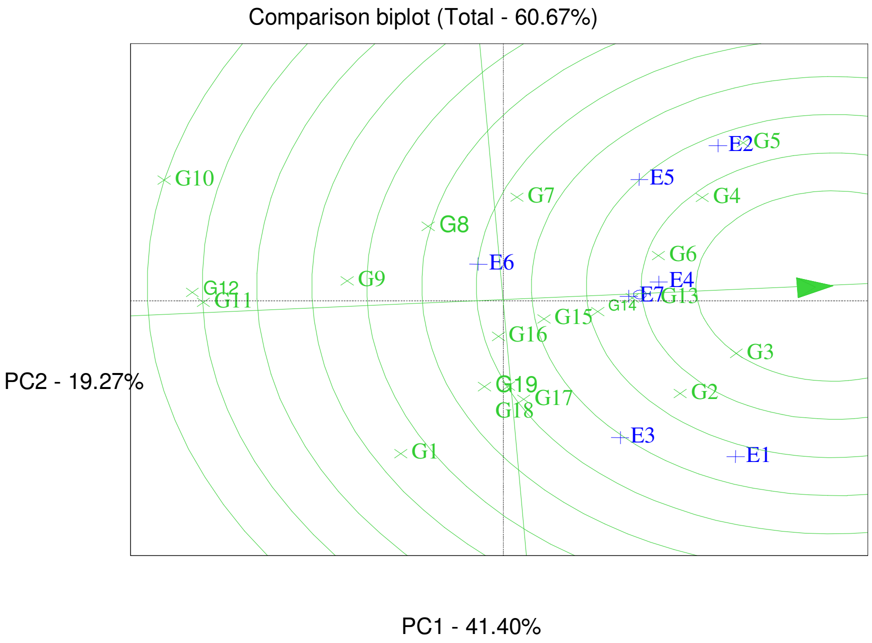

Figure 3. GGE biplot wıth scaling focused on genotypes, for the evaluation based on the ideal genotype of 19 bread wheat genotypes across seven environments. The genotypes are abbreviated as G1, G2, …, G19 and environments as E1, E2, …, E7 (see Tables 2 and 3).

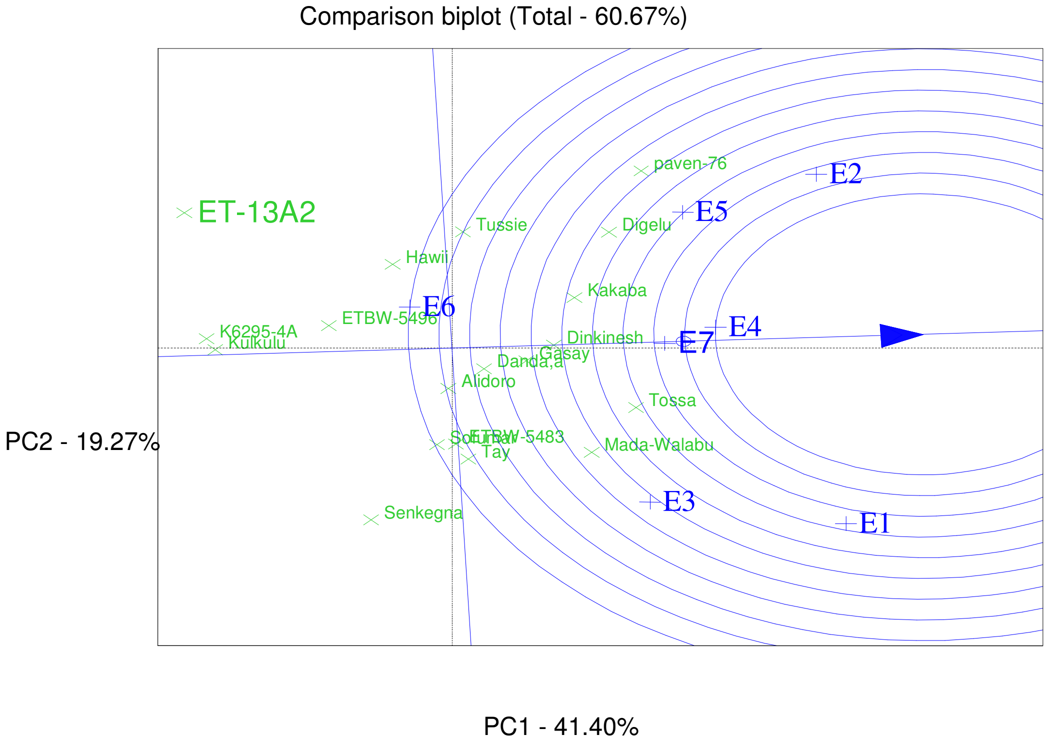

Figure 4. GGE biplot with scaling focused on environments, for the evaluation based on the ideal environment of 19 bread wheat genotypes across seven environments. Environments are abbreviated as E1, E2, ..., E7 (see Table 2).

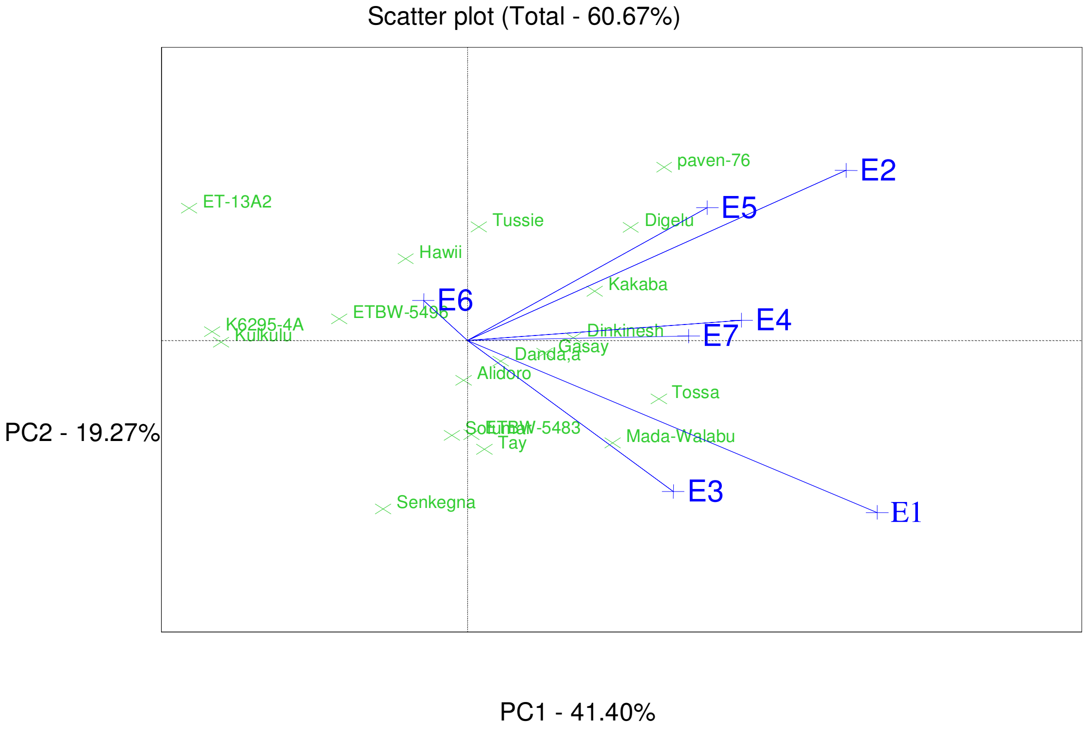

Figure 5. GGE biplot for the evaluation of the relationships among the seven environments. Environments are abbreviated as E1, E2, …, E7 (see Table 2).

RELATIONSHIP AMONG TEST ENVIRONMENTS

Further information about the discriminating power of environments, together with a representation of their mutual relationships, can be obtained by the environment-vector view of the GGE-biplot. In this case, a long environmental vector reflects a high capacity to discriminate the genotypes. Furthermore, the cosine of an angle between vectors of two environments approximates the correlation between them: a wide obtuse angle indicates a strong negative correlation, an acute angle indicates a positive correlation while a close-to-90° angle indicates lack of correlation (Yan and Tinker 2006).

With the longest vectors from the origin, environments E2 (A/gara, 2012) and E1 (A/gara, 2011) were the most discriminating. E5 (Atsella, 2012), E4 (Atsella, 2011), E7 (Mekhan, 2011) and E3 (A/gara 2013) were moderately discriminating while E6 (Atsella, 2013) was least discriminating. Considering the angles between environmental vectors, yield results in E6 (Atsella, 2013) E5 (Atsella, 2012), E2 (A/gara, 2012) were strongly correlated, similarly to those obtained in E4 (Atsella, 2011) and E7 (Mekhan, 2011), as well as in E1 (A/gara, 2011) and E3 (A/gara 2013).

CONCLUSIONS

The genotype and environment main effects and genotype-by-environment interaction effect were significant for bread wheat genotypes studied in South Tigray, Ethiopia. The environment contributed most to the variability in grain yield. Genotypes Tossa, Digelu, Kakaba and Dinkinesh were close to the ideal genotype and can thus be used as benchmarks for the evaluation of bread wheat genotypes in the Tigray region. Considering simultaneously mean yield and stability, Dinkinesh, Gasay, Danda'a, Alidoro and Kakaba were the best genotypes.

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REFERENCES

Abay F., Bjørnstad A. (2009). Specific adaptation of barley varieties in different locations in Ethiopia. *Euphytica* 167, 181–195.

Central Statistical Agency (CSA). (2013). A*gricultural sample survey 2012/13. Report on crop and livestock product utilization.* Adis Ababa, Ethiopia.

Central Statistical Authority (CSA). (1998). *Agricultural Sample Survey 1997/98. Volume 1. Report on Area and Production of Major Crops*. Statistical Bulletin 189. CSA, Addis Ababa, Ethiopia.

Eberhart S.T., Russell W.A. (1966). Stability parameters for comparing varieties. *Crop Science* 6, 36–40.

Farshadfar E., Mohammadi R., Aghaee M., Vaisi Z. (2012). GGE biplot analysis of genotype x environment interaction in wheat-barley disomic addition lines. *Australian Journal of Crop Science* 6, 1074–1079.

Francis T.R., Kannenberg L.W. (1978). Yield stability studies in short-season maize. I. A descriptive method for grouping genotypes. *Canadian Journal of Plant Science* 58, 1029–1034.

Gebremedhin W., Firew M,. Tesfye B. (2014). Stability analysis of food barley genotypes in northern Ethiopia. *African Crop Science Journal* 22,145–153.

Hailu G. (1991). Bread wheat breeding and genetics research in Ethiopia. In: Hailu G., Tanner D.G., Mengistu H. (Eds.) *Wheat Research in Ethiopia: A historical perspective*. IAR/CIMMYT, Addis Ababa, 73–93

Hinsta G., Hailemariam A., Belay T. (2011). Genotype-by-environment interaction and grain yield stability of early maturing bread wheat (*Triticum aestivum* L) genotypes in the drought prone areas of Tigray region, Northern Ethiopia. *Ethiopian Journal of Applied Science and Technology* 2, 51–57.

Hintsa G., Abay F. (2013). Evaluation of Bread Wheat Genotypes for their Adaptability in Wheat Growing Areas of Tigray Region, Northern Ethiopia. *Journal of Biodiversity and Endangered Species* 1, 104

Mohamed N.E., Ahmed. A.A. (2013). Additive main effects and multiplicative interaction (AMMI) and GGE-biplot analysis of genotype× environment interactions for grain yield in bread wheat (*Triticum aestivum* L.).*African Journal of Agricultural Research* 8, 5197–5203.

Payne R.W. (2009). GenStat. *Wiley Interdisciplinary Reviews: Computational Statistics* 1, 255–258.

Shukla G.K. (1972). Some statistical aspects of partitioning genotype environmental components of variability. *Heredity* 29, 237–245.

Tesemma T., Belay G. (1991). Aspects of tetraploid wheats with emphasis on durum wheat genetics and breeding research, In: Gebremariam H., Tanner D.G, Hulluka M.. (Eds.) *Wheat research in Ethiopia: A historical perspective*, 47–71.

White J.W., Tanner D.G., Corbett J.D. (2001). *An agro-climatologically characterization of bread wheat production areas in Ethiopia*. CIMMYT, Mexico

Yan W., Hunt L.A. (2001). Interpretation of genotype× environment interaction for winter wheat yield in Ontario. *Crop Science* 41, 19–25.

Yan W., Rajcan I. (2002). Biplot analysis of test sites and trait relations of soybean in Ontario. *Crop Science* 42, 11–20.

Yan W., Tinker N.A. (2006). Biplot analysis of multi-environment trial data: Principles and applications. *Canadian Journal of Plant Science* 86, 623–645.

Yan W., Hunt L.A, Sheng Q., Szlavnics Z. (2000). Cultivar evaluation and megaenvironment investigation based on the GGE biplot. *Crop Science* 40, 597–605.

Yan W., Kang M.S., Ma B., Woods S., Cornelius P.L. (2007). GGE biplot vs. AMMI analysis of genotype-by-environment data. *Crop Science* 47, 643–655.