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Full Length Research Paper

Biplot analysis of grain yield in barley grown under differing management levels in years of contrasting season-end drought

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Variance analysis and graphical biplots were used to understand the nature of genotype × environment interaction (G × E) in a grain yield data set obtained from 39 barley (*Hordeum vulgare L.*) genotypes grown in 18 environments (a combination of three sowing dates, two crop protection treatments and three years) at Holetta, central highlands of Ethiopia. Genotype × year interaction was much more important than genotype × management interaction. Season-end drought was the environmental variable and time to maturity was the genotypic variable responsible for the high G × year interaction variance. An elite breeding line gave the highest mean yield and was the best under low but not under high season-end drought stress. Sasa, an early maturing landrace, was the best in a year of high season-end drought. Biplots enabled visual identification of compromise genotypes such as 3304 - 11 and 3381 - 04 that yielded reasonably well under both low and high season-end drought conditions. Selection for post-anthesis drought tolerance may result in high and stable yields across years and wider geographical adaptation in Ethiopian barley. The importance of unique landraces for stress situations is ascertained.

Key words: Barley landraces, genotype × environment interaction, GGE biplot, season-end drought, sowing date, insecticidal seed treatment, fungicidal disease control.

INTRODUCTION

Raising crop yield in subsistence rain fed farming systems in Ethiopian highlands is constrained by a host of problems including unpredictable weather, low use of chemical inputs and unavailability or poor adoption of improved varieties. Integration of genetic and management approaches that optimize yield under variable environmental conditions and resource endowments can enhance incomes and minimize risk.

In Ethiopia, climate trend analysis reveals increase in temperatures and reduction in rainfall and season length (IGAD, 2007). With climate change looming so large, crops face an array of biophysical challenges such as increased temperature, unpredictable moisture and increased disease and insect pest pressures (Tubiello et al., 2007). Crop production can be adapted to climate change through, *inter alia*, selection of appropriate genotypes in tandem with modulation of management practices to fit into the changing circumstances (Howden et al., 2007). However, little information is available on how crop varieties that differ in phenology and morphology interact with management practices and season under the increasingly unpredictable environment in Ethiopia.

Crop genotypes respond differently to environments giving rise to complex genotype-by-environment (GE or G × E) interaction. The environmental factors inducing the G × E interaction can arise from predictable or unpredictable variations in the form of location, management levels or years. Biplots have been used to visualize differential response of genotypes to environments and identify winning cultivars for target production environments (Kempton, 1984). Two contemporary GE interaction analysis tools that make use of biplots are additive main effect and multiplicative interaction (AMMI) and genotype main effect plus GE interaction (GGE)

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(Zobel et al., 1988; Yan et al., 2000).

Broadly, barley exhibits specific adaptation, therefore, GE interaction particularly in stress-prone environments (van Oosterom et al., 1993; Ceccarelli, 1994; Sinebo, 2005). Barley in Ethiopia is grown mainly as a low input staple food crop in the higher altitudes, on steep slopes, eroded lands or in moisture stress areas (Gebre and van Leur, 1996). Ethiopian barleys display specific adaptation to variable stresses such as low nitrogen and drought (Gróny, 2001; Sinebo, 2002) owing to the large diversity of agroecology including marginal environments apparent in the country.

In many barley growing parts of Ethiopia, rainfall is perhaps the single most important factor determining crop growing season length, cultivar choice and grain yield. Reportedly, farmers have increasingly opted to growing low yielding but early maturing varieties instead of long cycle high yielding varieties in response to a perceived shortening trend of crop growing season length (Yirga et al., 1998).

Change of sowing date can be used as an adaptive strategy to climate change-induced shortening of the season length. When the season is favorable, early sowing may allow longer crop growth duration leading to larger biomass accumulation perhaps resulting in greater economic yield. In some barley growing areas such as Holetta, the main season rain may arrive at about early June but barley is sown from about late June to late July leading to the loss of potential crop growth duration. Despite this, a few sowing date trials conducted on barley at Holetta, Ethiopia, failed to establish the superiority for grain yield of early sowing (Mola et al., 1996). However, these studies were conducted with released varieties that had not been selected for early sowing. In addition, high incidence and damage by scald disease [*Rhynchosporium secalis* (Oud.) Davis.] was observed with early sowing (Mola et al., 1996), but whether this disease was the major cause of low yields was not established. Furthermore, early sowing is known to dispose young seedlings to attack by insects particularly of barley shoot fly (*Delia arambourgi* (Seguy)). It was hypothesized that subjecting a large number of genotypes to varying sowing dates in the presence or absence of insecticidal seed treatment plus fungicidal disease control would lead to differential genotype grain yield response enabling the exploitation of specific adaptation to the management levels particularly sowing date. This, in the end, is hoped to increase crop growth duration, biomass accumulation and grain yield and minimize yield penalty arising from season-end moisture stress in intermediate to late maturing varieties.

The objectives of this study are (i) to assess patterns and causes of GE interaction for grain yield, and (ii) to examine the relative contribution of genotype × management and genotype × season interaction to GE in a data set generated from 39 barley genotypes grown under three sowing dates and two crop protection treatments over three years in the central highlands of Ethiopia.

MATERIALS AND METHODS

Site, design and treatments

Thirty-nine barley cultivars and experimental lines (referred hereafter as genotypes) representing different phenological and morphological groups sampled from field books of the barley breeding program at Holetta were tested in a factorial combination of three sowing dates and two crop protection treatments for three years (2002 - 2004) on a red brown clay (a Eutric Nitosol) at Holetta Agricultural Research Center (9°03'N, 38°31'E, elevation 2400 m), 28 km west of Addis Ababa, Ethiopia. The environment is seasonally humid with long term (1976 - 2005) average annual rainfall of 1055 mm, 85% of which is received between the months of June and Sept., and mean max. and min. temperatures of 22.2 and 6.1°C, respectively. The three sowing dates were early (at about the on-set of main season rain), normal (15 days after the on-set of main season rain), and late (15 days after the normal sowing date). The two crop protection treatments were insecticidal seed treatment plus fungicide application vs. no insecticide seed treatment plus no fungicide application. The genotypes included 13 improved released varieties, nine landrace cultivars grown in different parts of the country, four experimental lines developed from local crosses, three introduced experimental lines, and 10 experimental lines developed from landrace populations (Table 1).

The experiment was planted after Ethiopian mustard (*Brassica carinata* A. Braun) rotation in 2002, after faba bean (*Vicia fabaea* L.) rotation in 2003 and after potato (*Solanium tuberosum* L.) rotation in 2004. A split-plot design with a factorial combination of sowing dates and crop protection treatments in the main plots and the genotypes in the sub-plots in three replications was used. The sub-plots consisted two rows of 2.5 m length separated by a blank row. The details of sowing and fungicide application dates are given in Table 2. Crop protection treatment included absence or presence of seed treatment with Gaucho (Imidacloprid) 70% WS at a rate of 1 g product per kg seed followed by the foliar application of Propiconazole (1–[2–(2,4–dichlorophenyl)–4–propyl–1,3–dioxolan–2–yl–methyl]–1H–1,2,4–triazole; Ciba-geigy, Whittlesford, Cambridge) at a rate of 125 g a.i. ha^{-1} depending on the incidence of fungal diseases (Table 2). Fertilizer was drilled in rows and slightly incorporated with sticks after which seeds were drilled at a rate of 80 kg ha^{-1} as uniformly as possible and lightly covered by hand. The total plot area was harvested for yield determination.

Data were collected on grain yield, yield components, vegetative growth and growth durations. Vegetative shoot height, from the ground level to the tip of the shoot, was measured as a proxy for early vegetative vigor (Sinebo, 2002) on the dates and mean growing degree days (GDD) given in Table 2. Mature plant height was measured from the ground level to the tip of the spike excluding the awns after physiological maturity had been reached. Heading date was recorded as when the spikes of 50% of the culms in a plot had fully extruded out. Physiological maturity was recorded when the plants had almost lost their green color from both vegetative and reproductive tissues. Grain filling duration was calculated as a difference of time to heading and time to maturity. Scald, net blotch (*Helminthosporium teres* Sacc.) and spot blotch (*H. sativum* Pam., King and Bakke) diseases were scored on a 0 to 9 scale (Loegering, 1959). In this scale 0 indicates free from infection, 1 indicates resistant with few isolated lesions on lower most leaves, 5 indicates moderate susceptibility with severe infection of lower leaves and 9 high susceptibility with severe infection on all leaves. Likewise, leaf rust (*Puccinia hordei* Otth.) infection was scored on a similar scale but on percentage basis.

Variance analysis

Analysis of variance was carried out with PROC MIXED of the SAS

Table 1. The list of genotypes used in the study.

Variety	Code	Description	Origin†
208038-90	2038	Landrace line	N. Shewa /Bita Belew
1829-76	1829	Landrace line	W. Shewa /Ambo
3381-04	3381	Landrace line	Arsi /Digelu & Tijo
3304-11	3304	Landrace line	Arsi /Kofele
3371-18	3371	Landrace line	Arsi /Sude
Tolese S8.2H.2	th2	Landrace line	N. Shewa
Tolese S8.SP.1	ts1	Landrace line	N. Shewa
Tolese S8.B.7	tb7	Landrace line	N. Shewa
Baleme S1.2H.2	bh2	Landrace line	W. Shewa
Baleme S1.3H.1	bh1	Landrace line	W. Shewa
EH 1682/F7.1H	eh82	Akalase × IBON 93/91	HARC
EH 1642/F7.3H	eh42	Baleme × IBON 93/91	HARC
EH 1665/F7.1H.28.40.16	eh65	White barley (W. Shewa) × Composite 29	HARC
EH 1507	eh07	White Sasa × EH538/F2-12B ×× White Sasa × 3336-03	HARC
ARDU 12/60B	ard	Landrace line selection, released	Arsi
Beka	bka	Introduction, released	HARC
HB-42	hb42	Released, IAR/H/81 × Composite 29 ×× Composite 14/20 × Coast	HARC
Shege	shg	Landrace line selection, released	Arsi /Guna
HB-120	hb20	Released, EH11/F3.A.1.A.L × Beka	HARC
HB-1533	hb33	Released, B.F2 (S×W) × 3284-11	HARC
HB-52	hb52	Released, Compound 29 × Beka	HARC
Holkr	hkr	Released, Holetta Mixed × Kenya Research	HARC
Ahor 880/61	ahr	Introduction, released	HARC
IAR/H/485	iar	Landrace line selection, released	Arsi
Abay	aby	Landrace line selection, released	Arsi /Sude
Dimtu	dim	Landrace line selection, released	Arsi /Sude
Misratch	mis	Landrace line selection, released	Arsi
EMBSN 13/98	em13	Introduced breeding line	ICARDA
EMBSN 44/98	em44	Introduced breeding line	ICARDA
EMBSN 42/98	em42	Introduced breeding line	ICARDA
Semereta	sem	Landrace cultivar	Gojam, Shewa
White Sasa	sas	Landrace cultivar	Tigray
Ehilzer	ehil	Landrace cultivar	Wollo
Shasho	sho	Landrace cultivar	Bale
Black barley T.Inchini	bbti	Landrace cultivar	W. Shewa
Chare - Degem	cha	Landrace cultivar	N. Shewa
Ginbote	gin	Landrace cultivar	W. Shewa
Feresgama	fer	Landrace cultivar	N. Shewa
Baleme	bal	Landrace cultivar	W. Shewa

† N. = north, W. = west, HARC = Holetta Agricultural Research Center, ICARDA = International Center for Agricultural Research in the Dry Areas, HARC = Holetta Agricultural Research Center.

statistical package version 8.12 (SAS Institute INC, Cary, NC) using the following model:

$$T_{ijklm} = \mu + Y_l + S_m + C_k + G_i + R(Y)_{jl} + YS_{lm} + YC_{lk} + CS_{lm} + YSC_{lkm} + SCR(Y)_{jklm} + GY_{il} + GS_{im} + GC_{ik} + GYS_{ilm} + GYC_{ikl} + GSC_{ikm} + GYSC_{iklm} + e_{ijklm},$$

where T is the observation of the ith variety G in the lth year Y of the mth sowing date S and kth crop protection treatment C in the jth replication R within year l; µ is the general mean, e is the variation

Table 2. List of sowing and fungicide application dates by sowing date treatments and year.

Sowing date treatments	Year 2002	Year 2003	Year 2004	Mean (GDD)
		Sowing dates		
Early	17 June	16 June	14 June	
Normal	1 July	30 June	28 June	
Late	15 July	14 July	12 July	
		Fungicide application dates		
Early	2 Sept	18 Aug and 8 Sept	24 Aug	
Normal	23 Sept	28 Aug and 17 Sept	8 Sept	
Late	23 Sept	28 Aug and 17 Sept	21 Sept	
		Vegetative height measurement dates and growing degree days in brackets (base T° = 5°C)		**Mean (GDD)**
Early	22 July (370)	25 July (349)	23 July (372)	363
Normal	5 Aug (355)	11 Aug (370)	9 Aug (387)	371
Late	21 Aug (361)	22 Aug (360)	20 Aug (360)	360
Mean (GDD)	362	360	373	

due to random error or the residual, and *YS*, *YC*, *CS*, *YSC*, *GY*, *GS*, *GC*, *GYS*, *GYC*, *GSC*, *GYSC*, and S*CR*(*Y*) are the interactions. In the analysis, Y, S, C, and all possible interactions among these three factors were considered fixed, and all the remaining effects were considered random. Genotypes were considered as a random sample of germplasm handled by the breeding program at Holetta in order to be able to draw broad inferences on the patterns of response of the barley materials in the breeding program with respect to the management levels and the years tested. Incidentally, the test years were contrasting manifesting features apparent in short and long season barley growing ecologies of the country. As a result, years were considered fixed representing short cycle and long cycle barley growing locations of the country.

Genotype plus genotype × environment interaction (GGE) biplot analysis

For the GGE analysis, grain yields of the 39 genotypes in each of the 18 environments (3 years × 3 sowing dates × 2 crop protection treatments) were expressed as best linear unbiased predictions (BLUPs). Environment centered residuals were obtained as:

$$y_{ij} - \hat{y}_{\cdot j},$$

for the genotype *i* and environment *j* cell.

The residuals were subjected to singular value decomposition using the PROC IML in SAS. The resulting singular values for the first and second principal components were partitioned to the respective genotype and environment eigenvectors using a factor of 0.5 (symmetric scaling; Yan *et al*., 2000) as:

$$g_{il} = \lambda_l^{0.5}\xi_{il} \text{ and } e_{jl} = \lambda_l^{0.5}\eta_{jl}$$

where g_{il} and e_{jl} are PC *l* scores (*l* = 1 or 2) for genotype *i* and environment *j*, respectively. The resulting genotype and environment PC scores were plotted using Microsoft® Excel 2000 Software (Microsoft Corporation).

RESULTS

Weather

The main crop-growing season started between 6 and 8 June in the three years. There was a 7 to 9 days delay for the first sowing from the presumed sowing with the onset of rainfall. Rainfall for the crop growing months of June to September were nearly similar amounting 668, 656 and 672 mm for the years 2002, 2003 and 2004, respectively (Table 3). Nonetheless, year 2002 was the most stressful because of early cessation of rainfall. The last shower of rain in 2002 was a 5.3 mm rain received on the 22nd of September. Total rainfall for September was 77.4 mm in 2002, 107.4 mm in 2003 and 119.7 mm in 2004. Total rainfall for the month of October was 0 mm in 2002, 10 mm in 2003 (received on the 12th of October) and 3.6 mm in 2004 (received on three dates within the first week of October) (Table 3). There were three rainy days with a total fall of 22.5 mm during the last week of September in 2003. There was a single rainy day of 6.1 mm during the same period in 2004. Maximum temperature and sunshine hours were greater and relative humidity lesser in 2002 than in 2003 or 2004 for the grain filling months of September, October and November (Table 3). Pan evaporation measurements for the same months in 2002 were comparable with those in 2003 but were greater than those in 2004 (Table 3).

Analysis of variance

Significance of grain yield variances for the fixed effects

Table 3. Mean monthly rainfall, minimum and maximum temperatures, Mean pan evaporation, sunshine hours and relative humidity during the cropping months of June - November for the test years 2002 - 2004 at Holetta, Ethiopia.

Year	June	July	Aug	Sept	Oct	Nov	Total
			Rainfall (mm)				
2002	123.2	273.1	194	77.4	0	0	667.7
2003	117.1	194	237.2	107.4	10	0	665.7
2004	121.4	204	226.6	119.7	3.6	0.7	676
			Minimum (°C)				**Mean**
2002	8.0	9.1	8.3	6.8	4.2	2.4	6.5
2003	7.9	9.3	9.1	7.8	3.8	2.2	6.7
2004	8.1	8.7	8.7	7.7	4.3	2.5	6.7
			Maximum (°C)				**Mean**
2002	22.9	21.0	20.3	21.2	23.3	23.9	22.1
2003	21.6	18.1	18.7	19.8	22	22.4	20.4
2004	21.2	19.4	19.1	19.8	20.9	22.5	20.5
			Pan evaporation (mm)				
2002	3.79	2.95	2.86	3.56	5.19	5.71	4.0
2003	5.00	3.52	3.01	3.18	5.60	5.73	4.3
2004	4.17	3.56	3.22	2.84	3.87	4.23	3.6
			Sunshine hours				
2002	5.8	3.4	2.8	5.8	7.8	10.6	6.1
2003	4.3	2.0	1.9	3.3	8.2	8.9	4.8
2004	3.6	2.5	2.7	3.8	6.3	8.7	4.6
			Relative humidity (%)				
2002	54	72	80	68	45	39	59.5
2003	63	83	85	82	57	52	70.3
2004	67	75	76	74	59	51	67.0

is given in Table 4. Year (Y), sowing date (S), crop protection treatment (C), Y × S and Y × C effects were highly significant (Table 4). Grain yield was significantly lower in 2002 (244 g m^{-2}) than either in 2003 or 2004. Mean grain yield difference between the years 2003 and 2004 was not significant, averaging 457 g m^{-2}. Grain yield was significantly lower for early sowing (362 g m^{-2}) than for normal or late sowing dates (each averaged 399 g m^{-2}). Grain yield averaged 332 g m^{-2} without crop protection treatment and 441 g m^{-2} with crop protection treatment. Mean grain yields in individual environments ranged from 178 g m^{-2} to 555 g m^{-2} (data not shown) and mean genotype grain yield ranged from 323 g m^{-2} to 517 g m^{-2} (Table 5). Mean genotype days to heading ranged from 56 to 89 days and time to maturity from 112 to 135 days(Table 5). Mature plant height ranged from 75 to 123 cm (Table 5).

Variance component estimates for genotype and interaction of genotype with year, sowing date and crop protection treatment are given in Table 6. Only genotype × year and genotype × crop protection treatment interaction variances were significant ($P < 0.05$). Genotype × year interaction was by far the largest variance making up for 80% the total G × E variance. (Table 6) The sum of genotype × management interaction variance was only 20% of the total G × E variance estimate.

GGE biplots

In GGE biplot analysis, the first PC accounted for 68.3% and the second PC for 17.1% of the GGE sum of squares making up for 85.4% of the total variation contained in the GE grain yield matrix. Environments aggregated much more based on year than based on either sowing dates

Table 4. Significance of variances for year, sowing date, crop protection treatment and interaction among these factors for grain yield of 39 barley genotypes tested under three sowing dates and two crop protection treatments for three years at Holetta, Ethiopia.

Source	df†	F-value	Probability
Year (Y)	2 (8.75)	22.53	0.0004
Sowing date (S)	2 (37)	7.84	0.0015
Crop protection (C)	1 (44.6)	119.19	< 0.0001
Y × S	4 (31)	14.67	< 0.0001
Y × C	2 (32.2)	16.76	< 0.0001
S × C	2 (31.9)	0.03	0.9661
Y×S×C	4 (29.7)	2.65	0.0529

† Numerator df with the denominator df (in brackets) estimated using the DDFM=SATTERTH option in the model statement of the SAS mixed procedure.

Table 5. Genotype mean grain yield expressed as best linear unbiased predictions for 39 barley genotypes tested under three sowing dates and two crop protection treatments in 2002, 2003 and 2004 at Holetta, Ethiopia.

Genotype	YLD	STR	SPK	KPS	KWT	HI	VHT	HT	HED	DMT	GFD	FLY	SCD	NET	SPT	RUS
	---g m^{-2}---		----no.---		mg		---cm---		--------days--------			no.	------(0-9)------			%
gin	323	780	242	40	41	0.28	37	107	77	125	48	13.6	3.8	4.2	2.3	36
fer	333	679	275	31	42	0.33	43	105	62	114	51	9.0	4.7	3.3	2.3	9
ehil	334	632	299	35	37	0.35	40	99	63	112	49	11.2	5.3	3.8	2.3	13
3371	335	709	301	29	43	0.32	44	107	62	113	51	7.4	4.2	2.5	1.4	8
em13	343	441	267	41	38	0.44	38	75	56	114	58	12.8	4.1	2.0	1.3	1
bal	344	1124	297	24	53	0.24	39	116	81	126	45	11.9	3.2	4.2	3.1	11
sem	345	975	306	28	46	0.27	38	111	78	124	46	10.6	2.6	3.9	2.8	19
bh2	346	1001	310	23	53	0.26	39	118	80	125	45	12.1	3.1	4.5	3.3	10
bh1	355	1111	307	25	52	0.25	39	119	82	125	43	10.3	3.1	4.4	3.0	15
1829	357	1222	315	22	57	0.23	42	123	81	126	45	9.0	3.1	3.7	2.7	11
em44	358	526	238	48	41	0.40	33	96	64	119	55	14.4	5.2	2.4	1.3	1
2038	361	792	281	32	45	0.32	40	108	73	118	46	7.6	2.8	3.5	2.2	25
tb7	364	788	255	39	48	0.32	39	108	72	125	53	10.3	2.4	3.2	2.5	16
sho	368	712	266	32	46	0.34	42	111	66	116	50	10.5	4.1	2.6	1.4	8
eh65	369	686	259	41	47	0.36	35	102	67	120	53	10.2	3.0	3.0	2.3	20
bbti	372	990	278	39	46	0.27	40	119	77	125	48	10.5	4.3	4.3	3.1	17
aby	372	856	287	48	37	0.31	37	111	72	120	47	9.3	4.3	3.0	1.9	4
cha	373	1017	309	24	51	0.27	39	114	77	124	47	9.8	3.4	4.0	3.0	16
eh07	381	1012	291	29	51	0.27	35	118	80	127	47	12.4	2.0	2.2	3.1	3
ahr	384	812	209	54	46	0.30	28	107	89	135	46	12.5	1.4	2.1	3.1	1
hb52	390	858	302	28	45	0.32	33	115	76	125	49	16.4	1.3	1.1	1.0	8
eh82	390	426	227	46	40	0.47	31	80	62	118	56	14.9	2.8	2.4	2.2	2
ard	390	959	266	45	43	0.29	39	115	82	126	45	10.5	4.0	4.2	2.7	8
hkr	392	749	299	26	49	0.34	34	100	76	124	49	13.7	2.3	2.3	1.6	4
hb42	393	861	240	44	49	0.31	35	115	82	128	47	11.7	2.4	3.2	2.3	5
th2	394	823	278	36	46	0.32	41	112	69	122	52	10.8	3.6	4.1	2.9	23
ts1	399	993	272	47	43	0.29	41	112	82	124	42	9.0	1.7	2.4	2.3	35
sas	401	627	316	24	49	0.39	44	94	60	112	52	9.8	5.1	2.6	1.5	6
bka	409	1004	315	28	43	0.29	36	115	77	126	49	14.3	1.6	1.3	1.5	10
em42	411	538	248	49	41	0.43	33	89	65	121	57	15.5	1.7	1.5	1.5	1
mis	416	755	287	44	41	0.36	41	104	68	117	49	9.6	4.0	3.3	1.9	19
hb33	418	1233	313	27	50	0.25	38	123	82	126	45	10.5	1.2	1.6	2.1	5

Table 5. Cont'd

shg	418	811	258	47	45	0.34	33	107	78	126	47	10.6	2.5	2.8	2.2	6
3381	421	725	272	46	42	0.38	40	103	68	117	49	11.5	3.4	2.9	1.9	21
hb20	423	961	324	28	45	0.31	34	116	76	126	50	13.8	1.0	1.2	1.4	11
iar	436	980	288	46	43	0.31	34	116	82	129	47	13.2	1.7	2.5	2.5	16
3304	440	762	286	43	43	0.38	40	104	68	116	48	12.1	3.7	3.2	1.9	15
dim	490	1124	307	40	47	0.31	41	120	80	126	46	8.0	3.2	3.2	2.8	9
eh42	517	991	336	27	56	0.34	38	107	78	128	50	11.8	2.0	1.8	2.1	23
SE (±)	18	33	11	1	0.9	0.01	0.4	2	0.4	0.6	0.6	0.8	0.2	0.2	0.3	2.1

YLD = grain yield; STR = straw yield; SPK = spike per square meter; KPS = kernels per spike; KWT = kernel weight; HI = harvest index; VHT = vegetative shoot height; HT = mature plant height; HED days to heading; FLY = number of seedlings attacked by shoot fly per unit area; DMT = days to maturity; GFD = grain filling duration; PHI = phase index; SCD = scald disease score; NET = net blotch disease score; SPT = spot blotch disease score; RUS = rust disease score.

Table 6. Variance components for genotype and interaction of genotype with year, sowing date and crop protection treatment for 39 barley genotypes tested at three sowing dates and two crop protection treatments for three years at Holetta, Ethiopia.

Variance Component	Estimate	Z value	Probability	% G × E variance
Genotype (G)	36.09	0.07	0.4737	
G × Year (Y)	4436.95	5.35	< 0.0001	80.4
G × Sowing date (S)	141.65	0.83	0.2038	2.6
G × Crop protection (C)	399.43	1.86	0.0314	7.2
G×Y×S	133.5	0.56	0.2887	2.4
G×Y×C	208.37	0.97	0.1663	3.8
G×S×C	180.25	0.85	0.1966	3.3
G×Y×S×C	20.73	0.06	0.4757	0.4
Residual	8388.39			

or crop protection treatments. In the biplot, the vertex genotypes were *eh42*, *dim*, *sas*, *3371*, *fer*, *gin* and *ahr* (Figure 1). According to Yan et al. (2000), these vertex genotypes are either universal winners or universal losers in environments towards which they project the most. For instance, *eh42* is the vertex genotype in the sector in which the 2003 and 2004 environments are located. Hence this genotype is the winner in all the management-year combination of environments that involve the highest yielding years of 2003 and 2004. The genotype *sas* projected the most and is the vertex genotype in year-management combinations that involve the most stressful year of 2002. Hence this genotype was the highest yielding in this set of environments. *Fer*, *gin* and *ahr*, although are vertex genotypes, did not project to sectors were any of the environments are located and are, therefore, universal losers. What is also interesting in this biplot is the possibility of selecting genotypes that give one of the highest yields under high yielding conditions such as those in the years 2003 and 2004 but at the same time giving better yields under stress conditions than any other high yielding genotype. For instance, if high yielding years are more common in a given location while there are some occurrences of low yielding years and farmers are risk-averse, recommending cultivars such as *dim* may be more appropriate than opting for cultivars such as *eh42*. On the other hand, in areas where the probability of short seasons are high, but the occurrence of extended season are also somewhat common, farmers may opt for growing cultivars such as *mis*, *3304* or *3381* for high yields under stressful conditions while also harvesting substantial yields under high yielding non-stressful conditions. But in areas where seasons are short and season-end moisture stress is most likely, the ultimate choice is a cultivar such as *sas*. The two rays at the top of Figure 1 indicate the direction for choosing varieties with increasing (right to left) and decreasing (left to right) intensity of stress. Genotypes such as *ahr* have negative response to stress environments.

Figure 2 depicts the mean vs. stability view of the GGE biplot (Yan, 2001). *Eh42* and *dim* are the most yielding with *eh42* more yielding than *dim* but *dim* being more stable than *eh42*. Genotypes such as *3304*, *mis*, *3381* and *sas* were the best under stress conditions but also responsive to high yielding conditions. *Dim* was the

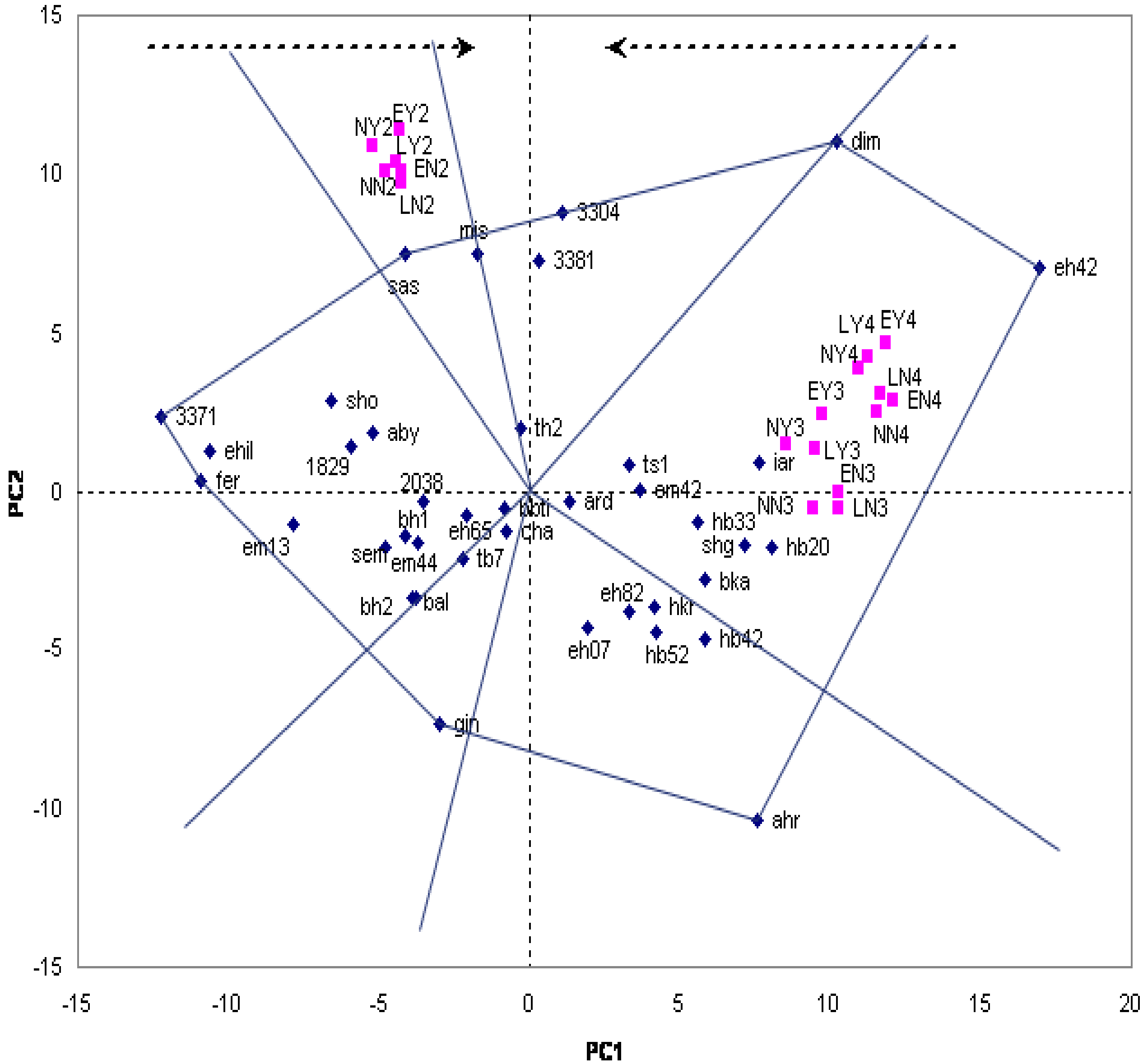

Figure 1. GGE biplot of the first and the second principal components resulting from singular value decomposition of environment centered grain yield expressed as best linear unbiased predictions for 39 genotypes grown in 18 environments at Holetta, Ethiopia.

second best under high yielding conditions but better than other high yielding genotypes in stress environ-ments. In general, each of the four sectors partitioned by the average environment coordinate (AEC)-c and AEC-y axis has unique distinguishing features (Figure 2). The first sector encompasses stress environments and stress tolerant genotypes such as *3304*, *mis*, *3381* and *sas* which also responded to high yielding conditions. Note the positive score for these genotypes on both AEC-c and AEC-y axis.

The second sector includes high yielding environments and genotypes with high yields in these environments as typified by *eh42*, *iar*, *hb20*, etc. The third sector includes genotypes such as *3371*, *ehil*, *fer*, *em13*, *sho*, etc. that did well under high stress condition but that did not respond to high yielding condition. The fourth sector encompasses genotypes such as *ahr* and *gin* which were relatively inferior under both high and low yielding conditions (Figure 2).

Genotypes such as *ahr* and *3371*, which lie furthest away from the center when projected perpendicular to the AEC-y axis, changed ranks the most and, therefore, were the most unstable (Yan et al., 2007). However, if stability is defined as risk reduction through ensuring a minimum yield level as is common in subsistence agriculture, stability of the genotypes decrease as one goes from left

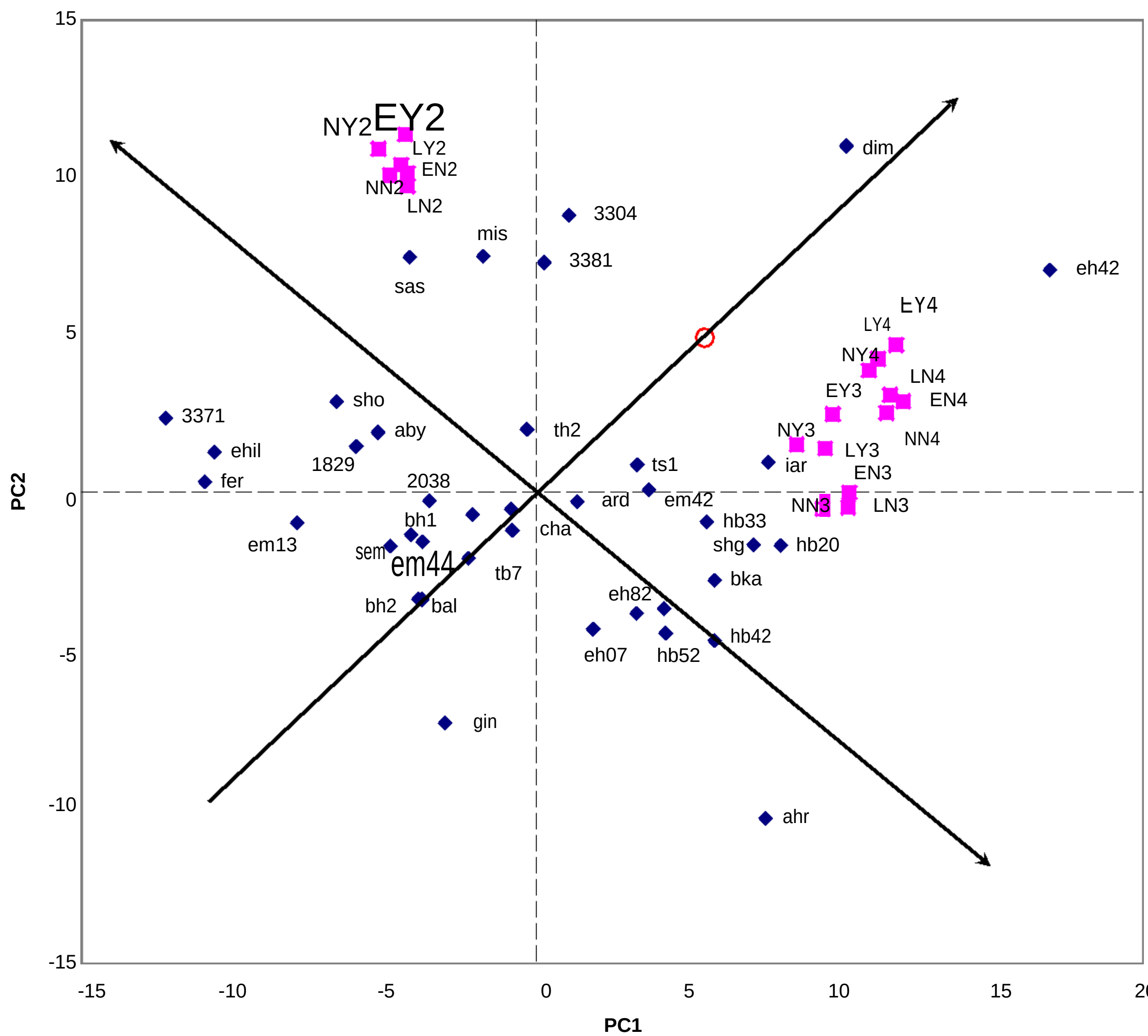

Figure 2. Mean yield vs. stability view of a GGE biplot resulting from singular value decomposition of environment centered grain yield expressed as best linear unbiased predictions for 39 genotypes grown in 18 environments at Holetta, Ethiopia.

to right along the AEC y-axis (Figure 2). This can be confirmed by the generally low regression coefficients for genotypes such as *3371*, *ehil*, *fer, sas*, *mis*, etc. and high regression coefficients for genotypes such as *eh42*, *ahr*, *iar*, etc. (Data not shown).

Correlation of PC scores with genotypic and environmental variables

The relationship among environmental PC scores, grain yield and some environmental variables are given in Table 7. Table 8 presents correlation coefficients among genotypic PC scores and genotypic variables. Environmental mean grain yield was highly positively correlated with PC1 score. Environmental PC2 score was highly negatively correlated with environmental mean grain yield and environmental PC1 score (Table 7). Environmental mean grain yield was highly negatively correlated with mean maximum temperature and sunshine hours measured during the vegetative stage and with maximum temperature measured during the grain filling stage. Environmental mean grain yield was positively correlated with relative humidity measured during grain filling period (Table 7).

The correlations of PC1 with environmental variables follow those of the correlations of environmental mean grain yield with environmental variables. Environmental

Table 7. Correlation coefficients between principal components for environments, environmental mean grain yield (YLD), and environmental variables.

Parameters	YLD	PC1	PC2
PC1	0.79***		
PC2	-0.68**	-0.91***	
		During vegetative period	
Heat units	-0.77***	-0.62**	0.66**
Rainfall	-0.42	-0.30	0.28
Minimum temperature	0.21	0.39	-0.52*
Maximum temperature	-0.77***	-0.87***	0.96***
Sunshine hours	-0.74***	-0.89***	0.95***
Relative humidity	0.42	0.42	-0.72***
Pan evaporation	0.54*	0.73***	-0.56*
		During grain filling period	
Heat units	0.34	0.37	-0.45
Rainfall	0.25	0.42	-0.28
Minimum temperature	0.01	0.20	0.06
Maximum temperature	-0.64**	-0.86***	0.62**
Sunshine hours	-0.33	-0.55*	0.25
Relative humidity	0.56*	0.77***	-0.64**
Pan evaporation	-0.26	-0.44	0.06

*, ** and *** indicate significance at $P \leq 0.05$, $P \leq 0.01$ and $P \leq 0.001$, respectively.

PC2 score, a measure of performance under high stress condition, was highly positively correlated with maximum temperature of both vegetative and grain filling stages and with sunshine hours of vegetative period. Environmental PC2 score was also negatively correlated with relative humidity of both periods and with minimum temperature and pan evaporation of vegetative period (Table 7).

Mean genotype grain yield was highly positively correlated with each of genotypic PC1 and PC2 scores (Table 8). Mean genotype grain yields under high season-end stress (year 2002) was negatively correlated with PC1 score and positively correlated with PC2 score (Table 8). Mean genotype yields under low season-end stress (years 2003 and 2004) was positively correlated with PC1 score.

Overall mean genotype grain yield was highly positively correlated with mean genotype grain yield under low stress but not with mean genotype grain yield under high stress (Table 8). Genotypic PC1 score was positively correlated with time to heading and time to maturity and with the number of seedlings damaged by shoot fly but negatively correlated with vegetative vigor and scald and net blotch diseases score (Table 8). Genotypic PC2 score was positively correlated with the number of spikes per square meter, vegetative vigor and scald disease score.

Correlation among environmental mean grain yields

Correlation coefficients among environmental mean grain yields (data not shown) revealed relationships that were also apparent from GGE biplot. Mean grain yields in individual environments within the same year were highly positively correlated. Grain yields in each of the 2002 environments were negatively correlated with environmental mean grain yields in the 2003 and 2004 environments. Mean grain yields in individual environments in the year 2003 and 2004 were highly positively correlated. This and observations in the biplots (Figures 1 and 2) imply a crossover interaction between the high yielding low stress years (2003 and 2004) and low yielding high stress year (2002).

Mean genotype grain yield and other trait relationships

Mean genotype grain yield was correlated with scald and net blotch diseases score only (Table 8). However, splitting overall mean genotype grain yield into mean

Table 8. Correlation among genotype principal component scores, grain and straw yields, grain yield under high stress, grain yield under low stress, yield components, growth durations and disease and insect pest data for 39 barley genotypes grown in 18 environments at Holetta, Ethiopia.

Trait	PC1†	PC2	YLD	YST	YNST	STR	SPK	KPS	KWT	HI	VHT	HT	HED	FLY	DMT	GFD	SCD	NET	SPT
PC2	0.00																		
YLD	0.84***z	0.53***																	
YST	-0.52***	0.84***	0.02																
YNST	0.99***	0.14	0.91***	-0.39*															
STR	0.31	-0.01	0.22	-0.21	0.29														
SPK	0.04	0.41**	0.24	0.33*	0.09	0.56***													
KPS	0.20	0.00	0.18	-0.1	0.2	-0.45**	-0.78***												
KWT	0.26	-0.06	0.16	-0.19	0.23	0.66***	0.44**	-0.63***											
HI	-0.01	0.27	0.18	0.27	0.05	-0.89***	-0.42**	0.47**	-0.57***										
VHT	-0.55***	0.63***	-0.16	0.78***	-0.45**	0.16	0.46**	-0.39*	0.10	-0.19									
HT	0.20	-0.05	0.11	-0.17	0.17	0.91***	0.44**	-0.38*	0.56***	-0.91***	0.19								
HED	0.54***	-0.36*	0.22	-0.62***	0.46**	0.82***	0.14	-0.10	0.55***	-0.78***	-0.29	0.77***							
FLY	0.36*	-0.45**	0.10	-0.54***	0.31	-0.28	-0.23	0.14	-0.16	0.31	-0.72***	-0.31	0.00						
DMT	0.68***	-0.48**	0.30	-0.78***	0.59***	0.65***	-0.03	0.03	0.51***	-0.58***	-0.54***	0.58***	0.92***	0.25					
GFD	-0.16	0.08	-0.05	0.17	-0.11	-0.82***	-0.34*	0.25	-0.44**	0.83***	-0.16	-0.80***	-0.81***	0.36*	-0.52***				
SCD	-0.72***	0.37*	-0.42**	0.67***	-0.66***	-0.41**	-0.08	0.05	-0.32*	0.25	0.55***	-0.31	-0.60***	-0.37*	-0.71***	0.26			
NET	-0.47**	0.05	-0.43**	0.22	-0.48**	0.22	-0.01	-0.11	0.19	-0.38*	0.46**	0.26	0.13	-0.47**	-0.06	-0.37*	0.53***		
SPT	0.01	-0.20	-0.14	-0.23	-0.02	0.54***	-0.01	-0.08	0.46**	-0.59***	0.09	0.48**	0.58***	-0.32*	0.48**	-0.55***	-0.03	0.70***	
RUS	0.00	0.19	0.03	0.08	-0.01	0.22	0.13	-0.02	0.04	-0.26	0.38*	0.24	0.16	-0.30	0.03	-0.31	-0.01	0.38*	0.24

† PC = principal component; YLD = grain yield; YST = grain yield with high stress; YNST = grain yield with low stress; STR = straw yield; SPK = spike per square meter; KPS = kernels per spike; KWT = kernel weight; HI = harvest index; VHT = vegetative shoot height; HT = mature plant height; HED = days to heading; FLY = number of seedlings attacked by shoot fly per unit area; DMT = days to maturity; GFD = grain filling duration; PHI = phase index; SCD = scald disease score; NET = net blotch disease score; SPT = spot blotch disease score; RUS = rust disease score.
*, ** and *** indicate significance at $P \leq 0.05$, $P \leq 0.01$ and $P \leq 0.001$, respectively.

genotype yield under low stress and mean genotype yield under high stress revealed a different pattern (Table 8). Mean genotype yield under high stress was positively correlated with the number of spikes per square meter, early shoot vigor and scald score but negatively correlated with both days to heading and maturity, and with the number of shoots damaged by shoot fly. Mean genotype grain yield under low stress was negatively correlated with early shoot vigor and scald and net blotch diseases score but positively correlated with both days to heading and maturity (Table 8).

DISCUSSION

Nature and causes of G × E interaction

The negative correlations among some groups of environments, the different signs for environmental PC1 scores and the large angle between the environments in the biplot (Figures 1 and 2) indicate that the GE interaction was because of rank changes rather than scale effects (Yan et al., 2000; Dehghani et al., 2006). In this study, year effect was the largest source of environmental variance and the GY interaction effect the largest contributor to GE interaction variance. However, the total rainfall amounts during the crop growing period in the three years were similar. Therefore, the major cause of grain yield differences among the years and the underlying cause for the significant GY interaction for grain yield was the variability among the years in the degree of season-end moisture stress (Table 3). This indicates that a slight deviation of rainfall towards season-end would cause a large sway in yield and a large crossover type of GY interaction. In this study, the G × management interaction component as a whole was small relative to GY interaction component. The large GY interaction indicates the greater importance of working to stabilize performance of genotypes across years than across management levels. Of the G × management interaction components, the GS was impor-tant only in stress years such as the year 2002. This may indicate lack of advantage from early sowing of late maturing genotypes in years of low season-end moisture stress.

The environmental and genotypic causes of the GE interaction can be visualized by relating information on environmental variables and PC scores in Table 7 with the corresponding information on genotypic variables and PC scores in Table 8.

Environmental (Table 7) and also genotypic (Table 8) mean yield were positively associated with PC1 scores indicating PC1 to be a measure of overall mean yield to some extent. As the association of both yield and PC1 scores with environmental variables indicates (Table 7), environments with high yield had lower daytime temperature, lesser sunshine hours and higher humidity. By inference, these environments tend to be cooler, cloudier and wetter (Table 3). High yielding genotypes in these environments had high PC1 score and more likely high overall yield.

On average, these genotypes had slower early vegetative shoot height growth, longer growth duration, higher shoot fly damage and lower incidence of scald and net blotch diseases (Table 8). These genotypes, as depicted by strong positive association of PC1 score with grain yield under low stress and strong negative association between PC1 score with grain yield under high stress (Table 8), are suitable for low but not high season-end moisture stress environments.

In barley grown in moisture stress environments, early vigor is associated with early heading. These early maturing genotypes when grown under low stress environments exhibit higher incidence of scald and net blotch diseases but lower shoot fly damage. PC2 was negatively associated with night temperature and relative humidity and positively associated with daytime temperature and sunshine hours.

In the highlands of Ethiopia, nights are increasingly cooler, days hotter and relative humidity lower as the rain recedes and the weather gets drier towards season-end. Environments with such features and genotypes that do well in these environments had large PC2 score (Figure 1). PC2 score was positively associated with vegetative shoot height but negatively associated with time to heading and time-to-maturity (Table 8). In effect, time to maturity and moisture status during the critical period of grain filling was the major factors contributing to the observed GE interaction.

Beyond a unique winning genotype

From the present study, it is evident that improved varieties selected for high mean yield were beaten by early maturing landraces in years of season end-moisture stress. This confirms rational choice by risk-averse subsistence farmers in preferring relatively low yielding early maturing varieties to high yielding late maturing varieties in order to minimize risk in bad years rather than maximize average production over the years. Because of this, in subsistence agriculture with a fairly unpredictable weather, a crop breeding program is tasked with providing options in the form of more than one “winning” genotypes rather than a unique winning genotype (for each mega-environment) – for instance, one genotype for risk taking farmers whose goal is high yield and another for risk averse farmers whose goal is to ensure harvest stability year after year.

A feature of merit with the present GGE analysis is the possibility for spotting in the biplot of genotypes that may not be winners in any of the mega-environments but that are appealing to farmers that want to trade certain level of risk-taking for some degree of yield reward. In our case, such genotypes that could easily be spotted from the GGE biplot are *3304*, *3381* and *mis* (Figure 1). These same genotypes could as well be grown in a barley production system where the season length allows late maturing barley variety but food shortages towards season-end necessitates leveraging the need for high yield with the requirement for earliness.

In Ethiopia, despite the diversity of barley growing agro-ecologies and availability of some multi-location variety trial data, no comprehensive assessment of G × location interaction has been reported. In this study, our familiarity with barley growing agroecologies in the country and our insights into cultivars with unique adaptations in contrasting agroecologies offered us an opportunity to infer the likely pattern of G × location interaction from G × Y interaction. The longer growing season with a relatively better season-end moisture regime observed in 2003 and 2004 is typical of the central, southeastern and north-western barley growing highlands whereas the shorter growing season with a high season-end moisture stress of the year 2002 is usually representative of the North-eastern and Northern highlands, namely Wollo and Tigray. In this study, the year with greater season-end moisture stress amplified the relative merits of early maturing varieties including prominent landrace varieties such as *sasa* that are adapted to short season drought prone highlands of northern Ethiopia, notably the Tigray region. Barely variety selections made for high yield in relatively high rainfall areas of central Ethiopia have yielded less than local landraces in Tigray (Abay and Bjørnstad, 2008).

Bearing in mind the unpredictable weather and the changing climate, be it the low rainfall areas of northern Ethiopia or the relatively better rainfall regimes of Central

Ethiopia, barley varieties that make best use of environmental resources and give high yield in favorable years while tolerating yield reductions in years of season-end drought are required. To this end, a still pending question is how to combine high yielding ability in favorable years with relative yield stability in years of early cessation of rainfall. One approach is breeding for post-anthesis drought tolerance while maintaining or even improving yielding abilities under favorable environments.

In the GGE biplot, genotypes that did well under high stress conditions were located further along the AEC y-axis (Figure 2) indicating their greater instability relative to many genotypes in the study. It is important to note that the AEC y-axis measures rank stability (Yan et al., 2007) rather than yield stability. In subsistence agri-culture, perhaps stability of yields is more important than stability of ranks. In the future, the analysis of multi-environment yield data for risk-averse subsistence farming needs to closely examine the relevance of rank stability vis-à-vis absolute yield stability.

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