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Durum wheat quality in Mediterranean environments III. Stability and comparative methods in analysing G × E interaction

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Abstract

Stability of grain quality characteristics is an interesting feature of today's durum wheat breeding programmes, due to the high annual variation in both grain yield and quality, particularly in the Mediterranean area. Ten field trials were carried out during two seasons (1998 and 1999) in both the north (Lleida) and south (Granada and Jerez) of Spain. Ten durum wheat genotypes were used, including four Spanish commercial varieties and six advanced lines from the durum wheat breeding programme of CIMMYT-ICARDA. Many quality parameters were evaluated in this study including thousand kernel weight, test weight, vitreousness, ash content, protein content, pigment content and the SDS sedimentation test. Several statistical methods and techniques were used to describe the genotype × environment (G × E) interaction and to define stable genotypes in relation to the seven quality parameters considered in this study. The partition and interpretation of the G × E interaction revealed that the joint regression analysis was not efficient and demonstrated the usefulness of AMMI for describing the interaction patterns. The study of genotypic stability demonstrated that the Spanish commercial varieties, Altar-aos and Jabato and the CIMMYT-ICARDA advanced line, Waha, had high stability for quality characteristics and proved to be the best within the pool of the studied genotypes.

Keywords: G × E interaction; Stability; Quality; Durum wheat

1. Introduction

Stability of quality parameters is becoming an important requirement for the milling and pasta industries, because of potentially high annual variation in both grain yield and quality, particularly under Mediterranean conditions. For this reason, a high stability of raw material quality, as defined by Robert and Denis (1996), is a desirable feature, since it guarantees constant procedures and low product loss during processing (Grausgruber et al., 2000). However, economic instability, as defined by the end-users, is commonly caused by both environment and genotype × environment (G × E) interaction effects. Among the environmental factors, high temperatures and humidity during grain filling (Jenner, 1991; Blumenthal et al., 1993), distribution of precipitation (Campbell et al., 1981) and nitrogen fertilisation (Rao

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et al., 1993) exert the most significance influence on wheat grain quality.

Some authors indicated that quality parameters follow a static concept of stability, meaning that a stable genotype is defined as one having an unchanged performance regardless of any variation in environmental conditions (Becker and Léon, 1988). Peterson et al. (1992) reported that the concept of optimal genotype stability and response for quality parameters differs somewhat from that conventionally used to describe yield stability. For breeders, stability of quality attributes is important in terms of changing ranks of genotypes across environments and affects selection efficiency. For end-users, such as millers and bakers, consistency in quality characteristics of cultivars is very important, regardless of changing cultivar ranks. However, as mentioned by Grausgruber et al. (2000), the quality of a genotype usually reacts like other quantitative characters to favourable or unfavourable environmental conditions. A genotype is therefore considered to be economically stable if its contribution to the $G \times E$ interaction is low.

Several statistical methods have been proposed for analysis stability with the aim of explaining the information contained in the $G \times E$ interaction data matrix. These range from univariate parametric, such as regression slope (Finlay and Wilkinson, 1963), deviation from regression (Eberhart and Russell, 1966) and environmental variance, to multivariate methods (e.g. AMMI analysis introduced by Zobel et al., 1988). The study of genotypes according to their slope through joint regression analysis provides information on both stability and adaptation. This stability can also be evaluated by AMMI analysis, which extracts genotype and environment main effects and uses principal component axes (PCA) to explain patterns in the $G \times E$ interaction or residual matrix (Romagosa and Fox, 1993). These two statistical methods can be used to evaluate stability after reduction of noise from the interaction effects. Stability can also be measured across all interaction effects, as devised by Shukla's (1972) σ^2 and the environmental variance statistics. Any of these two measures may be of interest for breeding programmes as an alternative to the regression statistic, given their greater simplicity of computation as compared with the AMMI method.

The objectives of this study were to (i) evaluate the efficiency of joint regression and AMMI analyses in describing $G \times E$ interaction patterns and (ii) highlight stable entries within the genotypic pool used in this study.

2. Material and methods

2.1. Field experiments and methodology

The genetic material and different field experiment details are described in the first paper of this series (Rharrabti et al., 2003) and are summarised here: 10 field trials were carried out during two seasons (1998 and 1999) in both the north (Lleida) and the south (Granada and Jerez) of Spain. In Lleida and Granada, the experiments were conducted both under irrigated and rainfed conditions, whereas the Jerez trials were carried out only under rainfed conditions. Ten durum wheat genotypes were used, including four Spanish commercial varieties and six advanced lines from the durum wheat breeding programme of CIMMYT-ICARDA. Genotypes were sown in a randomised complete block design with four replications. Seed rate was adjusted for a density of 350 seeds m^{-2} in Granada and Jerez and 550 seeds m^{-2} in Lleida. Plot size was 12 m^2 (six rows, 20 cm apart).

Quality determinations consisted of the following parameters: thousand kernel weight (TKW), test weight, vitreousness, ash content, protein content, pigment content and SDS volume.

2.2. Statistical analysis

Several statistical methods and techniques were used both to describe $G \times E$ interaction and to define stable genotypes regarding the seven quality parameters considered in this work.

Joint regression analysis was performed according to Finlay and Wilkinson (1963) and the slope value (*b*) was determined for each quality parameter. Deviation from regression (S^2_{di}) for each genotype was also calculated (Eberhart and Russell, 1966). Additive main effects and multiplicative interaction (AMMI) analysis was also performed as described in Zobel et al. (1988). From this analysis, the distance of each genotype from the origin v_i defined by the first two PCA was used as a stability parameter (Grausgruber et al., 2000). Shukla stability variance (Shukla, 1972), σ^2 and the environmental variance, S^2_{xi}, were used also as stability parameters.

Table 1
Partition of sum of squares and mean squares from the joint regression analysis of 10 durum wheat genotypes grown in different zones in Spain (Lleida, Granada and Jerez) during two growing seasons (1998 and 1999)

Source of variation[a]	d.f.	TKW[b]		Test weight		Vitreousness		Ash content		d.f.	Protein content		Pigment content		SDS volume	
		SS[c]	MS[d]	SS	MS	SS	MS	SS	MS		SS	MS	SS	MS	SS	MS
Environment	9	15869.6	1763.3***	1552.1	172.5***	4239.7	471.1***	61.7	6.86***	9	503.2	55.9***	28.1	3.13***	271.1	30.1***
Genotype	9	3405.3	378.4***	422.2	46.9***	396.7	44.1**	1.1	0.12***	9	58.4	6.5***	62.7	6.97***	244.4	27.2***
Block (E)	30	375.7	12.5	95.0	3.2	176.1	5.9	1.6	0.05*	10	31.3	3.1*	1.1	0.11	4.4	0.4
G × E	81	2242.4	27.7***	357.6	4.4***	2064.8	25.5***	5.7	0.07***	81	128.1	1.6	35.9	0.44***	84.5	1.0***
Regression	9	270.2	30.0	112.0	12.4***	214.2	23.8	1.5	0.17***	9	26.4	2.9***	4.0	0.44	28.8	3.2***
Residual	72	1972.2	27.4***	245.6	3.4***	1850.6	25.7***	4.2	0.06***	72	75.3	1.0	31.9	0.44***	55.7	0.8***
Error	270	2644.1	9.9	567.7	2.1	1211.6	4.5	8.8	0.03	90	136.1	1.5	12.8	0.14	38.5	0.4
Total	399	24486.9		2996.7		8089.0		78.8		199	862.1		140.7		643.0	

[a] E: environment, G: genotype.
[b] TKW: thousand kernel weight.
[c] Sum of squares.
[d] Mean squares.
* Significant at 0.05 probability level.
** Significant at 0.01 probability level.
*** Significant at 0.001 probability level.

Table 2
Partition of sum of squares and mean squares from the AMMI of 10 durum wheat genotypes grown in different zones in Spain (Lleida, Granada and Jerez) during two growing seasons (1998 and 1999)

Source of variation[a]	d.f.	TKW[b]		Test weight		Vitreousness		Ash content		d.f.	Protein content		Pigment content		SDS volume	
		SS[c]	MS[d]	SS	MS	SS	MS	SS	MS		SS	MS	SS	MS	SS	MS
Environment	9	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0
Genotype	9	164.9	18.3***	137.8	15.3***	43.8	4.9***	26.5	2.9***	9	33.9	3.8***	112.5	12.5***	132.2	14.7***
Block (E)	30	21.3	0.7***	30.6	1.0***	27.8	0.9*	56.3	1.9***	10	13.5	1.3	2.2	0.2	3.0	0.3
G × E	81	113.5	1.4***	88.5	1.1***	152.3	1.9***	125.5	1.5***	81	66.5	0.8	52.2	0.6***	27.5	0.3
PCA 1	17	49.4	2.9***	34.1	2.0***	47.8	2.8***	38.0	2.2***	17	26.3	1.6	22.0	1.3***	11.3	0.7**
PCA 2	15	29.6	2.0***	19.5	1.3***	39.3	2.6***	29.5	2.0***	15	16.2	1.1	10.8	0.7***	5.9	0.4
PCA 3	13	15.0	1.2***	14.6	1.1**	31.2	2.4***	22.7	1.7***	13	9.6	0.7	7.1	0.6*	4.1	0.3
PCA 4	11	9.8	0.9***	10.3	0.9	14.2	1.3*	14.8	1.3	11	6.8	0.6	5.5	0.5*	2.9	0.3
Residual	25	9.7	0.4	10.0	0.4	19.8	0.8	20.5	0.8	25	7.6	0.3	6.0	0.2	3.3	0.1
Error	270	88.3	0.3	132.1	0.5	166.1	0.6	176.7	0.7	90	74.2	0.8	23.0	0.3	27.4	0.3
Total	399	388.0		389.0		390.0		385.0		199	188.0		188.0		190.0	

[a] E: environment, G: genotype.
[b] Thousand kernel weight.
[c] Sum of squares.
[d] Mean squares.
* Significant at 0.05 probability level.
** Significant at 0.01 probability level.
*** Significant at 0.001 probability level.

Table 3
Stability parameters for the considered quality traits[a]

	b[b]	S^2_{di}[c]	σ^2_i[c]	S^2_{xi}[d]	v_i[d]
TKW					
Altar-aos	*1.02*	*2.63*	*3.48*	*48.03*	*0.68*
Awalbit	0.74	8.13	11.72	*31.18*	1.23
Jabato	*1.07*	7.40	*7.30*	56.40	*0.51*
Korifla	*1.08*	6.52	*5.00*	56.94	0.79
Lagost-3	*1.02*	14.78	12.85	58.91	*0.60*
Mexa	1.12	5.14	*4.51*	59.55	0.87
Omrabi-3	0.88	*4.56*	*5.23*	*38.11*	*0.71*
Sebah	*0.90*	11.75	13.48	*46.19*	1.25
Vitrón	1.23	*1.50*	*4.78*	67.63	*0.38*
Waha	*0.97*	*1.61*	*1.26*	*42.36*	*0.18*
Test weight					
Altar-aos	*1.02*	*0.40*	*0.18*	*4.90*	*0.52*
Awalbit	0.78	1.36	1.57	*3.87*	1.18
Jabato	1.59	1.78	3.36	12.54	1.11
Korifla	*0.99*	*0.84*	1.10	*4.98*	*0.42*
Lagost-3	0.61	1.10	2.14	2.59	0.98
Mexa	*0.94*	*0.35*	*0.38*	*4.16*	0.63
Omrabi-3	0.92	*0.35*	*0.51*	*3.98*	*0.34*
Sebah	1.33	*0.94*	1.09	8.56	0.71
Vitrón	*1.03*	*0.18*	*0.04*	*4.73*	*0.19*
Waha	0.80	*0.45*	0.76	*3.14*	*0.19*
Vitreousness					
Altar-aos	0.60	*0.47*	*2.32*	*4.68*	*0.20*
Awalbit	0.80	10.00	11.38	*16.36*	1.37
Jabato	*0.98*	4.05	*2.19*	*14.87*	*0.57*
Korifla	*1.01*	*1.75*	*0.59*	*13.54*	*0.25*
Lagost-3	*1.04*	25.64	28.57	35.43	1.09
Mexa	1.17	2.99	3.95	18.71	*0.58*
Omrabi-3	*1.05*	*1.03*	*1.87*	*13.87*	*0.55*
Sebah	1.22	*0.90*	*2.74*	18.37	*0.28*
Vitrón	1.40	9.03	10.32	31.03	1.52
Waha	0.74	*1.98*	*1.20*	*8.27*	*0.27*
Ash content					
Altar-aos	0.91	*0.008*	*0.011*	*0.15*	*0.30*
Awalbit	*1.03*	*0.009*	*0.007*	0.19	0.78
Jabato	1.12	0.021	*0.023*	0.23	*0.28*
Korifla	0.69	*0.011*	*0.031*	*0.09*	0.96
Lagost-3	1.09	*0.016*	*0.016*	0.22	*0.48*
Mexa	0.73	*0.010*	*0.027*	*0.10*	0.85
Omrabi-3	1.15	*0.011*	*0.011*	0.24	0.82
Sebah	1.12	*0.004*	*0.008*	0.22	*0.52*
Vitrón	1.13	*0.011*	*0.013*	0.23	0.79
Waha	*1.03*	0.031	0.033	0.21	1.26
Protein content					
Altar-aos	0.84	*0.32*	*0.29*	*2.30*	0.67
Awalbit	0.85	*0.32*	*0.20*	*2.36*	0.69
Jabato	*0.92*	*0.70*	*0.51*	*3.05*	*0.38*
Korifla	0.68	*0.50*	*0.64*	*1.75*	0.93
Lagost-3	*1.08*	*0.35*	*0.48*	*3.62*	*0.50*
Mexa	0.70	1.28	1.23	2.53	*0.58*
Omrabi-3	1.28	1.27	1.96	5.82	0.93
Sebah	1.17	*0.80*	*1.05*	4.61	*0.31*
Vitrón	1.33	*0.57*	1.31	5.60	0.92
Waha	1.24	*0.35*	*0.67*	4.72	*0.50*
Pigment content					
Altar-aos	1.49	0.63	0.71	0.90	0.97
Awalbit	*1.08*	0.14	*0.12*	*0.30*	*0.45*
Jabato	1.21	0.13	*0.14*	*0.35*	*0.54*
Korifla	1.38	0.08	*0.13*	0.37	*0.45*
Lagost-3	1.34	0.14	0.17	0.41	*0.09*
Mexa	*0.83*	0.37	0.35	0.43	1.03
Omrabi-3	0.15	0.08	*0.15*	*0.08*	0.58
Sebah	0.62	*0.03*	*0.03*	*0.09*	*0.14*
Vitrón	*0.99*	0.31	0.35	0.43	0.91
Waha	*0.91*	0.08	*0.08*	*0.20*	*0.31*
SDS volume					
Altar-aos	1.37	0.70	1.40	3.44	0.56
Awalbit	1.33	0.28	0.81	2.91	0.57
Jabato	0.79	*0.09*	*0.04*	*1.03*	*0.25*
Korifla	1.57	0.46	1.51	4.14	0.51
Lagost-3	0.64	0.27	*0.18*	*0.86*	*0.17*
Mexa	*1.05*	0.46	0.69	2.06	0.77
Omrabi-3	*0.97*	0.36	*0.26*	*1.74*	*0.39*
Sebah	0.81	*0.20*	*0.10*	*1.18*	*0.48*
Vitrón	*0.98*	0.23	*0.40*	*1.67*	0.65
Waha	0.47	0.43	0.51	*0.72*	0.70

[a] b: regression slope (Finlay and Wilkinson, 1963). S^2_{di}: deviation from regression (Eberhart and Russell, 1966). σ^2_i: Shukla stability variance (Shukla, 1972). S^2_{xi}: environmental variance. v_i: distance to the origin from the plan determined by the two first AMMI axes.

[b] Values in italics are non-significantly different from the unity at $P < 0.05$. Cultivars with values in italics are considered stables.

[c] Values in italics are non-significantly different from 0 at $P < 0.05$. Cultivars with values in italics are considered stables.

[d] Values in italics are lower than the mean. Cultivars with lower values than the mean are regarded as stables.

To define genotypic stability, a genotype was considered stable for a given quality parameter if it appeared stable in more than three (out of five) stability analyses. Genotypes that proved to be stable for most stability analyses were then selected as the best.

3. Results

Results from the joint regression analysis (Table 1) showed the high influence of environment on the

Table 4
Summary of the stability analyses of 10 durum wheat genotypes grown in different zones in Spain (Lleida, Granada and Jerez) during two growing seasons (1998 and 1999)

Genotypes	TKW[a]	Test weight	Vitreousness	Ash content	Protein content	Pigment content	SDS volume
Altar-aos	+[b]	+	+	+	+	−	−
Awalbit	−[c]	−	−	+	+	+	−
Jabato	+	−	+	−	+	+	+
Korifla	−	+	+	+	+	−	−
Lagost-3	−	−	−	+	+	−	+
Mexa	−	+	−	+	−	−	−
Omrabi-3	+	+	+	−	−	−	+
Sebah	−	−	+	+	+	+	+
Vitrón	+	+	−	−	−	−	+
Waha	+	+	+	−	+	+	−

[a] Thousand kernel weight.
[b] Stable for more than three stability parameters.
[c] Unstable.

majority of quality parameters, with the exception of pigment content and SDS volume, which were also under genetic control. G × E interaction was low in comparison with the additive effects. Although the regression model was significant for some characters, such as protein content or test weight, it explained less than 34% of the sum square of the interaction and the remainder was accumulated into the regression residual. Thus, in our case, regression analysis was unable to explain the G × E interaction pattern. Other stability parameters and methods were therefore used in order to consolidate the results from regression analysis.

AMMI analysis (Table 2) revealed the significance of almost four PCA, with the exception of protein content and SDS volume, where only the first PCA was significant. The two first PCA axes (which were used to determine the distance from the origin in the AMMI plot, one of the stability parameters used in our study), accounted for more than 54% of the sum square of the interaction, where the residual was not significant and of small magnitude. These results demonstrated the efficiency of the AMMI analysis, which extracted a large part of the G × E interaction.

The five statistical parameters used in our study to define genotypic stability gave fairly similar results (Tables 3 and 4). Between genotypes, Spanish commercial varieties Altar-aos and Jabato, as well as the advanced lines Sebah and Waha, demonstrated a high stability for the majority of quality parameters. Also, within these four best genotypes, Sebah was unstable for TKW and test weight and Jabato showed instability for test weight, a commercial trait that is highly valued in the cereal market. The other genotypes showed some variation in their degree of stability from one quality trait to another.

4. Discussion

In this study, partitioning and interpretation of the G × E interaction was based on linear regression techniques (Finlay and Wilkinson, 1963) and multivariate analysis (Zobel et al., 1988). The former method had shown certain deficiencies for determining G × E interaction patterns and explains a small part of some of squares of this interaction. This observation was encountered in this and other similar studies (Zobel et al., 1988; Nachit et al., 1992; Annicchiarico, 1997) because the regression technique confuses interaction and main effects (Wright, 1971) and is unable to predict non-linear genotypic response to the environments (Nachit et al., 1992). On the other hand, AMMI analysis appeared to be able to extract a large part of the interaction and is thus more efficient in analysing G × E interaction pattern, as demonstrated by Zobel et al. (1988).

The study of genotypic stability revealed why some genotypes are grown in the Mediterranean area. In fact, Altar-aos, a newly introduced Spanish commercial variety, demonstrated higher stability for grain quality. This variety was released by the IRTA in

Lleida (one of the regions of this study). It not only appears to have a specific adaptation to this region but can also be grown successfully in other zones of Spain, particularly under drought conditions. Thus, this promising entry could be recommended to farmers dealing with the production of good quality durums. Jabato, a Spanish commercial variety, also showed high stable quality parameters and may still be of interest for growers in Spain. From the advanced lines of the CIMMYT-ICARDA durum wheat breeding programme, Waha and Sebah could be used successfully as progenitors in breeding programmes for the production of high grain quality durum wheat in the Mediterranean countries. Some variability between measurements of stability within each genotype was observed in our study. Thus, some genotypes were stable for one trait and unstable for another, suggesting that the genetic factors involved in the G $\times$ E differed between traits (Grausgruber et al., 2000).

Genotypes selected according to stability of quality in our study verified the possibility of combining both stable and high quality. However, breeders must be aware of the difficulties in selection. As reported by Grausgruber et al. (2000), an integrated selection system designed to maximise the probability of producing stable quality wheats with a high level of performance should be developed.

5. Conclusions

AMMI analysis provided a better description of G $\times$ E interaction than joint regression analysis, which was ineffective in explaining this interaction. For genotypic stability, the Spanish commercial varieties, Altar-aos and Jabato and the ICARDA advanced line, Waha, showed high stability for quality characteristics and proved to be the best within the pool of the studied genotypes.

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