

N. Robert · J.-B. Denis

Stability of baking quality in bread wheat using several statistical parameters

Received: 26 July 1995 / Accepted: 24 November 1995

Abstract Stability of quality in bread wheat was investigated for the first time with the alveograph test, a rheological test providing four technological traits. Assessment of stability was reliable because a large set of varieties (ten) were grown over a wide range of environments (14). Varieties and environments were representative of French agricultural practices. A procedure to evaluate stability of quality is proposed. Stability was measured by ecovalence, which was then modelled to determine response to environments for each genotype. A joint regression model was compared to a biadditive model with two multiplicative terms. The regression model explained a very much smaller part of ecovalence than the biadditive model. The latter made it possible to pool cultivars for genotype×environment interactions and to characterize varieties for their responsiveness to environments. Two check varieties for stability and instability were identified.

Key words Wheat · Quality · Stability · Genotype × environment interaction · Joint regression · Biadditive model

Introduction

End-users of wheat (*Triticum aestivum* Thell) grain, millers, bakers and biscuit-makers, need a constant quality of raw material, grain or flour, in order to avoid their processes being modified and product loss during processing. This demand that one variety have a constant value is called stability by industry, but we prefer to call it economic stability. Different cultivars generally show different economic stabilities. For any given variety, a miller processes grain that has been harvested in different locations. He therefore observes only phenotypic values, which are the sum of the genotypic effect (G), the growing environment effect (E) and the interaction between the genotype and the environment (GXE). As the genotype is constant over the set of growing environments, stability as defined by the end-users is due to environment and GXE effects. A cultivar showing economic stability should have in each growing environment a GXE interaction that cancels out the environment effect. We consider that this situation is probably not realistic from a biological point of view and therefore have defined stability of a quality trait as the different responses to various environments exhibited by several genotypes grown in the same set of sites, responses based on GXE interactions. This definition corresponds to the agronomic concept (Becker 1981), also called the dynamic concept of stability (Becker and Léon 1988), for which the observed environment effects are common to each genotype studied and thus not involved in differential responses. It implies that each variety varies dependent on the environment and that constant values for a quality trait cannot be obtained. A cultivar will therefore be suitable for end-users if the amount of its phenotypic values due to GXE interactions is low. A stable genotype for quality will have reduced GXE interactions.

Ecovalence, the sum of squares of interactions for any genotype [Wricke (1962) in Lin et al. 1986; Becker and Léon 1988] is one measure of stability. Other methods, all of which assume a linear relationship between phenotypic values and environmental indices, have also been proposed to analyse GXE interactions and stability. Joint regression, that is the regression analysis of either phenotypic values or interactions on environmental indices, is currently in use (Finlay and Wilkinson 1963; Westcott 1986; Lin et al. 1986; Becker and Léon 1988). The slope of the regression line is the measure of stability, and the reference slope used to classify cultivars as stable depends on the definition chosen for stability (Lin et al. 1986; Becker and Leon 1988). However some authors have considered the slope to be the measure of response to varying environments; the mean

Communicated by G. Wenzel

N. Robert (✉)
INRA, Station d'Amélioration des Plantes, Domaine de Crouëlle, Clermont-Ferrand, F-63039 Cédex, France

J.-B. Denis
INRA, Laboratoire de Biométrie, Route de Saint-Cyr, Versailles, F-78026 Cédex, France

square of deviations from the regression (Eberhart and Russel 1966; Tai 1971) or the coefficient of determination (Bilbro and Ray 1976) were then defined as parameters of stability. Other simple statistics, such as the coefficient of variation or the variance of genotypic mean, have also been proposed (Jalaluddin and Harrison 1993). These various measures of stability are biometrically related (Langer et al. 1979; Becker 1981; Jalaluddin and Harrison 1993).

Mandel (1971) proposed a multiplicative partition of GXE interactions also called the Additive Main Effects and Multiplicative Interaction model (AMMI model) (Zobel et al. 1988) or biadditive models (Denis and Gower 1994), which is the singular value decomposition of the interaction matrix. Each genotype and location are characterized by multiplicative scores, whose biological interpretation is not always easy. Other methods based on cluster analysis and geometrical methods have also been recommended (Wescott 1985; Lin et al. 1986), in which the stability of a genotype is assessed by comparing it to checks well-known for stability. Factorial regression has also been proposed to structure GXE interactions using genotypic and environmental covariates (Denis 1988); these covariates can be external variates not obtained from the experiment (Denis 1988) or variates derived from the experiment (Baril 1992).

There is less documentation on analysis of stability for quality traits than on yield. In wheat, stability studies using the slope of joint regression (Busch et al. 1969; McGuire and McNeal 1974; Borghi et al. 1975), the slope associated to the mean square of deviations (Baezinger et al. 1985; Bassett et al. 1989; Peterson et al. 1992; Peltonen-Sainio and Peltonen 1993) or the slope associated to the coefficient of determination (Lukow and McVetty 1991) have been carried out using various breeding tests correlated to baking quality. In this study, we assessed the quality of wheat by means of the four traits provided by the alveograph test (Godon and Loisel 1984). The presence of interaction for that test was investigated and varieties were compared for stability. Stable varieties were defined as those with low ecovalences. After calculating the ecovalences, we compared regression on environmental indices and biadditive models with one or two terms in order to choose the statistical approach most suitable to depict stability of quality.

Materials and methods

Field experiment

Ten varieties ('Apollo', 'Baroudeur', 'Camp-Rémy', 'Récital', 'Renan', 'Rossini', 'Soissons', 'Talent', 'Thésée' and 'Viking'), that are well-adapted to French conditions were grown in 1991–1993 in randomized complete block designs. The range of quality was large, from a non-breadmaking variety ('Apollo') to good breadmaking cultivars ('Récital', 'Renan'). Fourteen environments defined by the site×year combinations were studied. They were located in different regions and represent the wheat-growing areas of France: Rennes in 1991–1993 (western France), Orgerus in 1991–1993 (west of the Paris Basin), Boigneville in 1991; 1992 (south-west of the Paris Basin), Saint-Hilaire in 1992; 1993 (in the east of the Paris Basin), Montans in 1991 (south-western France), Mons in 1992 (northern France), Verneuil in 1993 (east of the Paris Basin) and Clermont-Ferrand in 1993 (central France).

The experiment was slightly unbalanced (5 cases of missing data out of the 140 expected) due to a lack of seeds in some locations.

Quality assessment

In each site, grains of all replicates were blended, and one alveograph test was performed on each composite sample. This test measures four traits that determine empirical rheological characteristics of the dough: W (strength), P (tenacity), G (swelling) and P/L (ratio of tenacity to extensibility) (Godon and Loisel 1984). It is predictive of French baking quality since strength (W) and swelling (G) are positively correlated to bread volume and baking scores (Branlard et al. 1991). The ratio of tenacity to extensibility (P/L) is also a useful criteria for bakers.

Statistical analyses

As we had only one value per genotype in each environment, the complete interactive model could not be tested. We applied the additive model:

$$xij = \mu + gi + ej + rij.$$

S^2, variance of the residuals (rij), includes GXE interaction effects. To test the significance of these effects, we tested S^2 against a repeatability variance (RV) for each trait of the alveograph. Repeatability variances were obtained from an independent sample of size 21 performed in the same laboratory with a unique commercial flour stored at 4°C.

Ecovalences, $Wi = \sum jr^2ij$, were calculated for each genotype. This value contained both interaction effects and experimental error; the latter was assumed to be similar among genotypes. Each ecovalence was expressed as a percentage of the total ecovalence: $TW=\sum_i Wi$.

The joint regression model:

$$xij = \mu + gi + biej + dij$$

and the biadditive model with one or two terms:

$$xij = \mu + gi + ej + ui1.T1.vj1 + ui2.T2.vj2+r'ij$$

were applied to data in order to model GXE interactions using the software INTERA (Decoux and Denis 1991). All effects were considered fixed. The tests of the two models were made using the variances of repeatability as pure error variances. Graphics were made using S-PLUS software (Becker et al. 1988; Statistical Science 1993).

The quality of the models was evaluated at the variety level for each trait separately. We considered the amount of interaction still contained in the sum of errors of each genotype for the joint regression and the biadditive model (two multiplicative terms). For that purpose, a pseudo-mean square ratio was calculated as follows:

$$F' = [\sum j\, r_{ij}^2 /(dr/I)]/RV$$

where r_{ij} were the residuals of the model considered; dr, the residual degrees of freedom of the respective models (103 for the joint regression, 72 for the biadditive model); I, the number of genotypes and RV, the repeatability variance previously used to test the absence of interaction. The values of the *F* distribution either for 10 and 20 degrees of freedom (regression) or for 7 and 20 degrees of freedom (biadditive model) were considered to be indicative of the more or less high amount of ecovalence not modelled. In the same way, asymptotic confidence intervals at 95% (Denis and Gower 1994) were calculated for each multiplicative terms using the repeatability estimation of variance. For the sake of the programme, these confidence intervals were calculated on a complete dataset for which missing data were substituted by their estimates under the additive model (Denis and Baril 1992).

Assessment of stability was reliable for each genotype, since the varieties were well-adapted to the environments studied.

Table 1 Presence of GXE interaction for the four traits of the alveograph: test of the residual mean square of the additive model on a mean square of repeatability; components of variation due to genotypes, environments and GXE interactions in percentage of the total sum of squares

	W[a]	P	G	P/L
Source of variation				
Genotype	79.7%	84.4%	52.7%	47.7%
Environments	9.5%	7.6%	34.0%	30.8%
G × E interactions + error	10.8%	8.0%	13.3%	21.4%
Presence of interaction				
Residual mean square	778.96	45.97	2.23	0.0878
Mean square of repeatability	72.19	9.43	0.416	0.0135
F (112,20)	10.79***	4.87***	5.36***	6.50***

*** $P \leq 0.001$
[a] W, Strength; P, tenacity; G, swelling; P/L, ratio of tenacity to extensibility

Table 2 Percentages of total ecovalence of each variety (columns) for each trait (rows)

	Apollo	Baroudeur	Camp-Rémy	Récital	Renan	Rossini	Soissons	Talent	Thésée	Viking
W	6.1	7.0	5.9	12.8	28.6	13.6	9.2	8.2	4.2	4.3
P	10.0	14.4	1.9	16.0	5.5	7.7	5.7	11.3	15.1	12.3
G	11.5	3.7	6.7	10.9	13.6	7.8	14.5	6.5	7.9	16.9
P/L	5.9	4.0	3.3	19.2	6.2	25.6	4.6	5.9	14.2	11.0

Results

Tests of residual variance of the additive model against a variance of repeatability were all significant at $P<0.001$ (Table 1). The four traits of the alveograph exhibited GXE interactions. Components of the total variation due to genotypes, environments and interaction plus experimental errors were calculated as the proportions of the total sum of squares (Table 1). As expected from the wide range of breadmaking quality present in the varietal set, the genetic component represented the largest amount of total variation (47.7%–84.4%), and variations due to environment and GXE interactions were considerably lower. With the exception of swelling (G), the variation due to interactions was not very different from the environmental variation. The two variables related to extensibility of dough (G and P/L) were the most influenced by environment and GXE interaction effects.

Stability was measured by individual ecovalences expressed in percentage of total ecovalence (Table 2). The ten varieties showed a large diversity for ecovalence, whatever the technological trait considered. There was thus a diversity for stability of quality in this set of cultivars. Some genotypes were stable for one trait and unstable for another (for example, 'Baroudeur' was stable for G but rather unstable for P; 'Viking' stable for W but unstable for G), suggesting that the genetic factors involved in GXE interactions differed from one trait to another. 'Camp-Rémy' can be considered to be a check for stability, while 'Récital' could be a check for instability, as they respectively presented low and high values of ecovalences for the four traits. However, for some traits, other cultivars were either more stable (W, 'Thésée'; G, 'Baroudeur') or more unstable (W, 'Renan'; G, 'Viking'; P/L, 'Rossini') than these two varieties.

GXE interactions are characterized by their magnitudes and signs. Ecovalence, as a sum of squares, conceals signs and only accounts for the magnitudes of interactions. Similar values of ecovalence, and thus stabilities, can be obtained, although interactions are quite different. In order to better identify varietal patterns of response to environments, we considered necessary to model GXE interactions. The quality of a model was measured as the proportion of total ecovalence that could be explained. The joint regression was significant but it depicted ecovalence poorly, while the biadditive model with two multiplicative terms was clearly better (Table 3). The four traits exhibited different responses to the joint regression model. While total ecovalence for W and P was similarly modelled by the regression model (27.7% and 23.4% respectively), G was poorly depicted (8.4%) in contrast to P/L (40%). The percentages of total ecovalence explained by the biadditive model were more regular, between 38.8% (G) and 48.4% (P/L) when one multiplicative term was considered, between 61.1% (G) and 70.0% (W) with two multiplicative terms. The four traits of the alveograph are complementary for assessing baking quality. Thus, a model chosen to depict interaction should have a similar capacity to explain all of the technological traits studied. Consequently, the biadditive models were retained, even if they were less parsimonious (19% and 36%, for one or two terms, respectively, of residual degrees of freedom added to degrees of freedom for the model, against 8% for regression). The model with two multiplicative terms was preferred, since its greater ability to explain the sum of squares

Table 3 Residual sum of squares of the additive model (total ecovalence TW), residual sum of squares of joint regression and the biadditive model. Percentage of total ecovalence explained for each model

	Additive model	Joint regression		Biadditive model (2 terms)			
	RSS = TW $df = 112$	RSS $df = 103$	% TW	RSS $df = 72$	% TW (1st term+ 2nd term)	1st term	2nd term
W	87 246.4	63 064.0	27.7%	26 166.0	70.0%	44.5%	25.5%
P	5 148.5	3 946.6	23.4%	1 759.1	65.8%	38.8%	27.0%
G	249.4	228.5	8.4%	96.93	61.1%	41.3%	19.8%
P/L	9.9	5.9	40.0%	3.06	68.8%	48.4%	20.4%

Table 4 Pseudo-mean square ratios for the joint regression model and the biadditive model with two multiplicative terms (italics). Indicative significances are based on pseudo F-statistics with (10, 20) and (7,20) degrees of freedom

	Apollo	Baroudeur	Camp-Rémy	Récital	Renan	Rossini	Soissons	Talent	Thésée	Viking
W	5.54***	7.48***	6.01***	10.00***	27.58***	5.86***	10.42***	5.71***	3.45**	4.15**
	*5.31***	*7.04****	*6.44****	*3.03**	*2.12* ns	*12.89****	*2.84**	*7.79****	*1.87* ns	*3.86**
P	2.80*	6.01***	0.74 ns	7.70***	2.92*	3.80**	2.99*	4.21**	3.83**	6.14
	1.52 ns	*4.61***	*0.96* ns	*2.39* ns	*2.36* ns	*2.88**	*4.25***	*2.23* ns	*3.29* ns	*3.85***
G	6.69***	2.16 ns	2.83*	5.97***	7.60***	4.31**	6.26***	3.76**	4.42**	9.78***
	*3.59**	*2.04* ns	*4.85***	*0.97* ns	*3.09***	*5.75****	*2.77**	*2.33* ns	*5.34***	*4.39***
P/L	2.80*	2.63*	1.15 ns	9.24***	3.51**	8.65***	1.02 ns	1.04 ns	5.92***	6.36***
	2.18 ns	*3.35**	*1.79* ns	*1.60* ns	*4.00***	*1.25* ns	*1.81* ns	*2.24* ns	*9.21****	*5.22***

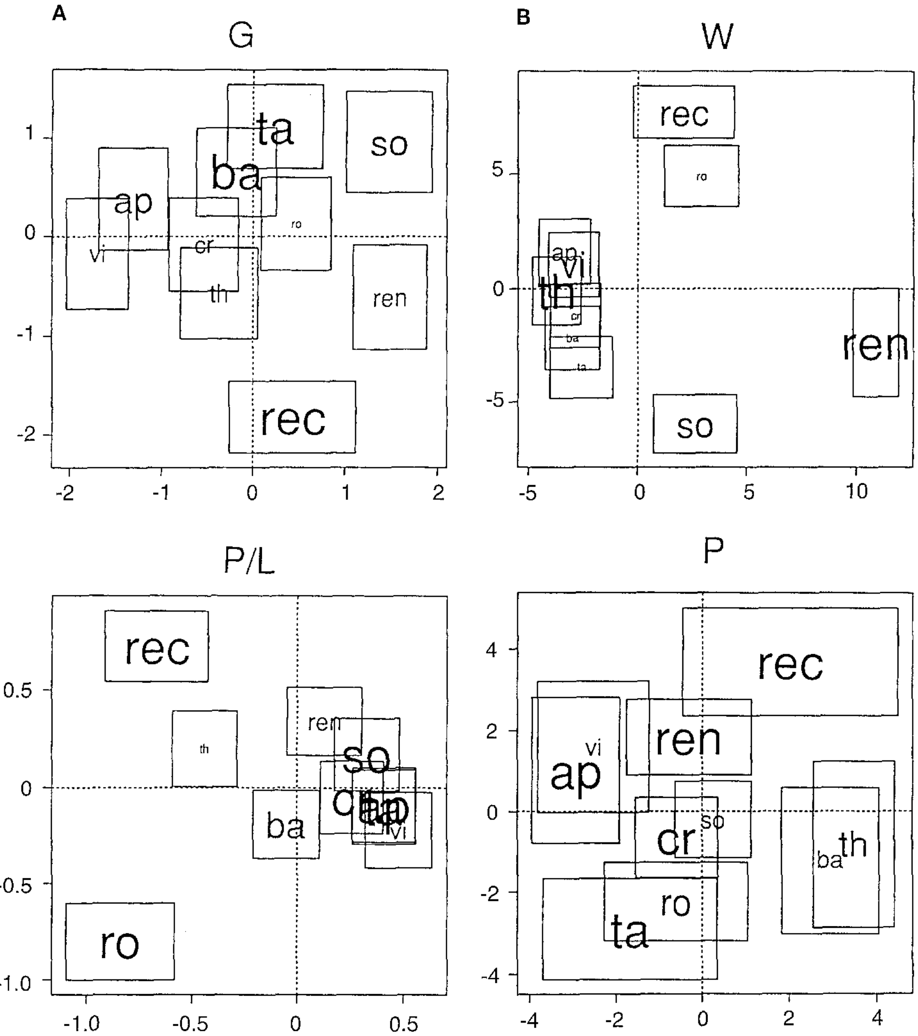
*, **, *** Means significant $P \leq 0.05$, 0.01, 0.001, respectively. ns, non significant

of interaction largely counterbalanced the difficult interpretation of the multiplicative scores provided.

As we were interested in the genetic diversity of stability in the set of varieties studied, we then compared the quality of the models at the variety level. For both models, there was a varietal heterogeneity for the amount of ecovalence not modelled (Table 4). However, except for W, differences between cultivars were smaller for the biadditive model. Comparison to the F values at the 5%, 1% and 0.1% levels (Table 4) showed that the biadditive model improved the modelization since the number of non-significant values increased whatever the trait considered. We therefore considered that the biadditive model was more suitable for depicting ecovalence at the individual level, even if a large part of interaction still remained unexplained for some genotypes. For these latter varieties, the model was not so well adapted to depict structure of interaction. Some varieties were well depicted by both models (F'i less than $F5\%$): 'Camp-Rémy', 'Soissons', 'Talent' for P/L, 'Camp-Rémy' for P and 'Baroudeur' for G. In fact, some of them, 'Camp-Rémy' (P and P/L), 'Baroudeur' (G) could be considered to be non-interactive, as their variances of interaction were not significantly different from the variance of repeatability; for the two other varieties, their F values were significant but not highly significant, therefore they were probably low interactive.

Each genotype was graphically described by its two multiplicative scores (multiplicative terms multiplied by the square root of the constants T1 and T2 in order to incorporate the magnitude of each multiplicative term in the representation) (Fig. 1). On the graph, the size of letters is related to the goodness of the modelling shown in Table 4 by the indicative significances of the pseudo-mean square ratios: the better the fit to the biadditive model, the larger the letters. These letter sizes showed the reliability of the graph for describing stability. From these, stability was well defined as follows: 'Thésée', 'Renan', 'Soissons', 'Récital' and 'Viking' for W; all genotypes but 'Viking', 'Soissons' and 'Baroudeur' for P; 'Récital', 'Baroudeur', 'Talent', 'Soissons', 'Apollo' for G; all genotypes except 'Renan', 'Thésée' and 'Viking' for P/L. A stable cultivar was identified on the graph as one near the origin; an unstable genotype was far from this point, since, whatever the environment considered, the first cultivar would have a low interaction and the second a high interaction, provided the model fitted the data. The asymptotic confidence intervals at 95% were calculated for each coordinate of each variety and used to draw a rectangle around each point. These rectangles can be a means to determine groups of varieties, based on overlaps and proximities, indicative of different types of interaction. It is clear that they do not correspond to exact confidence regions and must be used only as an exploratory tool for describing interactions; they can be regarded as bi-dimensional standard errors. This analysis was made only for well-defined varieties. Among the five varieties retained for W, four groups were identified: 'Thésée' and 'Viking' were pooled together, while 'Soissons', 'Récital' and Re-

Fig. 1 Representation of varieties by their multiplicative scores (biadditive model with two terms) for the four traits of the alveograph test. *ap* 'Apollo', *ba* 'Baroudeur', *cr* 'Camp-Rémy', *rec* 'Récital', *ren* 'Renan', *so* 'Soissons', *ta* 'Talent', *th* 'Thésée', *vi* 'Viking'. The *size* of the *letters* is related to the pseudo-mean square ratio. *X-axis* First score, *Y-axis* second score. Indication of the variability of the estimates is represented by *rectangles*



nen were individually classified. For P, the seven well-defined varieties were placed in six groups: 'Renan', 'Apollo', 'Récital', 'Thésée', 'Camp-Rémy' were classified as individuals; 'Rossini' and 'Talent' were grouped together. Four groups were identified both for G and P/L. Two varieties ('Baroudeur' and 'Talent') and three individuals ('Récital', 'Apollo' and 'Soissons') were grouped for G; for P/L, four less interactive varieties ('Camp-Rémy', 'Talent', 'Soissons', 'Apollo') were pooled in one group, while 'Baroudeur', 'Récital' and 'Rossini' were placed as individuals. For all traits, varieties well-defined by the model correctly represented the genetic diversity for interaction. Varieties pooled in the same group could be considered as reacting similarly to environments, as also could varieties having identical signs for their first multiplicative scores and for their second multiplicative scores. For example, 'Talent' and 'Camp-Rémy' or 'Apollo' and 'Renan' for P, 'Apollo' and 'Baroudeur' or 'Talent' and 'Soissons' for G and 'Baroudeur' and 'Rossini' for P/L reacted similarly to environments, but with different magnitudes. In contrast, pairs of varieties with multiplicative scores of opposite signs were identified as responding differently to environments when only well-depicted varieties were considered. 'Renan' and 'Viking' for W, 'Apollo' and 'Thésée' or 'Talent' and 'Récital' for P, Recital and 'Apollo' for G and 'Récital' and 'Apollo' or 'Rossini' and 'Soissons' for P/L were such pairs.

The same analysis could be made to classify environments. However, as our purpose was to assess the varieties for their stability of quality, the set of environments was considered only as a means of scrutinizing the varieties. Therefore, we did not apply the method to the data for environments.

Discussion

Previous studies on other quality tests showed that the GXE interaction component of variation is significant but very often smaller than genetic and location components (Borghi et al. 1975; Baenziger et al. 1985; Lukow and McVetty

1991; Peterson et al. 1992). In our experiment, the alveograph test behaved similarly to other technological tests as the amount of variation due to GXE interaction was small. However, as the genetic diversity studied was probably higher than in previous studies the environment-related component was also small and comparable to the interaction component. This result indicates that a reduction in GXE interactions by breeding might considerably improve the variation observed across locations for one genotype. Our measure of extensibility by the alveograph test confirmed the work of Lukow and McVetty (1991) who showed that extensibility assessed by the extensigraph also revealed strong interactions. Our results indicate that both reversal in ranks and scale effects are involved in interactions (data not shown). They disagree with those of Baenziger et al. 1985 and Peterson et al. 1992; who considered that GXE interactions are mainly due to changes in magnitude but agree with the absence of rank correlations between some locations as observed by Lukow and McVetty (1991).

We showed that joint regression explains a small proportion of total ecovalences for the four characteristics of the alveograph test. This result is in agreement with the results of Zobel et al. (1988) for soybean, Nachit et al. (1992) for durum wheat and Baril et al. (1995) for potato, all of whom showed that the joint regression explains a very small amount of GXE sum of squares for yield as opposed to AMMI. The fact that joint regression is not very useful in correctly depicting interactions is known for yield (Langer et al. 1979; Becker and Léon 1988), but this study revealed that it is also valid for some quality traits. The joint regression can be viewed as a particular case of biadditive models, the latter ones explaining the largest part of the sum of squares of interaction when compared to the factorial and joint regressions (Baril et al. 1995). So, if no biological explanation from the covariates used in the model is needed, biadditive models can be recommended.

Varietal differences for the amount of ecovalence not explained by the two models compared were revealed. Similar observations have been made in previous studies, although not discussed. Indeed, differences among coefficients of determination of the joint regression (Lukow and McVetty 1991) or among the sums of squares of deviations from regression (Baezinger et al. 1985; Peterson et al. 1992) partly take in consideration both the differences among ecovalences and the part of interactions not modelled by the regression. As the number of pseudo-mean square ratios less than the *F*1% value was higher for the biadditive model with two multiplicative terms, we consider that a multiplicative model with two axes is suitable to identify varietal differences for stability of quality traits. However, attention should be made to the proportion of ecovalence modelled in order to compare varieties. The more or less good depiction of interactions by the model probably caused the discrepancies between ranks of unadjusted means and ranks of predicted values by AMMI which observed by Crossa et al. (1991) for wheat yield trials. With respect only to the well-depicted cultivars, graphical representation of multiplicative terms obtained with the biadditive model appears to be a relevant tool for revealing differences and similarities between genotypes for GXE interactions. The same could be done for environments. In particular, a series of trials can be checked by this method, in order to know if the environments are very different with respect to the kind of interactions they induce, and therefore if the trials are relevant for providing information about GXE interactions, which is similar to the approach conducted by Baril et al. (1994).

Conclusion

This study presents the first investigation on wheat stability for the alveograph, a rheological test commonly used in France to assess baking quality. Previous studies dealing with the stability of quality directly evaluated stability with a joint regression model. We propose that the first stage should be the calculation of ecovalence, a statistical parameter which takes into account all the genotype environment interactions directly responsible for the stability of one variety. Using ecovalences, we showed that the ten varieties observed exhibited different stabilities for the alveograph test, and two checks, one for stability ('Camp-Rémy'), one for instability ('Récital'), were identified and could be used for further studies. In particular they could be genitors of a cross made to investigate the inheritance of stability of quality. However, it must be kept in mind that the assessment of stability depends on the sets of genotypes and environments studied. In a second stage, ecovalences had to be modelled to characterize the genotypes with respect to their responses to environments. Even if the joint regression model revealed heterogeneity for slopes, it modelled ecovalences poorly, and a multiplicative model of interactions was preferable. One argument in favour of the regression was the easier interpretation of the slope as the responsiveness of the cultivar to environments (Becker and Léon 1988). We showed that it was possible to characterize the genotypes for responsiveness to environments using the biadditive model. As already pointed out (Denis and Vincourt 1982), the biadditive model is an explanatory tool for analysing interactions. So, in our study, the graphical identification of groups of genotypes showing opposite or similar kinds of interactions across the set of environments was a first step towards the further biological understanding of GXE interactions. Indeed, the agronomic and biochemical covariables related to stability of quality, using factorial regression (Denis 1980; Baril 1992), will be investigated for those varieties well characterized by the study. The set of covariables identified might encourage studies on the physiological basis of stability.

Acknowledgements We are grateful to our colleagues at INRA, ITCF and Club of Five who carefully carried out field experiments, and to our colleagues in Grands Moulins de Reims who kindly performed alveograph tests. This research was partly supported by a grant from the Commission of the European Communities, ECLAIR programme, contract AGRE 0052.

References

Baenziger PS, Clements RL, McIntosh MS, Yamazaki WT, Starling TM, Sammons DJ, Johnson JW (1985) Effect of cultivar, environment, and their interaction and stability analyses on milling and baking quality of soft red winter wheat. Crop Sci 25:5–8

Baril CP (1992) Factor regression for interpreting genotype-environment interaction in bread-wheat trials. Theor Appl Genet 83:1022–1026

Baril CP, Denis J-B, Brabant P (1994) Selection of environments using simultaneous clustering based on genotype environment interaction. Can J Plant Sci 74:311–317

Baril CP, Denis JB, Wustman R, van Eeuwijk FA (1995) Analysing genotype by environment interaction in Dutch potato variety trials using factorial regression. Euphytica 82:149–155

Bassett LM, Allan RE, Rhubenthaler GL (1989) Genotype environment interactions on soft winter wheat quality. Agron J 81:955–960

Becker H (1981) Correlations among some statistical measures of phenotypic stability. Euphytica 30:835–263

Becker HC, Léon J (1988) Stability analysis in plant breeding. Plant Breed 101:1–23

Becker RA, Chambers JM, Wilks AR (1988) The new S language. Wadsworth & Brooks; Cole, advanced books & software. Pacific Grove, California. pp 702

Bilbro JD, Ray LL (1976) Environmental stability and adaptation of several cotton cultivars. Crop Sci 16:821–824

Borghi B, Testoni A, Cattaneo M, Corbellini M (1975) Effects of genetic-environment interaction on different tests for bread making quality evaluation. Genet Agric 29:391–404

Branlard G, Rousset M, Loisel W, Autran JC (1991) Comparison of 46 technological parameters used in breeding for bread wheat quality evaluation. J Genet Breed 45:263–280

Busch RH, Shuey WC, Frohberg RF (1969) Response of hard red spring wheat (*Triticum aestivum* L.) to environments in relation to six quality characteristics. Crop Sci 9:813–817

Crossa J, Fox PN, Pfeiffer WH, Rajaram S, Gauch HG Jr (1991) AMMI adjustement for statistical analysis of an international wheat yield trial. Theor Appl Genet 81:27–37

Decoux G, Denis JB (1991) INTERA. Logiciels pour l'interprétation statistique entre deux facteurs. Laboratoire de biométrie, INRA, route de Saint-Cyr, Versailles, France

Denis JB (1980) Analyse de régression factorielle. Biom Praxim 20:1–34

Denis JB (1988) Two-way analysis using covariates. Statistics 19:123–132

Denis JB, Baril C (1992) Sophisticated models with numerous missing values: the multiplicative interaction model as an example, Biul Oceny Odmian 24–25:33–45

Denis JB, Gower JC (1994) Asymptotic covariances for the parameters of biadditive models. Utilitas Math 46:193–205

Denis JB, Vincourt P (1982) Panorama des méthodes statistiques d'analyse des interactions génotype X milieu. Agronomie 2(3):219–230

Eberhart SA, Russell WA (1966) Stability parameters for comparing varieties. Crop Sci 6:36–40

Finlay KW, Wilkinson GN (1963) The analysis of adaptation in a plant-breeding programme. Aust J Agric Res 14:742–754

Godon B, Loisel W (1984) Guide pratique d'analyse dans les industries des céréales. Technique & documentation. Lavoisier, Paris

Jalaluddin Md, Harrison SA (1993) Repeatability of stability estimators for grain yield in wheat. Crop Sci 33:720–725

Langer I, Frey KJ, Bailey T (1979) Association among productivity, production response, and stability indexes in oat varieties. Euphytica, 28:17–24

Lin CS, Binns MR, Lefkovitch LP (1986) Stability analysis:Where do we stand? Crop Sci 26:894–900

Lukow OM, McVetty PBE (1991) Effect of cultivar and environment on quality characteristics of spring wheat. Cereal Chem 68:597–601

Mandel J (1971) A new analysis of variance model for non-additive data. Technometrics 13:1–18

McGuire CF, McNeal FH (1974) Quality response of 10 hard red spring wheat cultivars to 25 environments. Crop Sci 14:175–178

Nachit M, Nachit G, Ketata H, Gauch HG Jr, Zobel RW (1992) Use of AMMI and joint regression models to analyse genotype-environment interactions in durum wheat. Theor Appl Genet 83:597–601

Peltonen-Sainio P, Peltonen J (1993) Stability of quality traits in spring cereals cultivated under the growing conditions of southern Finland. Acta Agric Scand Sect B. Soil Plant Sci 43:45–52

Peterson CJ, Graibosch RA, Baezinger PS, Grombacher AW (1992) Genotype and environment effects on quality characteristics of hard red winter wheat. Crop Sci 32:98–103

Statistical Science 1993 S-PLUS programmor's manual, version 3.1. Statistical Science, Seattle, Wash.

Tai GCC (1971) Genotypic stability analysis and its application to potato regional trials. Crop Sci 11:184–190

Westcott B (1986) Some methods of analysing genotype-environment interaction. Heredity 56:243–253

Zobel RW, Wright MJ, Gauch HG Jr (1988) Statistical analysis of a yield trial. Agron J 80:388–393