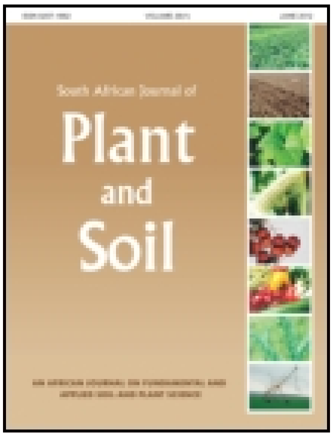

South African Journal of Plant and Soil
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tjps20

Genotype × environment interaction of winter wheat (Triticum aestivum L.) in South Africa: II. Stability analysis of yield performance

J. L. Purchase [a] , Hesta Hatting [a] & C. S. van Deventer [b]

[a] ARC-Small Grain Institute , Private Bag X29, Bethlehem , 9700 , Republic of South Africa

[b] Department of Plant Breeding , University of the Orange Free State , P.O. Box 339, Bloemfontein , 9300 , Republic of South Africa

Published online: 15 Jan 2013.

To cite this article: J. L. Purchase , Hesta Hatting & C. S. van Deventer (2000) Genotype × environment interaction of winter wheat (Triticum aestivum L.) in South Africa: II. Stability analysis of yield performance, South African Journal of Plant and Soil, 17:3, 101-107, DOI: 10.1080/02571862.2000.10634878

To link to this article: http://dx.doi.org/10.1080/02571862.2000.10634878

Genotype × environment interaction of winter wheat (*Triticum aestivum* L.) in South Africa: II. Stability analysis of yield performance

J.L. Purchase*, Hesta Hatting
ARC-Small Grain Institute, Private Bag X29, Bethlehem 9700, Republic of South Africa

C.S. van Deventer
Department of Plant Breeding, University of the Orange Free State, P.O.Box 339, Bloemfontein 9300, Republic of South Africa

Accepted 25 November 1999

Thirteen winter and intermediate type bread wheat cultivars were evaluated for yield stability under dryland conditions over a four year period from 1991 to 1994 and over a total of 120 environments in the Western, Central and Eastern Free State wheat producing regions of South Africa. The following statistical analyses were conducted and procedures followed to determine yield stability: (i) Shukla's procedure of stability variance(*²i); (ii) Lin and Binns cultivar performance measure (Pi); (iii) Finlay and Wilkenson's regression analysis and coefficient (b); (iv) Eberhart and Russel's deviation from regression (S^2d); (v) Wricke's ecovalence (W_i); (vi) AMMI model. Since the AMMI model does not make provision for a quantitative stability measure, such a measure was developed to rank genotypes. Total correspondence for significance of Spearman's rank correlation coefficients for the different analysis procedures was noted over the three production regions. No significant rank correlation coefficients were found in the pairwise comparisons of both Lin and Binns' and Finlay and Wilkenson's procedures with the other procedures, nor in the comparison between the two mentioned procedures. This indicates that the Lin and Binns procedure, as well as the Finlay and Wilkenson procedure, differ significantly from the other procedures in stability determination and definition, and due to noted deficiencies are consequently not recommended for use. From the study it would appear that if a single method of describing the stability of a genotype had to be selected, the proposed AMMI Stability Value (ASV) AMMI model would be the most appropriate. Certain cultivars showed similar stability over the three regions, while others varied considerably over the three regions.

Keywords: AMMI Model, genotype × environment interaction, stability analysis, wheat.

*To whom correspondence should be addressed, (E-mail: jlpurchase@igg2.agric.za).

Introduction

Dryland wheat production in the Free State province of South Africa accounts for approximately 45% of the mean national wheat crop of 2.1 million metric tons. However, this contribution to wheat production in South Africa varies considerably due to the high-risk nature of production. Winter and facultative types are planted in the fall (April/May) and winter months (June/July) on residual soil water conserved during the summer rainfall months. The crop, especially in the Central and Eastern Free State, is dependent on highly variable spring rainfall in September and October to ensure economic grain yields. The considerable variation in soil and climate has resulted in significant variation in yield performance of the wheat cultivars cultivated in the region. In assessing the performance of cultivars in this region, it is thus essential that the yield stability of such cultivars, in addition to their yield performance, be determined in order to make specific recommendations to producers.

The concept of yield stability of a genotype in an evaluation and breeding programme is, however, ambiguous (Lin, Binns & Lefkovitch, 1986), often used in quite different senses (Becker & Léon, 1988) and based on different statistical determinations and analyses (Crossa, 1990; Hohls, 1995). Lin *et al.* (1986) identified three concepts of stability: Type I is defined as a genotype being stable if its variance over a range of environments is small; Type II is defined as a genotype being stable if its response to environments is parallel to the mean response of all genotypes in the trial (this type of stability is primarily based on the interpretation of the regression coefficient in joint linear regression); *Type III* stability is defined as a genotype being stable if the residual mean squares from the regression model on the environment index is small, and the concept was first introduced by Eberhart and Russel (1966).

Becker and Léon (1988) also distinguished between two different concepts of stability, termed static stability and dynamic stability respectively. Static stability is defined as a stable genotype possessing unchanged performance regardless of variation of the environments, thus implying that its variance over environments is zero. This is equivalent to the the biological concept of stability and similar to Type I stability of Lin *et al.* (1986). Dynamic stability is defined as a genotype having a predictable response to environments and thus having no deviation from this particular response to environments. Becker (1981) termed this type of stability the agronomic concept to distinguish it from the biological or static concept. Becker and Léon (1988) stated that all stability procedures based on quantifying G × E interaction effects belong to the dynamic stability concept. Included are procedures partitioning G × E interaction, such as Wricke's ecovalance (Wricke, 1962) and Shukla's stability of variance (Shukla, 1972), procedures using the regression approach such as proposed by Finlay and Wilkenson (1963), Eberhart and Russel (1966) and Perkins and Jinks (1968), as well as non-parametric stability statistics.

Lin and Binns (1988a;1988b) also proposed the use of a totally different stability concept, viz. the cultivar performance measure (P_i), and defined P_i of genotype *i* as the mean squares of distance between genotype *i* and the genotype with maximum response, as: $P_i=[n(Y_i-M..)^2 + (Y_{ij}-Y_{i.}+M_j+M..)^2]/2n$, where Y_{ij} is the average response of genotype *i* in environment *j*, Y_i is the mean deviation of genotype *i*, M_j is the genotype with maximum response among all genotypes at environment *j*, and n is the number of locations. The smaller the value of P_i, the less its distance to the genotype with maximum yield and thus the better the genotype.

Multivariate techniques are also extensively applied in stability analysis to provide further information on the real multivariate response of genotypes to environments. The three main purposes of multivariate analysis are: (i) to eliminate noise from the data pattern, (ii) to summarise the data, and (iii) to reveal a structure in the data. Through multivariate analysis, genotypes with similar responses can be clustered, hypotheses generated and later tested, and the data can be summarised and analysed more easily (Gauch, 1982; Crossa, 1990; Hohls, 1995). Becker and Léon (1988) defined the aim of the various multivariate classification methods as being to assign genotypes into qualitatively homogeneous stability subsets. Within subsets, no significant G × E interactions occur, while differences among subsets are due to G × E interactions. A criticism is that numerous clustering strategies exist and choosing between them can result in considerably different cluster groups. Another drawback is that a non-existent structure could be forced onto the data (Hohls, 1995). However, if well-known cultivars are included in the test they can respectively be used as paradigms for other genotypes in the same subset (Lin *et al.*, 1986). Techniques falling into this category are principal components analysis (PCA), principal coordinates analysis, factor analysis, cluster analysis and the additive main effects and multiplicative interaction method, widely known as the AMMI model, which combines analysis of variance for genotype and environment main effects with principal components analysis of the G × E interaction into a unified approach (Gauch, 1988; Zobel, Wright & Gauch, 1988).

The objective of the study was to compare the various statistical procedures for assessing the yield stability of the wide range of wheat genotypes grown under dryland conditions in the Free State, and thereby to determine the most suitable method. This will enable scientists and breeders to use the most appropriate procedure to estimate genotype performance and yield stability, to select superior wheat genotypes for the region and to understand the interaction of these genotypes with the environment in order to make more reliable recommendations to producers.

Materials and Methods

Thirteen genotypes were evaluated over a four year period from 1991 to 1994 over a total of 120 environments in the Western, Central and Eastern Free State wheat producing regions of South Africa. Detailed information regarding the genotypes, sites and rainfall, as well as of the three distinct regions, is presented in Purchase, Hatting and Van Deventer (2000).

An analysis of variance (ANOVA) was performed on the yield data of each of the individual trials, as well as on the pooled data for the Western Free State (39 environments), Central Free State (33 environments) and Eastern Free State (48 environments), respectively, using Agrobase 4. Bartlett=s test was used to test the homogeneity of variances between environments to determine the validity of the analyses of variance on the data. Various transformations were done on the data set but without success. Subsequently, weighted analyses were conducted for the different regions using the SAS statistical computer software programme and the G × E interactions were all very highly significant, after the differences in variances had been accounted for. This indicates that the significant interactions noted were not spurious in any way (data not shown).

The following statistical analyses were conducted and procedures followed to determine yield stability: (i) Shukla's procedure of stability variance (Shukla, 1972); (ii) Lin and Binns cultivar performance measure (P_i) (Lin & Binns, 1988a); (iii) Finlay and Wilkenson's regression analysis and coefficient (b) (Finlay & Wilkenson, 1963); (iv) Eberhart and Russel's deviation from regression (S^2d) (Eberhart & Russel, 1966); (v) Wricke's ecovalence (W_i) (Wricke, 1962); AMMI model (Gauch, 1988). Since the AMMI model does not make provision for a quantitative stability measure, and as such a measure is essential in order to quantify and rank genotypes in terms of yield stability, the following measure is proposed:

$$\text{AMMI Stability Value (ASV)} = \sqrt{\left[\frac{\text{IPCA1SumofSquares}}{\text{IPCA2SumofSquares}}(\text{IPCA1score})\right]^2 + [\text{IPCA2score}]}$$

In effect the ASV is the distance from zero in a two dimensional scattergram of IPCA1 (Interaction Principal Component Analysis axis 1) scores against IPCA2 scores. Since the IPCA1 score contributes more to G × E sum of squares, it has to be weighted by the proportional difference between IPCA1 and IPCA2 scores in order to compensate for the relative contribution of IPCA1 and IPCA2 scores to total G × E sum of squares. The distance from zero is then determined by using the theorem of Pythagoras.

To statistically compare the six stability analysis procedures, Spearman's coefficient of rank correlation (r_S) was employed (Steel & Torrie, 1980). All the genotypes evaluated were respectively assigned stability values according to the procedure and definition used, and were then ranked in order to determine Spearman's rank correlation coefficient between the different procedures. The significance of r_s was tested by means of Student's *t* test, where:

$$t = \frac{r_s\sqrt{n-2}}{\sqrt{1-r_s^2}}$$

with n-2 degrees of freedom. If $t \geq t_{(0.01,\, n-2)}$, the null hypothesis was discarded and r_s was described as highly significant.

Results and Discussion

Tables 1, 2 and 3 indicate the ranking orders for stability of the 13 wheat genotypes, according to the six different G × E statistical analysis procedures, for respectively the Western, Central and Eastern Free State. Spearman's coefficient of rank correlation was then determined for each of the possible

Table 1 Values and ranking order for stability according to six different G × E stability procedures on 13 wheat cultivars evaluated over 39 sites in the Western Free State

	G × E stability analysis procedure											
	Shukla		Lin and Binns		Finlay and Wilkenson		Eberhart and Russel		Wricke		AMMI	
Cultivar	$*^2_i$	R[a]	P_i	R	b	R	S^2d_i	R	W_i	R	ASV	R
Betta	134 464	6	210 383	11	0.83	3.5*	9 120	6	1 209 267	6	32.8	7
Molopo	96 310	4	158 860	10	0.90	5.0	7 826	4	902 564	4	21.6	5
SST 102	47 706	1	134 463	8	0.97	6.5	760	1	511 846	1	12.1	3
Karee	227 102	10	217 379	12	0.79	1.0	24 882	10	1 953 933	10	37.9	11
Oom Charl	76 681	2	124 379	6	1.01	8.0	7 420	3	744 782	2	7.7	1
Molen	148 530	7	74 317	4	1.07	10.0	21 169	9	1 322 334	7	17.0	4
SST 124	161 873	8	233 113	13	0.81	2.0	13 015	7	1 429 592	8	35.4	9
Letaba	324 563	12	89 022	5	1.05	9.0	60 575	13	2 737 372	12	36.8	10
Scheepers 69	124 068	5	149 888	9	0.83	3.5	7 374	2	1 125 696	5	25.5	6
Caritha	310 684	11	73 958	3	1.30	12.0	26 369	11	2 625 846	11	52.8	13
Carina	332 445	13	44 743	1	1.36	13.0	17 475	8	2 800 731	13	50.5	12
Carol	215 576	9	48 004	2	1.13	11.0	31 611	12	1 861 282	9	35.0	8
Tugela-DN	87 768	3	126 251	7	0.97	6.5	8 620	5	801 743	3	8.7	2

* For Spearman,s rank correlation coefficient, equal rank values are averaged.
[a] Ranking order.

pairwise comparisons of the different stability analysis procedures for the respective production regions (Tables 4, 5 and 6). Subsequently Student's *t* test was performed to determine the significance of Spearman's rank correlation coefficients and the results are indicated in Tables 7, 8 and 9 for the Western, Central and Eastern Free State production regions, respectively.

Remarkable and total correspondence for significance of Spearman's rank correlation coefficients between certain analysis procedures was noted over the three production regions (Tables 4, 5 and 6). Over all three regions Shukla's stability analysis procedure correlated highly significantly ($P_{0.01}$) with those of Eberhart and Russel, Wricke and the AMMI model, while the same held true for Eberhart and Russel with Wricke and AMMI, as well as for Wricke with AMMI.

No significant rank correlation coefficients were found in the pairwise comparisons of Lin and Binns' and Finlay and Wilkenson's procedures with the other procedures, nor in the comparison between these two procedures. This indicates that

Table 2 Values and ranking order for stability according to six different G × E stability procedures on 13 wheat cultivars evaluated over 33 sites in the Central Free State

	G × E stability analysis procedure											
	Shukla		Lin and Binns		Finlay and Wilkenson		Eberhart and Russel		Wricke		AMMI	
Cultivar	$*^2_i$	R[a]	P_i	R	b	R	S^2d_i	R	W_i	R	ASV	R
Betta	41 882	1	159 751	11	0.97	5	1 669	1	368 309	1	3.8	1
Molopo	87 425	4	173 230	12	0.90	2	3 656	4	676 608	4	11.3	5
SST 102	82 897	3	137 293	10	1.03	8	7 211	6	645 953	3	7.1	3
Karee	238 163	12	188 452	13	0.82	1	26 856	11	1 696 986	12	28.8	13
Oom Charl	57 464	2	118 056	8	0.99	7	1 962	2	473 792	2	5.1	2
Molen	101 226	7	58 388	4	0.97	5	11 116	8	770 028	7	14.6	8
SST 124	100 365	6	123 544	9	0.90	2	6 653	5	764 198	6	10.2	4
Letaba	230 399	10	49 203	3	1.04	10	39 261	12	1 644 425	10	20.2	10
Scheepers 69	98 431	5	111 497	7	0.92	4	7 883	7	751 105	5	11.6	6
Caritha	232 423	11	93 065	6	1.17	12	26 852	10	1 658 132	11	27.6	12
Carina	246 483	13	47 175	2	1.09	11	39 403	13	1 153 308	13	26.9	11
Carol	126 675	8	26 241	1	1.18	13	2 074	3	942 296	8	19.9	9
Tugela-DN	147 605	9	63 184	5	1.03	8	21 294	9	1 083 973	9	12.1	8

[a] Ranking order.

Table 3 Values and ranking order for stability according to six different G × E stability procedures on 13 wheat cultivars evaluated over 48 sites in the Eastern Free State

	G × E stability analysis procedure											
	Shukla		Lin and Binns		Finlay and Wilkenson		Eberhart and Russel		Wricke		AMMI	
Cultivar	$*^2_i$	R[a]	P_i	R	b	R	S^2d_i	R	W_i	R	ASV	R
Betta	56 336	1	281 595	11	0.93	4	4 848	2	815 959	1	16.6	5
Molopo	243 626	7	263 004	10	0.94	5	36 914	9	2 678 060	7	8.6	3
SST 102	69 138	2	162 695	5	1.05	9	629	1	943 246	2	7.5	1
Karee	650 738	13	302 424	12	0.91	2	121 298	13	6 725 694	13	80.6	13
Oom Charl	127 462	3	227 937	9	1.02	8	13 413	3	1 523 126	2	8.6	2
Molen	173 322	6	147 885	4	0.96	6	22 497	8	1 979 079	7	31.1	7
SST 124	150 328	4	225 845	8	0.92	3	14 334	4	1 750 462	9	36.9	9
Letaba	610 290	12	221 577	7	1.08	11	114 334	12	6 353 544	12	77.5	12
Scheepers 69	528 296	11	446 316	13	0.73	1	55 870	11	5 508 342	11	60.2	11
Caritha	326 876	10	175 306	6	1.06	10	54 347	10	3 505 764	10	33.0	8
Carina	302 840	9	23 914	1	1.22	13	22 425	7	3 266 789	9	30.1	6
Carol	278 880	8	42 445	2	1.21	12	19 809	5	3 028 572	8	45.6	10
Tugela-DN	161 781	5	100 723	3	0.98	7	20 765	6	1 864 330	5	9.9	4

[a] Ranking order.

the Lin and Binns procedure, as well as the Finlay and Wilkenson procedure, differ significantly from the other procedures in stability definition.

The Lin and Binns procedure showed the greatest deviation from the other procedures, generally having negative rank correlation coefficients over all three the regions concerned. The procedure defines stability as the deviation of a specific genotype's performance from the performance of the best performing cultivar in a trial. This implies that a stable cultivar is one that performs in tandem with the environment. Therefore, in most cases, a close correlation will be found between such a genotype and the environment. In other words, a genotype with an inherently high yield would be classified as stable as its yields over sites will always be close to that of the top performer over the respective sites. Cultivars such as Betta, Molopo, SST 124 and Karee, with a relatively lower yield potential, will thus always be classified as unstable. The Lin and Binns procedure thus appears to be a genotype performance measure, rather than a stability measure over sites. The mean yield (main effect) could then rather be used to identify a genotype with superior yield performance. A further limitation of this method, and also the reason for the lack of agreement with other models, is that the best performing genotypes in the different regions can differ considerably from trial to trial. This implies that stability in one trial is determined against a specific genotype, but in another trial against another genotype. In the case of crossover interaction, which has clearly been illustrated to exist in this study, this leads to distortion of the data. This method is unacceptable for the purpose of characterising wheat genotype × environment interaction in the Free State.

Finlay and Wilkenson's procedure also shows limited correspondence to the procedures of Shukla, Eberhart and Russel, Wricke and the AMMI model. The procedure principally defines stability as the sensitivity of a genotype to changing environments, and this is measured and reflected by the regression coefficient (b) of joint regression analysis. This definition is similar to the static concept of stability as defined by Becker and Léon (1988), as well as to Type I stability as defined by Lin *et al.* (1986). Further limitations of

Table 4 Spearman's coefficients of rank correlation for six G × E stability analysis procedures conducted on 13 cultivars evaluated over 39 sites in the Western Free State

Statistical procedure	Shukla	Lin and Binns	Finlay and Wilkenson	Eberhart and Russel	Wricke	AMMI
Shukla	-					
Lin and Binns	-0.38	-				
Finlay and Wilkenson	0.37	-0.90	-			
Eberhart and Russel	0.85*	-0.41	0.60	-		
Wricke	1.00*	-0.38	0.37	0.85*	-	
AMMI	0.92*	-0.16	0.24	0.70*	0.92*	-

* Significant according to Student's *t* test at the P = 0.01 level

Table 5 Spearman's ranking order correlation coefficient matrix for six G × E stability analysis procedures conducted on 13 cultivars evaluated over 33 sites in the Central Free State

Statistical procedure	Shukla	Lin and Binns	Finlay and Wilkenson	Eberhart and Russel	Wricke	AMMI
Shukla	-					
Lin and Binns	-0.46	-				
Finlay and Wilkenson	0.33	-0.82	-			
Eberhart and Russel	0.87*	-0.29	0.20	-		
Wricke	1.00*	-0.46	0.33	0.87*	-	
AMMI	0.95*	-0.40	0.30	0.81*	0.95*	-

* Significant according to Student's *t* test at the P = 0.01 level

Table 6 Spearman's ranking order correlation coefficient matrix for six G × E stability analysis procedures conducted on 13 cultivars evaluated over 48 sites in the Eastern Free State

Statistical procedure	Shukla	Lin and Binns	Finlay and Wilkenson	Eberhart and Russel	Wricke	AMMI
Shukla	-					
Lin and Binns	0.11	-				
Finlay and Wilkenson	0.05	-0.80	-			
Eberhart and Russel	0.93*	0.27	-0.16	-		
Wricke	1.00*	0.11	0.05	0.93*	-	
AMMI	0.79*	0.22	-0.18	0.71*	0.79*	-

* Significant according to Student's *t* test at the P = 0.01 level

this technique are those generally associated with joint linear regression of genotype yield on trial site mean, viz. (i) that the trial site mean is not independent of the data being analysed, (ii) that regression coefficients are biased because of a critical assumption of regression analysis, viz. that the independent variable is measured without error, could not be met, and (iii) that regression coefficients are not always significant, in other words that a linear relationship between interaction and environmental (site) means is assumed. Due to statistical and biological limitations inherent to this technique, it is not recommended as a method of describing G × E interaction and determining stability of wheat genotypes in the Free State.

The Eberhart and Russel procedure shows highly significant correspondence with the procedures of Shukla and Wricke, as well as with AMMI but to a lesser degree than with Shukla and Wricke. Their definition of stability is based on a genotype's average sensitivity to environmental fluctuations and is determined by using joint linear regression analysis in which the average deviation from the regression, or response to environments, is determined. Hence, Eberhart and Russel's definition of a stable genotype is one of unit regression coefficient (b = 1.0) and deviations from the regression as small as possible ($S^2d_i = 0$). From this definition it is clear that Eberhart and Russel's stability can be aligned to Becker and Léon's (1988) dynamic concept of stability, as well as to Type III stability as defined by Lin *et al* (1986). However, Lin *et al.* (1986) found Type III stability to be the least attractive type of stability since a poor fit (S^2d_i large) should be taken as an indication that the use of the regression model to estimate stability is not adequate, and not taken as a measure of instability, and that other approaches to determine stability should be investigated. Many conflicting opinions still surround this type of stability measure, least of which are the limitations also generally ascribed to linear regression analysis (see discussion on Finlay and Wilkenson procedure). While this type of stability analysis may be useful due to its simplicity and certain biological relevance, it must be used

Table 7 Student's *t* test for significance[a] of Spearmans rank correlation coefficient for the Western Free State

Statistical procedure	Shukla	Lin and Binns	Finlay and Wilkenson	Eberhart and Russel	Wricke	AMMI
Shukla	-					
Lin and Binns	-1.36	-				
Finlay and Wilkenson	1.32	-6.85	-			
Eberhart and Russel	5.36*	-1.49	2.49	-		
Wricke	*	-1.36	1.32	5.36*	-	
AMMI	7.79*	-0.54	0.82	3.25*	7.79*	-

[a] t t(0.01; 11df) = *

Table 8 Student's *t* test for significance[a] of Spearmans rank correlation coefficient for the Central Free State

Statistical procedure	Shukla	Lin and Binns	Finlay and Wilkenson	Eberhart and Russel	Wricke	AMMI
Shukla	-					
Lin and Binns	-1.72	-				
Finlay and Wilkenson	1.16	-4.76	-			
Eberhart and Russel	5.86*	-1.01	0.68	-		
Wricke	*	-1.72	1.16	5.86*	-	
AMMI	10.10*	-1.45	1.04	4.59*	10.10*	-

[a] t t(0.01; 11df) = *

Table 9 Student's *t* test for significance[a] of Spearmans rank correlation coefficient for the Eastern Free State

Statistical procedure	Shukla	Lin and Binns	Finlay and Wilkenson	Eberhart and Russel	Wricke	AMMI
Shukla	-					
Lin and Binns	0.36	-				
Finlay and Wilkenson	0.17	-4.43	-			
Eberhart and Russel	8.40*	-0.93	0.54	-		
Wricke	*	-0.36	0.17	8.40*	-	
AMMI	4.28*2	-0.75	0.61	3.35*	4.28*	-

[a] t t(0.01; 11df) = *

with caution and the limitations noted with this analysis approach should be considered when interpreting results. The use of this model in describing G × E interaction and stability of genotypes is recommended on condition that it is used in conjunction with other, preferably multivariate, methods of analyses. Becker and Léon (1988) noted that the regression approach is most useful in either very low- or very high-yielding environments to which certain genotypes may be specifically adapted. This is typical of the production regions of the Free State where especially very low-yielding environments, such as parts of the Western (South Western area) and Central Free State, are common. This also explains why genotypes such as SST 124, Karee and Scheepers 69 have been particularly popular in these low yield potential areas over the past few years. Using the regression approach could assist in identifying and recommending the best genotypes for these environments.

From Tables 6, 7 and 8 it can be seen that rank correlation coefficients of 1.0 exist between Shukla's and Wricke's procedures over all three regions. This indicates that the two procedures are equivalent for ranking purposes, as Wricke and Weber (1980) also noted. The procedures of Wricke and Shukla are statistically similar and are based on using the G × E interaction effects for each genotype as stability measures. Shukla's stability variance can be defined as a linear combination of deviation mean squares, in other words of Wricke's ecovalence. Both procedures have Type II stability, according to Lin *et al.* (1986), and fall into the dynamic stability concept of Becker and Léon (1988). They furthermore show highly significant correspondence to the AMMI model stability. Since the Wricke and Shukla stability measures are in essence so similar, either can be used to good effect to describe the stability of the respective genotypes. However, the information supplied is limited in that the response pattern and adaptation of these genotypes can not be gleaned from these procedures. For this reason it is recommended that these two stability measures either be used in conjunction with the regression approach, despite the noted deficiencies inherent to this approach, or preferably with the AMMI model in identifying and recommending superior genotypes for wheat producers in the Free State.

Following the comparison of stability procedures and identification of the most suitable techniques, the yield stability of the genotypes can be described. The cultivars with the best stability in the Western Free State were Oom Charl, Tugela-DN, SST102, Molen, Molopo and Scheepers 69, while Caritha, Carina, Letaba, Karee and SST 124 showed the greatest instability. In the Central Free State, the cultivars with the best stability were Betta, Oom Charl, SST 102, SST 124, Molopo and Scheepers 69, with Karee, Caritha, Carina, Letaba, Carol and Tugela-DN having the greatest instability. In the Eastern Free State, the cultivars with the greatest yield stability were SST 102, Oom Charl, Molopo, Tugela-DN, Betta and Carina, while Karee, Letaba, Scheepers 69, Carol and Caritha showed the greatest instability. The response pattern showed certain similarities over regions, for example, Oom Charl, SST 102, Molopo and to a lesser extent Betta always showing good yield stability, and Karee, Letaba, Caritha and Carol showing consistent instability. However, cultivars such as Scheepers 69, Tugela-DN, Carina, SST 124 and Molen showed variable stability over regions.

Conclusion

From the study it would appear that if a single method of describing the stability of a genotype had to be selected, the AMMI Stability Value, derived from the AMMI model, would be the most appropriate. Becker and Léon (1988) stated that multivariate methods are too sophisticated to provide any simple measure of yield stability which allow a ranking of genotypes. However, a relatively simple estimate has been proposed in this study, using IPCA1 and IPCA2 scores to determine an AMMI Stability Value, which can be ranked in order to identify superior genotypes. Not only has it been shown to be highly correlated with the stability measures of Eberhart and Russel and especially Wricke and Shukla, but the sources of instability can be ascribed to different principal components, which in turn can more clearly be explained in terms of environmental and/or biological factor(s). For this reason it is recommended that this proposed stability measure (ASV) form the basis of analysing yield stability of wheat genotypes in the Free State wheat producing regions, as well as to be used in identifying superior genotypes to be released as cultivars for commercial production.

Acknowledgements

We hereby gratefully acknowledge the contribution of the following technical personnel who assisted in making this study possible: Mrs Jeanette du Plessis for making up the trials, as well as supervising the cleaning of seed and data collection and Mr Adriaan Botha for the planting, maintenance and harvesting of the trials. Our sincere appreciation also goes to Dr Ben Eisenberg and Mrs Marie Smith for valuable suggestions and comments. Finally our sincere thanks and appreciation to the Director of Small Grain Institute, Dr J. le Roux, as well as the Agricultural Research Council, who made this study possible.

References

BECKER, H.C., 1981. Correlations among some statistical measures of phenotypic stability. *Euphytica* 30, 835–840.

BECKER, H.C. & LÉON, J., 1988. Stability analysis in plant breeding. *Plant Breeding* 101, 1–23.

CROSSA, J., 1990. Statistical analyses of multilocation trials. *Advances in Agronomy* 44, 55–86.

EBERHART, S.A. & RUSSEL, W.A., 1966. Stability parameters for comparing varieties. *Crop Sci.* 6, 36–40.

FINLAY, K.W. & WILKENSON, G.N., 1963. The analysis of adaptation in a plant-breeding programme. *Aust. J. Agric. Res.* 14, 742–754.

GAUCH, H.G., 1982. In: Multivariate analysis in community ecology. 1st ed. Cambridge Univ. Press, London and New York.

GAUCH, H.G., 1988. Model selection and validation for yield trials with interaction. *Biometrics* 44, 705–715.

HOHLS, T., 1995. Analysis of genotype-environment interactions. *S. Afr. J. of Sci.* 91, 121–124.

LIN, C.S. & BINNS, M.R., 1988a. A superiority measure of cultivar performance for cultivar × location data. *Can. J. Plant Sci.* 68, 193–198.

LIN, C.S. & BINNS, M.R., 1988b. A method of analyzing cultivar × location × year experiments: A new stability parameter. *Theor. Appl. Genet.* 76, 425–430.

LIN, C.S., BINNS, M.R. & LEFKOVITCH, L.P., 1986. Stability analysis: Where do we stand? *Crop Sci.* 26, 894–900.

PERKINS, J.M. & JINKS, J.L., 1968. Environmental and genotype-environmental components of variability. III. Multiple lines and crosses. *Heredity* 23, 339–356.

PURCHASE, J.L., HATTING, H. & VAN DEVENTER, C.S., 2000. Genotype × Environment interaction of winter wheat (*Triticum aestivum* L.) in South Africa: I. AMMI analysis of yield performance. *S. Afr. J. Plant Soil* (submitted).

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

STEEL, R.G. & TORRIE, J.H., 1980. Principles and procedures of statistics. McGraw-Hill, New York.

WRICKE, G., 1962. Über eine methode zur erffassung der ökologischen Streubreite in feldversuchen. *Z. Pflanzenzüchtg.* 47, 92–96.

WRICKE, G. & WEBER, W.E., 1980. Erweiterte analyse von wechselwirkungen in versuchsserien. In: Biometrie- heute und morgen. Eds Köpcke & Überla. Springer-Verlag, Berlin.

ZOBEL, R.W., WRIGHT, M.J. & GAUCH, H.G., 1988. Statistical analysis of a yield trial. *Agron. J.* 80, 388–393.