PARAMETRIC ANALYSIS TO DESCRIBE GENOTYPE X ENVIRONMENT INTERACTION AND YIELD STABILITY IN WINTER WHEAT

BY

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Chapter 1

INTRODUCTION

The Free State province of South Africa produces on average approximately 45 per cent 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 predominantly during the summer rainfall months of December, January, February and March.

Based on soil and climatic characteristics, the Free State is subdivided into three distinct production regions, vizably the Western, Central and Eastern Free State. (i) The Western Free State is generally characterised by deep (1.2 - 2.0 m) sandy loam soils with a fairly good water holding capacity. There are areas in this region (north western Free State) that have a fluctuating watertable that can influence yields considerably in certain years. Long term rainfall varies from 450 - 550 mm per annum. However rainfall is extremely variable and erratic within seasons and especially over years. High spring and especially summer maximum temperatures, as well as low humidity, often result in a very high evaporative demand which regularly leads to serious drought and heat stress of the wheat crop. Together with other risk factors, such as poor secondary root development and frost damage, the region generally has a highly variable grain yield potential ranging from low (0.5 ton ha^{-1}) to high (4.0 ton ha^{-1}), and coupled with considerable risk. The optimum planting date is generally early and ranges from mid April to the end of May to improve the chances of secondary root development, as well as to escape the high maximum temperatures of late October, November and December.

(ii) The Central Free State is characterised by relatively shallow loamy soils (effective depth of 0.5 m to 1.0 m), predominantly of a duplex nature. The restricted water-holding capacity of these soils necessitates the supplementation of conserved soil

water by significant rainfall during the growing season, especially at around anthesis and then during the grain filling stage. The optimum planting date is late May to mid June to ensure the crop is generally at a development stage at which it can still benefit significantly from spring rains commencing in October. The timing and amount of spring rainfall largely determines the yield per hectare. This region generally has a higher annual rainfall of 550 to 650 mm and with a relatively lower evaporative demand. The region is however often subject to low yields due to drought stress conditions in the spring and early summer. The grain yield potential generally varies from 0.5 to 3.0 tons ha^{-1}.

(iii) The Eastern Free State is generally characterised by loamy soils of medium effective depth (0.7 m to 1.2 m) and fairly good water-holding capacity. However supplementation of conserved soil water by spring rainfall is essential to achieve economic yields in this region. Due to the ability to plant considerably later in this region (optimum planting date is 20 June to 20 July), and due to the higher rainfall (650 to 750 mm) and improved reliability of the rainfall, the crop can benefit from spring rainfall at a much earlier development stage (from flag leaf stage) to achieve higher and more consistent grain yields. Together with lower temperatures and a considerably lower evaporative demand, the area generally has a grain yield potential of 1.0 to 4.0 tons per hectare.

The considerable variation in environmental conditions, both of soil and climate, has led to considerable variation in performance of winter and facultative type wheat cultivars generally grown under dryland conditions in the Free State. This in turn has led to a remarkably wide range of winter to facultative to even spring type cultivars being released and recommended for commercial production, which again complicates cultivar choice for the producer. This considerable variation also creates considerable problems in a breeding programme as selection for genotypes with improved adaptation, quality and especially yield stability is based on data generated over a limited, and possibly not representative, number of years and sites.

A number of parametric statistical procedures have been developed over the years to analyse genotype x environment interaction and especially yield stability over environments. A number of different approaches have been used, for example joint regression analysis and multivariate statistics, to describe the performance of genotypes over environments. To date considerable differences in opinion still exist between the leading protagonists of the different statistical approaches as to the best and most suitable procedure to be used for a specific data set or production region.

The objectives of this study are thus to:

i) compare the various statistical methods of analysis with new statistical approaches to determine the most suitable parametric procedure to evaluate and describe wheat genotype performance under dryland conditions in the Free State province of South Africa,

ii) compare the various statistical procedures for assessing yield stability of the wide range of wheat genotypes grown under dryland conditions in the Free State, and thus determine the most suitable method,

iii) identify potential biological and statistical limitations that may influence biological and statistical interpretation of the specific data set,

iv) recommend to scientists/breeders the most appropriate procedure to estimate genotype performance and stability more accurately, 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.

CHAPTER 2

LITERATURE STUDY

Introduction

Genotype x Environment interactions (G x E) are an important issue facing plant breeders and agronomists world-wide and also in South Africa with its characteristically variable climate. Breeders constantly strive to develop improved genotypes that are superior not only in grain yield, but also in a number of other agronomic and quality characteristics, over a relatively wide range of environmental conditions. Plant breeders and agronomists generally agree on the importance of high yield stability, but there is less agreement on the most appropriate definition of stability and on methods to measure and improve yield stability. The basic cause of differences in yield stability between genotypes is the wide occurrence of G x E interactions. These interactions of genotypes with environments can be partly understood as a result of differential reactions to environmental stresses, such as drought, diseases and other factors (Becker & Léon, 1988).

Data collected in G x E trials are intrinsically complex and have three fundamental aspects: (a) structural patterns, (b) non-structural noise, and (c) relationships among genotypes, environments, and genotypes and environments considered jointly. Pattern implies that a number of genotypes respond to certain environments in a systematic, significant and interpretable manner, whereas noise suggests that the responses are unpredictable. The function of experimental design and statistical analyses of multilocation trials is thus to eliminate and discard as much of this unexplainable noise as possible (Crossa, 1990).

This literature study reviews some of the conventional and new methodologies of statistical analyses, and specifically stability analyses, for genotype evaluation trials. Certain statistical and biological limitations are also discussed. The objective is to test

these methodologies on a comprehensive wheat yield data set generated in the Free State province of South Africa for the period 1991 to 1994, and to determine which methodologies best suit stability analysis in this region.

Analysis of variance

In a conventional cultivar evaluation trial in which the yield of G genotypes is measured in E environments over R replicates, the classic model to analyse the total yield variation contained in GER observations, is the analysis of variance (Fisher, 1918; 1925). After removing the replicate effect when combining the data, the GE observations are partitioned into two sources: (a) additive main effects for genotypes and environments and (b) the non-additive effects due to genotype-environment interaction. The analysis of variance of the combined data expresses the observed (Y_{ij}) mean yield of the i^{th} genotype at the j^{th} environment as

$$Y_{ij} = \mu + G_i + E_j + GE_{ij} + e_{ij} \qquad (1)$$

Where μ is the general mean, G_i, E_j and GE_{ij} represent the effect of the genotype, environment and genotype x environment interaction respectively, and e_{ij} is the average of random errors associated with the r^{th} plot that receives the i^{th} genotype in the j^{th} environment. The non-additivity interaction (GE_{ij}) defined in (1) implies that an expected value (Y_{ij}) depends not only on the levels of G and E separately, but also on the particular combination of levels G and E (Crossa, 1990).

The most important limitation in this analysis is that error variances over environments should be homogeneous to test for genotype differences. If error variances are heterogeneous, this analysis is open to criticism as the F-test of the G x E interaction mean squares against the pooled error variances is biased towards significant results. A correct test of significance has however been used and proposed by Yates & Cochran (1938) and Cochran & Cox (1957), by weighting each genotype mean by the inverse of its estimated variance. This weighted analysis gives less weight to

environments that have a high residual mean square. The disadvantage of weighted analysis is however that weights may be correlated to environment yield responses (high-yielding environments showing higher error variance and low-yielding sites presenting lower error variances) and this could mask the true performance of some genotypes in certain environments (Crossa, 1990).

One of the principal deficiencies of the combined analysis of variance of multilocation yield trials is that it does not explore the underlying structure within the observed non-additivity genotype x environment interaction. Analysis of variance fails to determine the pattern of response of genotypes and environments, in other words the valuable information contained in (G-1)(E-1) degrees of freedom is practically wasted if no further analysis is performed (Crossa, 1990).

A useful aspect of analysis of variance is that variance components related to the different sources of variation, including genotype and G x E interaction, can be estimated. In general, variance component methodology is important in multilocation trials since errors in determining yield performance of a genotype arise largely from G x E interaction. Therefore knowledge of the size of the interaction is required to obtain efficient estimates of genotype effects and determine optimum resource allocations (number of plots and locations to be included in future trials). In a breeding programme, variance component methodology is used to measure genetic variability and to estimate the heritability and predicted gain of trait under selection. However, the nature and causes of the G x E interaction can not be established with variance components (Crossa, 1990).

Crossover interactions and non-parametric analysis

When genotype x environment interactions are present, the effects of genotypes and environments are statistically non-additive, which simply means that differences between genotypes depend on the environment. Existing genotype x environment interactions may, but must not necessarily, lead to different rank orders of genotypes

in different environments. For two genotypes A and B, and two environments Z and Y, the basic types of relationships between genotype and environment interactions and changes of rank are demonstrated schematically in Figure 2.1. It is especially crossover or qualitative interactions that are important in agricultural production, in contrast to non-crossover or quantitative interactions (Baker, 1988; Gail & Simon, 1985; Crossa, 1990).

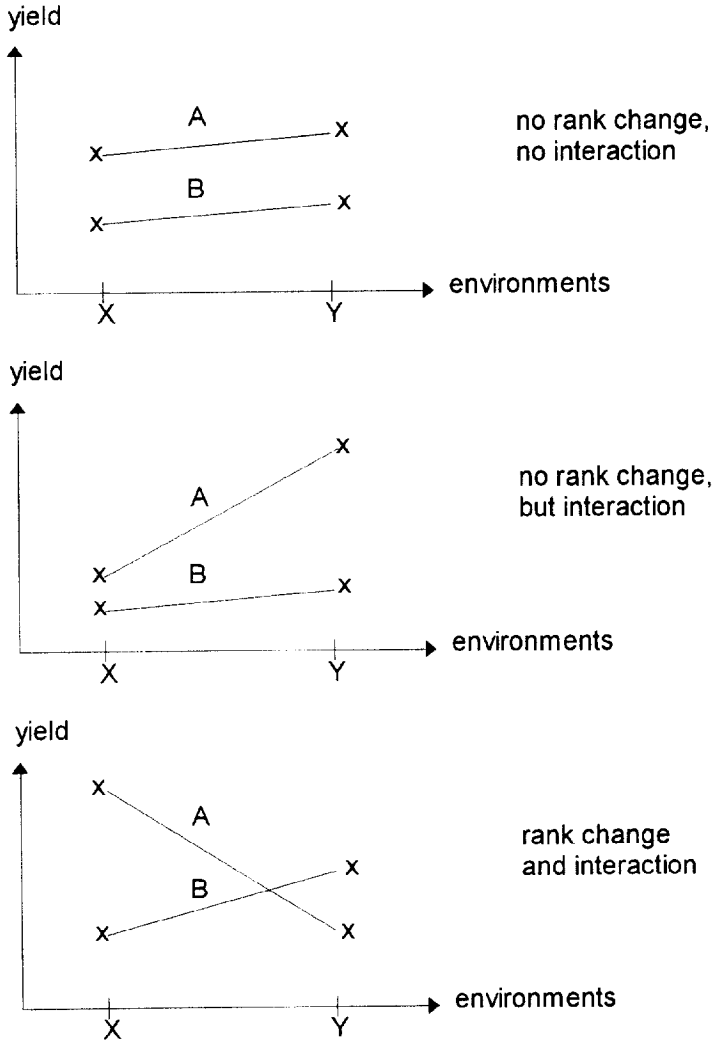

Figure 2.1 Genotype x environment interactions and changes of rank orders - different types of relationships (modified from Wricke, 1965).

In certain instances the breeder or agronomist is only interested in the existence of rank order differences over environments, which means that relative characteristics and comparisons of the genotypes are more important than absolute characterisations and comparisons. Therefore rank information, or so-called non-parametric analysis, can be used for a quantitative description of these relationships. Non-parametric statistics for genotype x environment interactions based on ranks provide a useful alternative to parametric approaches currently used, which are based on absolute data. Some essential advantages of non-parametric statistics compared to parametric ones are: (i) reduction or avoidance of the bias caused by outliers, (ii) no assumptions are needed about the distribution of the analysed values and (iii) homogeneity of variances and additivity of effects are not necessary requirements. Statistics based on ranks and rank-orders are often easy to use and interpret. Hühn (1996) has studied non-parametric analysis in detail and concluded that the procedure proposed by De Kroon & Van der Laan (1981) appears to be the most appropriate one for plant breeding and cultivar evaluation.

Stability analysis : Concepts and classical analysis techniques

The concepts of adaptation and more specifically the stability of a genotype in a breeding programme are ambiguous (Lin, Binns & Lefkovitch, 1986), often used in quite different senses (Becker & Léon, 1988) and consist of different statistical determinations and analyses (Crossa, 1990; Hohls, 1995). Lin *et al* (1986) identified three concepts of stability:

Type 1 is defined as a genotype being stable if its variance over a range of environments is small.

Type 2 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 3 stability is defined as a genotype being stable if the residual mean squares from the regression model on the environmental index is small, and was first introduced by Eberhart & Russel (1966).

Joint linear regression has been and still is an extensively used method for analysing and interpreting the non-additive G x E interaction of two-way classification data. The G x E interaction is partitioned into a component due to the linear regression (b_i) of the i^{th} genotype on environmental mean, and a deviation (d_{ij}):

$$(GE)_{ij} = b_i E_j + d_{ij} \quad (2)$$

$$\text{and thus } Y_{ij} = \mu + G_i + E_j + (b_i E_j + d_{ij}) + e_{ij} \quad (3)$$

Yates & Cochran (1938) first proposed the model in their evaluation of a barley yield trial. Detail about the interaction is obtained by regressing the performance of each genotype (genotype mean) on environmental means or indeces. Joint linear regression analysis also provides a way of testing whether genotypes have characteristic linear responses to changes in environment (Hohls, 1995). The regression technique has over the years been described and elaborated on. Finlay & Wilkenson (1963) determined the regression coefficient by regressing Y_{ij} values (see (1)) on the environmental mean, and then plotting the obtained genotype regression coefficients against the genotype mean yields. Figure 2.2 is a generalised interpretation of the genotype pattern obtained when genotype regression coefficients are plotted against genotype mean yields.

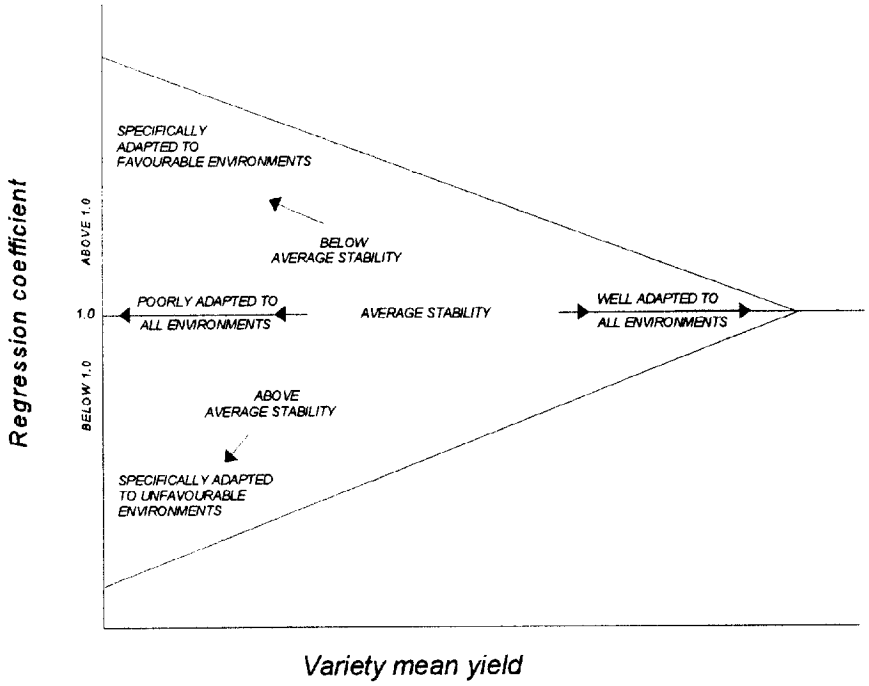

Figure 2.2 A generalised interpretation of the variety population pattern obtained when variety regression coefficients are plotted against variety mean, according to Finlay and Wilkenson (1963).

Perkins & Jinks (1968) proposed an equivalent statistical analysis whereby the GE interaction effects are regressed on the environmental effects.

Eberhart & Russel (1966) proposed pooling the sum of squares for environments and genotype x environment interactions and subdividing it into a linear effect between environments (with 1df), a linear effect for genotype x environment (with G-1 df), and a deviation from regression for each genotype (with E-2 df). In effect the residual mean squares from the regression model accross environments is used as an index of stability, and a stable genotype is one in which the deviation from regression mean squares ($S^2 d_i$) is small:

$$S^2 d_i = \frac{1}{E-2}[E_j(X_{ij} - \overline{X}_{i\cdot} - \overline{X}_{\cdot j} + \overline{X}_{\cdot\cdot})^2 - (b_i - 1)^2 E_j(\overline{X}_{\cdot j} - \overline{X}_{\cdot\cdot})^2]$$

It was not until this era that the problem of solving the intractable genotype x environment interaction problem could be solved. Subsequently Freeman (1973), Hill (1975) and Westcott (1986) have reviewed the regression approach to study G x E interaction extensively, while Pinthus (1973) proposed to use the coefficient of determination (r_i^2), instead of deviation mean squares, to estimate stability of genotypes. However r_i^2 is strongly related to S^2d_i, but the application of r_i^2 and b_i have the advantage that both statistics are independent of the units of measurement (Becker & Léon, 1988).

However, despite the advantage of certain meaningful interpretations of G x E interaction through joint linear regression, several statistical and biological limitations and criticisms of this method should be noted.

The first statistical criticism is that the environmental index is not independent of the data analysed. Regressing one set of variables on another that is not independent violates one of the assumptions of regression analysis and Freeman & Perkins (1971), as have others, suggested that the regression approach should be based on the use of an independent measure of environment. This interdependence is however only a major problem for small numbers of genotypes, but not when the number is relatively large (> 12), as the relative contribution of each genotype to environmental average is considerably smaller and this results in greater independence between the X and Y value.

The second statistical limitation is that a linear relationship between interaction and environmental means is assumed (Westcott, 1986). When this assumption is violated, the effectiveness of the analysis is reduced and the consequent results may be misleading (Mungomery, Shorter & Blyth, 1974). When more than one factor, for example drought and disease, limit yields over years and sites, reducing G x E to a single factor, which linear regression does, then the linear regression will not be valid.

The third statistical limitation is that errors associated with the slopes of genotypes are not statistically independent because the sum of squares for deviation, with (G-1)(E-2) df, cannot be subdivided orthogonally among the G genotypes (Crossa, 1990).

Furthermore, a major biological problem arises when only a few very low or very high yielding sites are included in the analysis. The genotype fit may be determined largely by its performance in a few extreme environments, which in turn generates misleading results, as has been indicated by Westcott (1986). Crossa (1990) also found that regression analysis should be used with caution when the data set includes results from only a few extremely high or low yielding locations. Similarly, Becker & Léon (1988) stated that it would be impossible to calculate useful stability measures from a few environments only. Locations, years and cultural practices will sometimes result in similar reactions of a genotype and these can replace each other, but this depends upon the material and the geographic region and should not generally be taken for granted.

According to Crossa (1990), a second biological criticism of the regression method is that the relative stability of any two genotypes depends not only on the particular set of environments included, but also on the other genotypes that are included in the analysis. It has been shown that the stability of a genotype depends on the mean performance of the group of genotypes with which it is being compared.

In discussing the most appropriate biometrical method, Becker & Léon (1988) noted that the regression approach is of little use if the regression coefficient (b_i) is included in the definition of "stability" . For this reason b_i is generally viewed by authors not as a measure of stability, but rather as additional information on the average response of a genotype to advantageous environmental conditions. This approach is schematically presented in Figure 2.3.

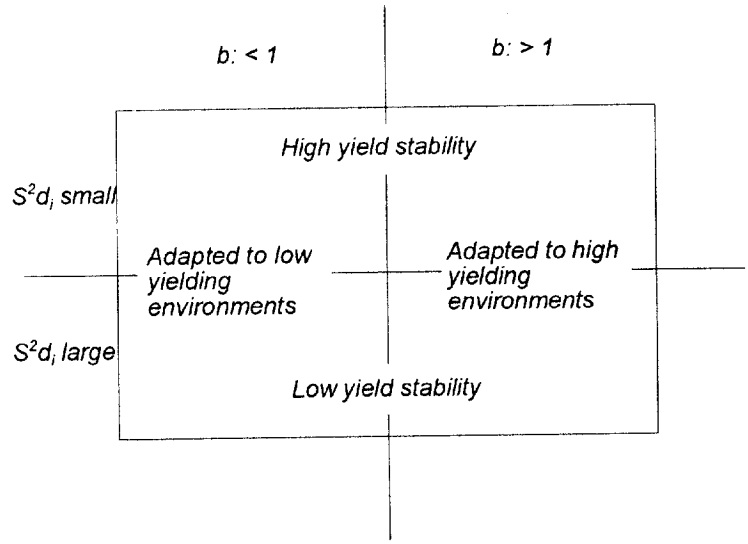

Figure 2.3 Interpretation of the parameters b_i and S^2d_i of the regression approach (adapted from Haufe and Geidel (1978) by Becker & Léon, 1988).

Usually only a small part of G X E interactions can be explained by a heterogeneity of regression lines since in a "normal" series of trials most environments have near-average yield levels which lead to genotypes generally having b_i values close to 1. However, in situations where there is considerable variability from year to year or over environments, the regression approach may be very useful in determining b_i as an indicator of response to variable environmental conditions. Becker & Léon (1988) also cautioned that the choice of material will always influence an analysis of G X E-interaction and has to be considered when discussing the results.

There are however also alternative methods of determining genotype stability based on G X E interaction effects. The more important and frequently used methodologies are examined and discussed.

Wricke (1962) proposed using the contribution of each genotype to the G X E interaction sum of squares as a stability measure and defined this concept or statistic as ecovalence (W_i). Ecovalence is simple to compute and is expressed as:

$$W_i = \sum_j [Y_{ij} - \overline{Y}_{i\cdot} - \overline{Y}_{\cdot j} + \overline{Y}_{\cdot\cdot}]^2$$

where Y_{ij} is the mean performance of genotype *i* in the j^{th} environment and $Y_{i.}$ and $Y_{j.}$ are the genotype and environment mean deviations respectively, and $Y_{..}$ is the overall mean. For this reason, genotypes with a low W_i value thus have smaller deviations from the mean across environments and are thus more stable. Becker & Léon (1988) illustrated ecovalence by using a numerical example of plot yields of genotype *i* in various environments against the respective mean of environments (Figure 2.4).

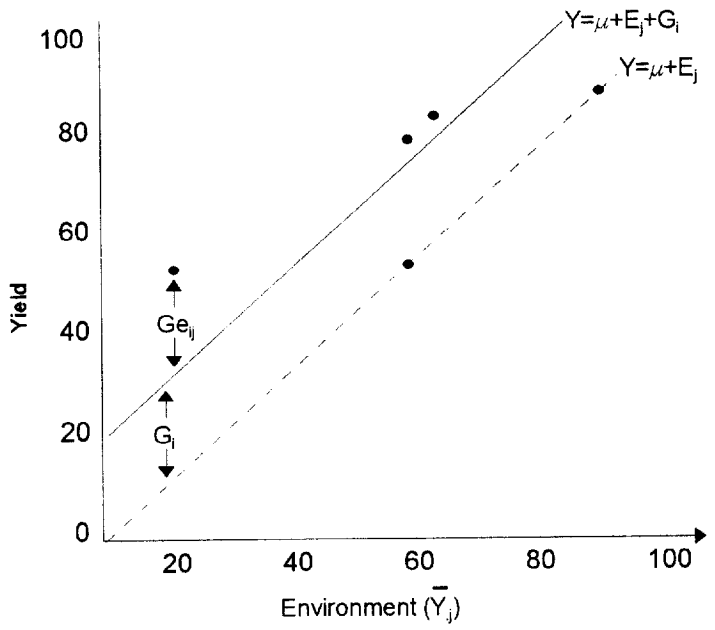

Figure 2.4 Graphical representation of G X E interactions: the stability statistic ecovalence (W_i) is the sum of squares of the deviations from the upper straight line.

The lower straight line estimates the average yield of all genotypes simply using information about the general mean (μ) and the environmental effects (E_j), while the upper line additionally takes into account the genotype effect (G_i) and therefore estimates the yield of genotype *i*. Deviations of yields from the upper straight line are the G X E interaction effects of genotype *i* and are summed and squared across environments and constitute ecovalence.

Shukla (1972) defined the concept of stability variance as an unbiased estimate of the variance of genotype *i* across environments after the removal of environmental main effects. Since the genotype main effect is constant, the stability variance is thus based on the residual (GE_{ij} + e_{ij}) matrix in a two-way classification. The stability statistic is termed "stability variance" (σ^2_i) and is estimated as follows:

$$\sigma_i^2 = \frac{1}{(G-1)(G-2)(E-1)}[G(G-1)\sum_j (Y_{ij} - \overline{Y}_{i\cdot} - \overline{Y}_{\cdot j} + \overline{Y}_{\cdot\cdot})^2 - \sum_i \sum_j (Y_{ij} - \overline{Y}_{i\cdot} - \overline{Y}_{\cdot j} + \overline{Y}_{\cdot\cdot})^2]$$

A genotype is called stable if its stability variance (σ^2_i) is equal to environmental variance (σ^2_e), which means that $\sigma^2_i = 0$. A relatively large value of σ_i^2 will thus indicate greater instability of genotype *i*. As the stability variance is the difference between two sums of squares, it can be negative, but negative estimates of variances are not uncommon in variance components problems. Negative estimates of σ^2_i may be taken as equal to zero as usual.

Shukla (1972) used the data of Yates & Cochran (1938) to illustrate the concept of stability variance. Stability variance as a stability statistic makes use of the usual regression approach and is equivalent to ecovalence for ranking purposes (Wricke & Weber, 1980). Shukla's (1972) definition of stability is similar to that of Eberhart & Russel (1966) in which a significant departure of the regression of a genotype from zero will be indicated by a relatively high "stability variance", but a regression coefficient of zero need not mean that the particular genotype is stable, which is Type I stability according to Lin *et al.* (1986). Stability variance can be associated with Type II stability, as can Wricke's (1962) ecovalence and Finlay and Wilkenson's (1966) procedure, according to Lin *et al*, 1986.

Lin & Binns (1988a; 1988b) proposed the use of 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 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 first term of the equation represents the genotype sum of squares, and the second term is the G X E sum of squares. The smaller the value of P_i, the less its distance to the genotype with maximum yield and thus the better the genotype. A pairwise G X E interaction mean square between the maximum and each genotype is also determined and is similar to the method used by Plaisted & Peterson (1959). The difference however is that, firstly, the stability statistic is based on both the average genotypic effects and G X E interaction effects, and secondly, each genotype is compared only with the one maximum response at each environment (Crossa, 1990).

Stability methods based on the genotype-environment interaction sum of squares correspond to Type II stability, whereas the Eberhart & Russel (1966) method is Type III stability. Lin *et al.* (1986) point out that the parametric approach has the advantage of computational simplicity and only addresses certain aspects of stability, without giving an overall picture of the genotype's response. For example, a genotype may have Type II stability and simultaneously Type III instability (Crossa, 1990). Lin *et al* .(1986) recommended that scientists should firstly define what type of stability they require, as well as understand the kind of environments that are to be used in the experiment, before considering what statistic to use.

Becker & 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 any variation of the environments, thus implying that its variance among environments is zero. This is equivalent to 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 has no deviation from this response to environments. Becker (1981) termed this type of stability the agronomic concept to distinguish it from the biological or static concept. Becker & Léon (1988) stated that all stability procedures based on quantifying G X E interaction effects belong to the dynamic stability concept. Included are procedures partitioning G X E interaction, such as Wricke's (1962) ecovalence and Shukla's (1972) stability of variance, procedures using the regression approach such as proposed by Finlay & Wilkenson (1963), Eberhart & Russel (1966) and Perkins and Jinks (1968), as well as non-parametric stability statistics.

Stability analysis : Multivariate analysis techniques

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 (Crossa, 1990; Gauch, 1982b; Hohls, 1995). Becker & 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 X E-interactions occur, while differences among subsets are due to G X E-interactions. Numerous dissimilarity measures and 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). The basic aim of the geometrical methods is to represent each genotype by a point in a Euclidean space, a dimensional space representative of environments with the coordinate of an individual axis being the yield (or other parameter) of the genotype in a particular environment.

Crossa (1990) distinguished between two groups of multivariate techniques to explain the internal structure of G X E interaction:

- The first is ordination techniques, such as principal component analysis, principal coordinates analysis and factor analysis, which assume data to be continuous. They attempt to represent data realistically in a low-dimensional space, with similar genotypes and environments near each other, and dissimilar items further apart. Ordination is effective for showing relationships and reducing noise (Gauch, 1982a; 1982b; cited by Crossa, 1990).

- The second is classification techniques, such as cluster analysis and discriminant analysis, that seek discontinuities in the data. These methods involve grouping similar entities in clusters and summarising redundancies in data effectively.

Principal components analysis (PCA) is one of the most frequently used multivariate methods (Pearson, 1901; Hotelling, 1933; Gower, 1966, cited by Crossa (1990)). Its aim is to transform the data from one set of coordinate axes to another, which preserves, as far as possible, the original configuration of the set of points and concentrates most of the data structure in the first principal components axis. Various limitations have been noted for this ordination technique. Crossa (1990) notes that PCA is a generalisation of linear regression, but that it overcomes the problem of univariate analysis by giving more than one statistic (scores on principal component axes) to describe the response pattern of a genotype (Eisemann, 1981).

Principal coordinates analysis, first used by Gower (1966), is a generalisation of principal components analysis in which any measure of similarity between individuals can be used. Its objectives and limitations are similar to those of PCA (Crossa, 1990), but has been used and advocated by Westcott (1987) and Crossa *et al,* (1988).

Factor analysis is similar to PCA in that the variables of factor analysis are similar to the components of the latter. Variation is explained in terms of general factors common to all variables and in terms of factors unique to each variable (Crossa, 1990).

Cluster analysis is a numerical classification technique that defines groups or clusters of individuals, and is distinguished by two types of classification, vizably non-hierarchical and hierarchical classification. Crossa (1990), as did Becker & Léon (1988), noted several limitations to this technique.

Stability analysis: AMMI analysis

The additive main effects and multiplicative interaction method, widely known as the AMMI model, combines analysis of variance for genotype and environment main effects with principal components analysis of the G X E interaction into a unified approach (Gauch, 1988; Zobel, Wright & Gauch, 1988). The results can be graphically represented in an easily interpretable and informative biplot which shows both main effects and G X E interaction. The AMMI model has been used extensively and with success over the past few years to analyse and understand various crop genotype x environment interactions by Yau (1995), Smith & Smith (1992), Steyn, Visser, Smith & Schoeman (1993), Crossa *et al.* (1990), and by many others.

The AMMI model equation is expressed as follows:

$$Y_{ij} = \mu + G_i + E_j + (\sum_{n-i}^{h} k_n V_{ni} S_{nj}) + e_{ij}$$

Where k_n is the singular value for interaction principal component of the n^{th} axis, V_{ni} is the eigenvector of the i^{th} genotype for the n^{th} axis, S_{nj} is eigenvector of the j^{th} environment for the n^{th} axis and $\sum_{n-1}^{h} V_{ni} = \sum_{n-1} S_{nj} = 1$ (Gauch, 1988; Zobel *et al.*, 1988).

In any multilocation or yield trial research aimed at breeding or recommending superior genotypes, the breeder/agronomist faces two fundamental problems and challenges: interaction and noise. Were there no interaction, a single variety of wheat would for

example yield the most world over, and furthermore, the variety trial need then only be conducted at one location to provide universal results. Were there no noise, results would be exact and there would be no need for replication. Gauch & Zobel (1996), citing Ceccarelli (1989), Simmonds (1991), Zavala-Garcia, Bramel-Cox & Eastin (1992), further state that there are two options to the problem, one aimed at the genotypes and the other at the environments.

One option is to seek a high-yielding, widely adapted genotype that wins throughout the growing region of interest. The second option, especially relevant if the first fails, is to subdivide the growing region into several relatively homogenous macro-environments and then breed and/or recommend genotypes for each. Gauch & Zobel (1996) indicated that AMMI addresses both the challenges of interaction and noise, as well as assists in investigating the abovementioned options. This is particularly relevant to the objectives of this study.

The AMMI model is particularly useful in understanding G X E interactions and summarising patterns and relationships of genotypes and environments (Zobel, 1990; Crossa *et al*, 1990; Crossa, 1990). In the initial analysis of variance (ANOVA) the total variation is partioned into three orthogonal sources, vizably genotypes (G), environments (E) and G X E interactions. Gauch & Zobel (1996) cite Romagosa, Fox, Garcia Del Moral, Ramos, Garcia Del Moral, Roca De Togores & Molina Cano, (1993) as saying that "in most yield trials, the proportion of sum of squares due to differences among sites ranged from 80 to 90 per cent, and variation due to G X E interactions was usually larger than genotypic variation". They further state that in AMMI analysis the IPCA sum of squares alone is usually larger than for G. As the genotypes become more diverse and environments likewise, G X E tends to increase and may reach 40 per cent to 60 per cent of total variation. Normally the environment main effect, which contributes up to 90 per cent of the total variation, is fairly irrelevant, especially in selection procedures. The AMMI model can produce graphs (biplots) that focus the data structure relevant to selection, in other words on the G and G X E sources.

In using the part of the AMMI analysis, PCA partitions G X E interaction into several orthogonal axes. Concern has been expressed by the number of axes the best AMMI model includes in its analysis, and how assessments and presentations of genetic stability can be made if too many axes are included. Gauch & Zobel (1996) state that generally AMMI 1 and AMMI 2 models, with IPCA 1, and IPCA 1 and IPCA 2 respectively, are usually selected and that the graphical representation of axes, either as IPCA 1 or IPCA 2 against main effects, or IPCA 1 against IPCA 2, is not a problem and generally is informative. With AMMI 3 and higher models, IPCA 3 and higher axes are generally dominated by noise, have little or no predictive value and no biological interpretability, and can thus be discarded.

Several authors, including Westcott (1986), Becker & Léon (1988) and Hohls (1995), have questioned whether significant IPCA axes are interpretable in terms of known properties of the genotypes and environments. Gauch & Zobel (1996) state that not only has extensive experience indicated the interpretability of a relatively large IPCA 1, but that from a statistical perspective, significant model parameters indicate that identifiable physical or biological causes are at work. By various means the pattern in AMMI parameters or biplot can usually be interpreted clearly in terms of evident environmental or genetic factors. AMMI results may also illuminate plant physiological processes that cause genotypes to interact with environments, for example the growth period of a variety (Smit & De Beer, 1991).

Another primary use of the AMMI model is to improve the accuracy of yield estimates. Gains in accuracy of yield estimates are equivalent to increasing the number of replicates by a factor of two to five (Zobel *et al*, 1988; Crossa *et al,* 1990), so that AMMI analysis offers a remarkably cost-effective means for improving research efficiency and increasing returns on investment (Gauch 1993, cited by Gauch & Zobel, 1996).

Traditional analysis of variance of genotype yield trials is intended to forecast yield performance but focuses only on the postdictive assessment of the genotype yield response, without evaluating the model's predictive accuracy with validation data not

used in constructing the model (Crossa, 1990). Gauch (1988) emphasised the AMMI model's success in predicting validation data in contrast to its success in only fitting its own data. A simple method for quantifying a model's predictive accuracy is data-splitting or cross validation, for which part of the data is used for model construction and the remainder for model validation (Gauch 1988; Gauch & Zobel, 1988). This procedure is used for AMMI in the MATMODEL computer software programme (Gauch & Furnas, 1991). The resultant statistic is RMS prediction difference (RMSPD), which is the root mean square difference between a model's predicted value and a validation observation's actual value. A low RMSPD is desirable, meaning the model's predictions are close to the validation data. A table showing RMSPD values for the AMMI family can be used to select the most predictively accurate member of the AMMI family for a given data set. The outcome is typically "Ockham's hill", with an intermediate model (often AMMI 1 or AMMI 2 as stated earlier) most accurate, with simpler models underfitting real patterns and more complex models overfitting spurious noise (Gauch & Zobel, 1996).

Summary

The subject of statistical analyses of multilocation trials and more specifically of Genotype x Environment interaction and the concomitant stability analysis involved, has been reviewed extensively by among others, Lin *et al* (1986), Becker & Léon (1988), Crossa (1990) and in South Africa by Hohls (1995). The respective authors differ considerably in their opinions as to which methodology is best suited in describing G X E interaction and genotype stability. However, there is accord on the necessity to describe the genotypic and environmental (climate and geographic) factors accurately to draw meaningful conclusions from the resultant analyses.

CHAPTER 3

MATERIALS AND METHODS

3.1 Materials

Thirteen genotypes listed in Table 3.1 were evaluated over a four year period from 1991 to 1994 over a total of 120 environments in the Free State province of South Africa.

Table 3.1 Pedigree, type and date of release of genotypes evaluated over 120 environments in the Free State province from 1991-1994

Genotype	Release date	Type	Pedigree
Betta	1969	Tall, facultative pureline	Klein Impacto
Molopo	1988	Tall, facultative pureline	Betta//Monon/ATR.OH 130
SST 102	1979	Tall, facultative pureline	Betta*2//Agent
Karee	1982	Tall, facultative pureline	Betta//Triumph/CI 13523
Oom Charl	1987	Tall, facultative pureline	Betta//M.N.*1972
Molen	1986	Tall, winter pureline	Betta/3/Yt//N10B/MZ
SST 124	1987	Tall, facultative pureline	Bezostaya//Betta/Line W
Letaba	1987	Semi-dwarf, winter pureline	WRR*5/AG/Kavkaz
Scheepers 69	1967	Tall, winter pureline	Selection from Scheepers
Caritha	1986	Semi-dwarf, winter hybrid	Not available
Carina	1985	Semi-dwarf, winter hybrid	Not available
Carol	1986	Semi-dwarf, winter hybrid	Not available
Tugela-DN	1992	Semi-dwarf, facultative pureline	Tugela*4/SA 1684

Table 3.2 indicates the sites at which the trials were conducted. Different planting dates were used at each site to sample within the relatively wide planting date range for wheat in each area. The severe drought of 1992 precluded the planting of wheat in most of the Free State. The years 1991 and 1993 were characterised by fair to good

Table 3.2 Location, coordinates and dominant soil type of genotype evaluation trials in the Free State province from 1991-1994

Region	Site (District)	Coordinates	Dominant soil type	Number of trials			
				91	92	93	94
Western Free State	Petrusburg	29° 7' S 25° 7' E	Hutton	2	2	2	2
	Bainsvlei Monoc	29° 0' S 25° 58' E	Bainsvlei	2	-	-	-
	Bainsvlei Fallow		Bainsvlei	2	-	-	-
	Christiana	28° 5' S 25° 11' E	Clovelly	1	-	-	-
	Bultfontein Monoc	28° 18' S 26° 27' E	Clovelly	2	-	-	2
	Bultfontein Fallow		Clovelly	2	2	2	2
	Hennenman	27° 55' S 27° 4' E	Avalon	2	-	2	2
	Hoopstad	27° 50' S 25° 57' E	Clovelly/Oakleigh	2	-	-	-
	Wesselsbron	27° 41' S 26° 33' E	Clovelly	-	-	2	2
	Leeudoringstad	27° 38' S 27° 14' E	Clovelly	1	-	-	1
Central Free State	Kroonstad	27° 36' S 27° 14' E	Westleigh	2	-	2	-
	Arlington	27° 3' S 27° 47' E	Westleigh	-	-	2	2
	Senekal	28° 18' S 27° 42' E	Westleigh	-	-	2	2
	Marquard	28° 30' S 27° 20' E	Westleigh	2	-	2	-
	Excelsior	28° 51' S 27° 7' E	Westleigh	2	-	2	2
	Tweespruit	29° 15' S 27° 2' E	Westleigh	2	-	2	-
	Ladybrand Valley	29° 15' S 27° 18' E	Westleigh	2	-	2	1
	Ladybrand Plato	29° 13' S 27° 19' E	Avalon	-	-	2	2
Eastern Free State	Clocolan	28° 58' S 27° 30' E	Avalon	2	-	2	1
	Clarens Monoc	28° 22' S 28° 26' E	Avalon	2	-	-	-
	Clarens Fallow		Avalon	2	-	2	1
	Bethlehem	28° 12' S 28° 18' E	Avalon	7	5	4	3
	Warden	27° 42' S 28° 52' E	Avalon	1	-	-	1
	Petrus Steyn	27° 43' S 28° 8' E	Avalon	2	-	2	1
	Reitz	27° 45' S 28° 33' E	Avalon	1	2	1	-
	Frankfort	27° 9' S 28° 27' E	Avalon	2	-	2	2

conditions which resulted in average to above average yields in certain areas. Severe drought over the whole wheat producing region limited yields considerably during the 1994 season. Table 3.3 indicates rainfall figures of each season for the respective sites (nearest weather station data).

Table 3.3 Annual rainfall* for the 22 cultivar trial sites over the period 1991 to 1994

Trial site	Weather Station Number	Long term average rainfall (mm)	Annual rainfall (January - December)			
			1991	1992	1993	1994
South Western						
Petrusburg	19849	406	714.5	175.1	548.7	256.2
Bainsvlei	20579	494	763.9	190.5	403.7	429.5
Christiana	19899	444	592.2	222.2	422.7	258.4
North Western						
Bultfontein	14588	466	579.0	318.5	371.0	249.5
Hennenman	13438	487	809.0	237.6	546.5	402.3
Hoopstad	20369	402	635.0	234.0	540.0	291.0
Wesselsbron	19865	442	511.3	357.7	737.0	292.2
Leeudoringstad	15608	457	378.7	216.0	579.0	366.0
Central						
Kroonstad	15147	503	681.9	387.3	481.5	314.5
Arlington	14659	621	714.5	535.5	606.5	432.0
Senekal	20451	535	667.0	387.5	468.0	455.0
Marquard	19896	521	719.7	367.1	603.4	479.8
Excelsior	14178	493	826.7	340.5	593.3	327.6
Tweespruit	13837	578	771.8	351.5	592.8	494.6
Ladybrand	13880	653	761.0	420.9	561.3	563.6
Eastern						
Clocolan	13438	563	1008.5	237.6	546.5	500.3
Clarens	14740	626	636.9	598.2	650.5	634.5
Bethlehem	19833	655	767.5	649.4	814.6	577.1
Warden	15303	570	524.6	507.2	697.6	395.5
Petrus Steyn	15226	556	692.5	499.7	739.6	504.9
Reitz	19887	666	755.4	556.4	762.2	542.9
Frankfort	15723	571	501.0	438.0	778.0	498.0

* Data supplied by Agromet, ISCW.

A randomized block trial design with four replications was used throughout. Each trial was randomized individually. Trials were planted with a 5 row pneumatic precision drill to achieve a uniform plant density of approximately 50 plants m^{-2}. A constant plot length of 5 m and row width of 45 cm was used throughout to achieve a gross plot size of 11.25 m^2 and a nett plot of 6.75 m^2. Both the seeding rate and row width are optimal for dryland wheat production in the Free State. Fertilisation was performed according to target yield recommendations for each region. Sites in the North Western and Eastern Free State were fertilised at 240 kg 3:2:1 (25) to achieve fertilisation rates of 30 kg N ha^{-1}, 20 kg P ha^{-1} and 10 kg K ha^{-1} for the higher yield potential regions. Fertilisation for the lower yield potential South Western and Central Free State was 160 kg 3:2:1 (25) per hectare to achieve fertilisation rates of approximately 18 kg N ha^{-1}, 12 kg P ha^{-1} and 6 kg K ha^{-1}. P and K fertilisation was applied somewhat in excess of recommended levels for respective soil analysis results, so as not to be limiting. Supra-optimal application of P and K, within limits, do not influence yield and development either negatively or positively. However, supra-optimal N applications could lead to over-expansive growth with the available residual soil moisture and thus deplete the soil water sooner, often with disastrous consequences.

3.2 Determinations

Yield per unit area and the grade quality of the wheat grain, together with the costs involved to produce that yield, determine the profitability of wheat production. To this end the primary determination of genotype productivity is the yield per unit area, which is expressed in kg ha^{-1}. Three rows of 5 m length, with an interrow spacing of 45 cm, were harvested with a Wintersteiger plot harvester. Thereafter the grain was dried to 12.5 per cent moisture and passed through Dockage Tester sieves to rid the sample of any remaining chaff. The samples were then weighed and the data converted to kg ha^{-1} on a 12 per cent moisture basis.

The grading of wheat in South-Africa is based on two dominant quality aspects, vizably

hectolitre mass and protein content. Hectolitre mass is a density parameter (kg hl^{-1}) and is an indication to the miller of the potential flour yield of that sample. Protein content, together with protein quality, again indicates the bread-baking potential of that specific genotype. Generally, the higher the protein content, the better the bread-baking potential. For this reason hectolitre mass (kg hl^{-1}) and protein content (%) were also determined. In addition, certain agronomic characteristics were also noted to further characterise genotypes. For the purpose of this study, these quality and agronomic characteristics were however not included in the investigation.

3.3 Statistical analyses

A range of statistical analyses were conducted as follows:

3.3.1 Analysis of Variance

An analysis of variance (ANOVA) was performed on the yield data of each of the individual trials, using the statistical software computer programme, Agrobase 4. Thereafter combined analyses of variance were performed on the pooled data of all the trials for respectively the Western Free State (39 environments), Central Free State (33 environments) and Eastern Free State (48 environments), over the 4 year period using Agrobase 4.

3.3.2 Homogeneity of variances

Bartlett's test was used to establish the homogeneity of variances between environments to determine the validity of the combined analyses of variance on the data. Various transformations were conducted on the data set, but without success. Subsequently, weighted analyses were conducted for the different regions using the SAS statistical computer software programme.

3.3.3 *Shukla's procedure of stability variance*

Shukla's stability variance for each genotype across environments was determined by Agrobase 4 statistical programme. Shukla (1972) defined the stability variance (σ^2_i) of genotype *i* as its variance across environments after the main effects of environmental means had been removed. Since the genotype main effect is constant, the stability variance is based on the residual ($GE_{ij} + e_{ij}$) matrix. The stability variance (σ^2_i) is estimated as follows:

$$\sigma^{2_i} = \frac{1}{(G-1)(G-)(E-1)}[G(G-1)\sum_j (X_{ij}-\overline{X}_{i\cdot}-\overline{X}_{\cdot j}+\overline{X}_{\cdot\cdot})^2 - \sum_i \sum_j (X_{ij}-\overline{X}_{i\cdot}-\overline{X}_{\cdot j}+\overline{X}_{\cdot\cdot})^2]$$

3.3.4 *Lin & Binns' cultivar performance measure (P_i)*

The data set was analysed according to the procedure recommended by Lin & Binns (1988) where the values estimated are the squares of the differences between an entry (genotype) mean and the maximum genotype mean at a location, summed and divided by twice the number of locations. The computations were performed with the aid of Agrobase 4 statistical programme.

3.3.5 *Finlay & Wilkenson's joint regression analysis*

The data set was analysed according to the procedure proposed by Finlay & Wilkenson (1963). For each genotype a linear regression of genotype yield on the mean yield of all genotypes for each trial was computed to measure adaptation. The mean yield of all genotypes for each trial provided a quantitive grading of the environments. The two important indices in this analysis are the regression coefficient and the genotype mean yield over all environments. Regression coefficients approximating to 1.0 indicate average stability. When this is associated with high mean yield, genotypes have general adaptability, when associated with low mean yield, genotypes are poorly adapted to all the environments. Regression values increasing above 1.0 describe genotypes with increasing sensitivity to environmental change (below average stability),

and great specific adaptability to high-yielding environments. Regression coefficients decreasing below 1.0 provide a measure of greater resistance to environmental change (above-average stability), and therefore increased specific adaptability to low-yielding environments. The second index, the genotype mean yield over all environments, provides a comparative measure of performance of the individual genotypes. These two indices are plotted together as coordinates in a two dimensional scatter diagram to achieve further analysis (see Chapter 2).

3.3.6 Eberhart & Russel's joint regression analysis

Joint linear regression of the mean of the genotype on the environmental mean as an independent variable, was performed according tot the procedure proposed by Eberhart & Russel (1966). Of importance are the regression coefficient (b), the deviation from regression for each genotype (S^2d) and the mean yield (kg ha^{-1}) of the genotype over all the environments. Their model, $Y_{ij} = \mu_i + \beta_i I_j + \delta_{ij}$, defines stability parameters that may be used to describe the performance of a genotype over a series of environments. Y_{ij} is the genotype mean of the i th genotype at the j th environment, μ is the ith genotype mean over all environments, β_i is the regression coefficient that measures the response of the i th genotype to varying environments, β_{ij} is the deviation from regression of the i th genotype at the j th environment, and I_j is the environmental index.

3.3.7 Wricke's ecovalence

Wricke (1962) defined the concept of ecovalence as the contribution of each genotype to the genotype x environment interaction sum of squares. The ecovalence (Wi) or stability of the ith genotype is its interaction with environments, squared and summed across environments, and expressed as

$$W_i = \sum_j (Y_{ij} - \overline{Y}_{i\cdot} - \overline{Y}_{\cdot j} + \overline{Y}_{\cdot\cdot})^2$$

where $\overline{Y}_{ij}$ is the mean performance of genotype *i* in the jth environment and $\overline{Y}_i$ and $\overline{Y}_j$

are the genotype and environment mean deviations respectively, and $\overline{Y}_{..}$ is the overall mean. Accordingly, genotypes with low ecovalence have smaller fluctuations from the mean across different environments and are therefore more stable.

3.3.8 Additive Main Effects and Multiplicative Interaction Method (AMMI Model)

The additive main effect and multiplicative interaction (AMMI) method integrates analysis of variance and principal component analysis into a unified approach (Gauch, 1988) and is especially useful in analysing multi-location trials (Gauch & Zobel, 1988). The AMMI analysis first fits the additive main effects of genotypes and environments by the usual analysis of variance and then describes the non-additive part, the genotype-environment interaction, by principal component analysis (PCA). The AMMI analysis was performed using Matmodel 2.0 developed by Gauch (1988).

Since the AMMI model does not make provision for a specific stability measure to be determined, and as such a measure is essential in this study in order to rank genotypes in terms of stability, such a measure is proposed as follows:

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

In effect the AMMI Stability Value (ASV) is the distance from zero in a two dimensional scattergram of IPCA1 (Interaction Principal Component Analysis axis 1) scores against IPCA2 scores. (See Figures 4.8, 4.10 and 4.12). Since the IPCA1 score, however, generally contributes proportionately more to genotype x environment 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 X E sum of squares. The distance from zero is then determined by simply using the theorem of Pythagoras.

3.3.9 *Combined comparison of stability analysis procedures*

To statistically compare the six stability analysis procedures used in this study, it was decided to use Spearman's coefficient of rank correlation (Steel and Torrie, 1980). Spearman's coefficient of rank correlation applies to data in the form of ranks. All the cultivars evaluated in the three regions were respectively assigned stability values according to the procedure and definition used, which were then ranked in order to determine Spearman's rank correlation coefficient between different procedures.

Assume n genotypes are arranged in the same following order according to two stability parameters, and X_i indicates the ranking order (or ranking number) of the i^{th} genotype for the first parameter, while Y_i indicates the ranking number for the i^{th} genotype of the second parameter, then $d_i = X_i - Y_i$ ($i = 1,2, \ldots, n$) and Spearman's rank correlation coefficient (r_s) can be described as

$$r_s = 1 - \frac{6\sum d_i^2}{n(n^2-1)}$$

Ranking numbers are whole numbers and when two or more equal ranking numbers occur, the average of the ranking numbers that they otherwise would have received, are ascribed to each genotype.

The significance of r_s can be 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 is discarded and r_s is described as highly significant.

Chapter 4

RESULTS AND DISCUSSION

4.1 Analysis of variance

Tables 4.1a, 4.2a and 4.3a indicate the analyses of variance results for the Western, Central and Eastern Free State regions respectively. All three ANOVA's indicated highly significant differences for treatments, genotypes, environments and, most importantly, genotype x environment interaction. Variance components (%) of the sum of squares for treatments, ranged from 3.0 - 5.1 per cent for genotypes, from 85.6 - 89.9 per cent for environments and from 6.5 - 10.0 per cent for genotype x environment interaction. This indicates the overwhelming influence of the environment on yield performance of wheat cultivars in the respective wheat producing regions of the Free State. Additionally of important consequence is the relatively large proportion of variance (about double) attributable to genotype x environment interaction when compared to that of genotypes as main effect.

Tables 4.1b, 4.2b and 4.3b indicate the mean yield of the thirteen wheat genotypes evaluated over 39, 33 and 48 sites respectively in the Western, Central and Eastern Free State, as well as the significant differences between genotypes as main effect using Tukey's pairwise comparison procedure. In the Western Free State the hybrids Carina and Carol yielded significantly higher than all the other genotypes. The purelines Molen, Letaba and Tugela-DN, as well as the hybrid Caritha, also performed well. SST 124, Betta and Karee were the worst yield performers. In the Central Free State, it was again the two hybrids, Carol and Carina, that were the top two genotypes. However their mean yields were not significantly higher that those of the purelines Letaba and Tugela-DN. Molen, as a pureline, also performed very well. The worst yield performers were Molopo, Karee, Betta and SST 102, which did not differ significantly from one another. In the Eastern Free State, Carina and Carol again had the highest yields and these were significantly higher than those of any other genotype.

Table 4.1a **Combined analysis of variance results for 13 wheat genotypes evaluated over 39 sites in the Western Free State for the period 1991-1994**

Source	df	Sum of Squares X 1 000 000	Mean Squares X 1 000 000	Prob
Total	2027	874	0.43	
Treatment	506	789	1.56	***
Genotypes (G)	12	28	2.35	***
Environments (E)	38	681	17.93	***
G X E	456	79	0.17	***
Error	1521	84	0.05	
Grand mean = 1319.3		R-squared = 0.929	CV = 17.9%	

Table 4.1b **Mean yield (kg ha^{-1}) and Tukey's pairwise comparison of genotype main effect of 13 wheat genotypes evaluated over 39 sites in the Western Free State for the period 1991-1994**

Genotype	Mean yield (kg ha^{-1})	Cv	Rank
Carina	1532 a	55.7	1
Carol	1522 a	48.6	2
Molen	1415 b	48.9	3
Caritha	1390 b	58.1	4
Letaba	1384 b	50.1	5
Tugela-DN	1312 bc	46.7	6
Oom Charl	1290 c	48.9	7
SST 102	1281 c	47.2	8
Scheepers 69	1264 cd	42.3	9
Molopo	1245 cde	45.3	10
Karee	1196 def	44.6	11
Betta	1170 ef	45.0	12
SST 124	1150 f	45.0	13
LSD $_{T(0.05)}$ for entry = 78.66 kg ha^{-1}		q(1-sided a = 0.05; 1521 df) = 4,685	

Table 4.2a Combined analysis of variance results for 13 wheat genotypes evaluated over 33 sites in the Central Free State for the period 1991-1994

Source	df	Sum of Squares X 1 000 000	Mean Squares X 1 000 000	Prob
Total	1715	871	0.51	
Treatment	428	802	1.87	***
Genotypes (G)	12	28	2.38	***
Environments (E)	32	721	22.55	***
G X E	384	52	0.14	***
Error	1287	68	0.05	
Grand mean = 1398.0		R-squared = 0.949	CV = 16.5%	

Table 4.2b Mean yield (kg ha^{-1}) and Tukey's pairwise comparison of genotype main effect of 13 wheat genotypes evaluated over 33 sites in the Central Free State for the period 1991-1994

Genotype	Mean yield (kg ha^{-1})	Cv	Rank
Carol	1611 a	50.6	1
Carina	1581 a	49.4	2
Letaba	1520 ab	48.5	3
Tugela-DN	1517 ab	47.9	4
Molen	1507 b	44.6	5
Caritha	1400 c	58.1	6
Scheepers 69	1366 cd	47.2	7
SST 124	1331 cde	47.2	8
Oom Charl	1327 cde	51.9	9
SST 102	1300 def	54.6	10
Betta	1243 ef	53.3	11
Karee	1242 ef	47.8	12
Molopo	1229 f	51.3	13
LSD $_{T(0.05)}$ for entry = 94.30 kg ha^{-1}		q(1-sided a = 0.05; 1287 df) = 4,685	

Table 4.3a Combined analysis of variance results for 13 wheat genotypes evaluated over 48 sites in the Eastern Free State for the period 1991-1994

Source	df	Sum of Squares X 1 000 000	Mean Squares X 1 000 000	Prob
Total	2495	1847	0.74	
Treatment	623	1718	2.76	***
Genotypes (G)	12	87	7.27	***
Environments (E)	47	1471	31.31	***
G X E	564	159	0.28	***
Error	1872	129	0.07	
Grand mean = 2091.8	R-squared = 0.942		CV = 12.5%	

Table 4.3b Mean yield (kg ha^{-1}) and Tukey's pairwise comparison of genotype main effect of 13 wheat genotypes evaluated over 48 sites in the Eastern Free State for the period 1991-1994

Genotype	Mean yield (kg ha^{-1})	Cv	Rank
Carina	2481 a	40.0	1
Carol	2396 a	41.1	2
Tugela-DN	2281 b	35.9	3
Molen	2170 c	36.4	4
Caritha	2108 cd	42.8	5
SST 102	2076 de	40.7	6
Letaba	2059 def	45.3	7
SST 124	2013 efg	37.6	8
Karee	1972 fgh	41.4	9
Oom Charl	1970 gh	42.6	10
Molopo	1949 gh	41.1	11
Betta	1911 h	39.3	12
Scheepers 69	1811 I	36.1	13
$LSD_{T(0.05)}$ for entry = 88.76 kg ha^{-1}	q(1-sided a = 0.05; 1872 df) = 4,685		

Tugela-DN was ranked third and significantly out-yielded the other purelines, as well as the hybrid Caritha. Scheepers 69, especially, but also Betta, Molopo, Oom Charl and Karee, did not perform well in terms of yield. As far as genotype performance as main effect over the three production regions was concerned, fairly similar results were obtained.

As we are primarily concerned with genotype performance as main effect, and especially the genotype x environment interaction, the large environmental effect is only taken note of and discarded for practical purposes. No underlying pattern to describe genotype x environment interaction can be elucidated from the ANOVA, as has been pointed out by various authors.

However, to determine the validity of the respective analyses of variance on the data, the homogeneity of variance between environments had to be determined.

4.2 Bartlett's test for homogeneity and weighted analysis

Consequently Bartlett's test for establishing the homogeneity of the variances over environments was used. The environments for all three combined ANOVA's were found to be heterogeneous, thus necessitating transformation of the data to achieve homogeneity of error variances. However, no data transformation, including log transformation which is sometimes successfully used, could be identified to remove the heterogeneity of variances. Annicchiarico (1992) similarly found that no data transformation was capable of removing the heterogeneity of error variances of cultivar adaptation trials performed in Italy. Subsequently a weighted analysis was performed and the G x E interactions were all very highly significant, after the differences in variances had been accounted for. This indicates that the significant interactions noted are not spurious in any way (Table 4.4).

Table 4.4 **Weighted analyses on the yield data of 13 genotypes over 39, 33 and 48 sites in the Western, Central and Eastern Free State respectively**

Source	Western Free State					Central Free State					Eastern Free State				
	df	SS	MS	Fval	Pr>F	df	SS	MS	Fval	Pr>F	df	SS	MS	Fval	Pr>F
Model	623	22.72	36.47	47.14	0.0001	527	29.84	56.6	83.9	0.0001	767	31.14	40.6	60.4	0.0001
Error	1404	1.08	0.773			1188	0.80	0.7			1728	1.16	0.7		
Corrected total	202	23.81				1715	30.65				2495	32.31			
	R^2 = 0.954 CV = 2.85 $\sqrt{MSE}$ = 27.81					R^2 = 0.97 CV = 3.0 $\sqrt{MSE}$ =25.99					R^2 = 0.96 CV = 1.54 $\sqrt{MSE}$ =25.9				
	Type III					Type III					Type III				
	df	SS	MS	Fval	Pr>F	df	SS	MS	Fval	Pr>F	df	SS	MS	Fval	Pr=F
Environments	38	20.20	531.6	687.2	0.0001	32	27.59	862.4	1277.1	0.0001	47	28.10	597.9	888.9	0.0001
Genotypes	117	0.36	3.1	4.0	0.0001	99	0.42	4.3	6.3	0.0001	144	0.28	1.9	2.9	0.0001
Replications	12	0.43	36.6	47.3	0.0001	12	0.52	43.3	64.1	0.0001	12	0.96	79.8	118.6	0.0001
G x E	456	1.77	3.89	5.0	0.0001	384	1.26	3.3	4.9	0.0001	564	1.82	3.2	4.8	0.0001

4.3 *Shukla's procedure of stability variance*

Table 4.5 indicates Shukla's (1972) stability variance (σ^2_i) values, as well as the ranking order of the genotype's stability. In the Western Free State the most stable genotypes were SST 102, Oom Charl and Tugela-DN, with Carina, Letaba and Caritha being the most unstable. In the Central Free State the most stable genotypes were Betta, Oom Charl and SST 102, while Carina, Karee, Caritha and Letaba were the most unstable. In the Eastern Free State the most stable genotypes were Betta, SST 102 and Oom Charl, with Karee, Letaba and Scheepers 69 showing the most instability (Table 4.5).

Over the whole region, Oom Charl, SST 102, Betta and Molopo indicated superior stability. It is interesting to note that all four cultivars belong to the Betta group of cultivars, being either Betta or a derivative of Betta. Molen, SST 124, Tugela-DN, Scheepers 69 and Carol generally indicated intermediate stability, while Carina, Letaba, Karee and Caritha indicated poor stability over all three regions. The three hybrids, vizably Carina, Caritha and Carol generally showed relatively poor stability.

Table 4.5 Stability variance (Shukla, 1972) results for the Western, Central and Eastern Free State wheat producing regions over the period 1991-1994

Cultivar	Western Free State		Central Free State		Eastern Free State	
	Stability variance	Rank	Stability variance	Rank	Stability variance	Rank
Betta	134 464	6	41 882	1	56 336	1
Molopo	96 310	4	87 425	4	243 626	7
SST 102	47 706	1	82 897	3	69 138	2
Karee	227 102	10	238 163	12	650 738	13
Oom Charl	76 681	2	57 464	2	127 462	3
Molen	148 530	7	101 226	7	173 322	6
SST 124	161 873	8	100 365	6	150 328	4
Letaba	324 563	12	230 399	10	610 290	12
Scheepers 69	124 068	5	98 431	5	528 296	11
Caritha	310 684	11	232 423	11	326 876	10
Carina	332 445	13	246 483	13	302 840	9
Carol	215 576	9	126 675	8	278 880	8
Tugela-DN	87 768	3	147 605	9	161 781	5

4.4 *Lin & Binn's cultivar performance measure (P_i)*

The Lin & Binn's cultivar performance measure (P_i) for each cultivar in the respective production regions of the Free State is indicated in Table 4.6.

Table 4.6 The Lin & Binn's cultivar performance measure (P_i) for 13 cultivars included in G x E trials in the Western, Central and Eastern Free State respectively, for the period 1991 - 1994

Cultivar	Western Free State		Central Free State		Eastern Free State	
	P_i	Rank	P_i	Rank	P_i	Rank
Betta	210 383	11	159 751	11	281 595	11
Molopo	158 860	10	173 230	12	263 004	10
SST 102	134 463	8	137 293	10	162 695	5
Karee	217 379	12	188 452	13	302 424	12
Oom Charl	124 319	6	118 056	8	227 937	9
Molen	74 317	4	58 388	4	147 885	4
SST 124	233 113	13	123 544	9	225 845	8
Letaba	89 022	5	49 203	3	221 577	7
Scheepers 69	149 888	9	111 497	7	446316	13
Caritha	73 958	3	93 065	6	175 306	6
Carina	44 743	1	47 175	2	23 914	1
Carol	48 004	2	26 241	1	42 445	2
Tugela-DN	126 251	7	63 184	5	100 723	3

In the Western Free State, Carina, Carol and Caritha had the lowest P_i values and thus the best stability, while SST 124, Karee and Betta had the worst stability. In the Central Free State the most stable genotypes were Carol, Carina and Letaba, while Karee, Molopo and Betta were the most unstable. In the Eastern Free State, the genotypes Carina, Carol and Tugela-DN were the most stable, and Scheepers 69, Karee and Betta the most unstable.

According to the cultivar performance measure (P_i) of Lin & Binn's (1988), as stability statistic, the hybrids Carol, Carina and Caritha, together with Molen, Tugela-DN and Letaba, appeared to be the superior genotypes over the region as a whole. SST 102 and Oom Charl showed intermediate stability, while Karee, Betta, Molopo, Scheepers 69 and SST 124 indicated poor stability.

4.5 Finlay & Wilkenson procedure

Figures 4.1 to 4.3 graphically represent the regression coefficient (b_i) plotted against the genotype mean yield as an indication of stability (Finlay & Wilkenson, 1963) for the Western, Central and Eastern Free State respectively. According to Finlay & Wilkenson (1963), regression coefficients approximating to 1.0 indicate average stability. Regression coefficient values increasing above 1.0 describe genotypes with increasing sensitivity to environmental change, thus below average stability. Regression coefficients decreasing below 1.0 provide a measure of greater resistance to environmental change, thus above average stability. However, the regression coefficient must also be associated and interpreted with the genotype mean yield to determine adaptability. (See Table 4.8 for regression coefficients and genotype mean yields.)

For the Western Free State, the genotypes Karee, SST 124, Scheepers 69 and Betta indicated above average stability, but also specific adaptability to unfavourable environments (see Figure 2.2). The genotypes Molopo, SST 102, Oom Charl, Tugela-DN, Letaba and Molen all showed average stability and increasing adaptability to all environments in that order. The hybrids Caritha, Carina and Carol indicated below average stability, but good specific adaptability to high potential conditions.

For the Central Free State, Karee, SST 124 and Molopo showed above average stability, but also specific adaptability to unfavourable environments. The genotypes Betta, SST 102, Oom Charl, Scheepers 69, Molen, Letaba and Tugela-DN all indicated average stability ($0.9 < b_i < 1.1$), with increasing adaptability to all environments in that

order. Again the hybrids, Caritha, Carol and Carina showed below average stability, with Carina and Carol having good specific adaptability to high potential conditions, but Caritha showing generally poor adaptability.

For the Eastern Free State, Scheepers 69 alone showed above average stability, and also very specific adaptation to low potential or unfavourable conditions. The genotypes Karee, SST 124, Betta, Molopo, Oom Charl, Letaba, SST 102, Caritha, Molen and Tugela-DN showed average stability and increasing adaptability , in mentioned order, to all environments, with Tugela-DN especially prominent in this regard. Carol and Carina showed below average stability, but with specifically good adaptation to high potential or favourable conditions.

Generally Scheepers 69, Karee and SST 124 indicated above average stability and specific adaptability to unfavourable environments. These three cultivars also have the shortest growth periods and so are possibly more drought escapers, rather than specifically drought tolerant genotypes. Betta, Molopo, Oom Charl, SST 102, Caritha, Letaba, Molen and Tugela-DN have average stability, and with increasing adaptability to all environments in that ranking order. The hybrids Carol and Carina show below average stability but good specific adaptability to highly favourable environments. The average mean yield of these hybrid genotypes was approximately 12.5 per cent higher than the average mean yield for the pureline genotypes with average stability, indicating good hybrid vigour. A fairly similar pattern of adaptability and stability was evident over the three respective production regions, with only Scheepers 69, SST 124, Karee, Molopo and Caritha showing significantly variable responses over the regions.

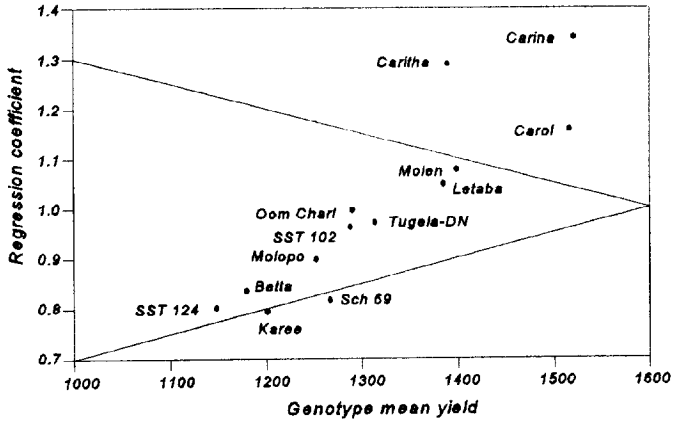

Figure 4.1 Regression coefficients plotted against genotype mean yield for the Western Free State

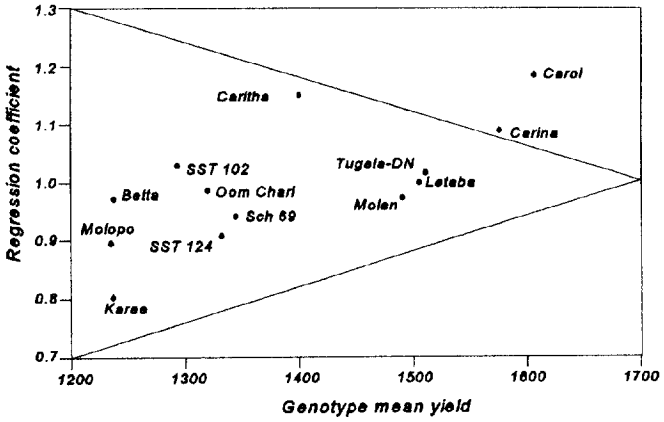

Figure 4.2 Regression coefficients plotted against genotype mean yield for the Central Free State

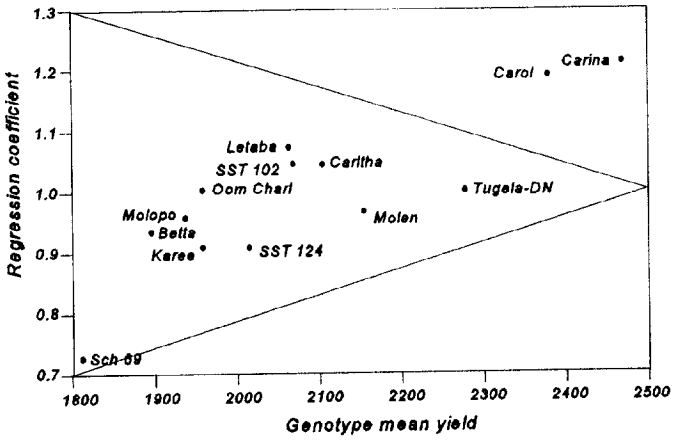

Figure 4.3 Regression coefficients plotted against genotype mean yield for the Eastern Free State

4.6 Eberhart & Russel's procedure

The Eberhart & Russel procedure involves the use of joint linear regression where the yield of each genotype is regressed on the environmental mean yield. The appropriate

Table 4.8 **The mean yield, regression coefficient (b) and deviation from regression (S^2d) for the 13 genotypes evaluated in the respective production regions of the Free State for the period 1991-1994, according to the Eberhart & Russel (1966) proposed procedure**

Genotype	Western Free State					Central Free State					Eastern Free State				
	Mean yield (kg ha^{-1})	R*	b**	S^2d***	R	Mean yield (kg ha^{-1})	R	b	S^2d	R	Mean yield (kg ha^{-1})	R	b	S^2d	R
Betta	1170	12	0.83	9120	6	1243	11	0.97	1669	1	1911	12	0.93	4848	2
Molopo	1245	10	0.90	7826	4	1229	13	0.90	3656	4	1949	11	0.94	36914	9
SST 102	1281	8	0.97	760	1	1300	10	1.03	7211	6	2076	6	1.05	629	1
Karee	1196	11	0.79	24882	10	1242	12	0.82	26856	11	1972	9	0.91	121298	13
Oom Charl	1290	7	1.01	7420	3	1327	9	0.99	1962	2	1970	10	1.02	13413	3
Molen	1415	3	1.07	21169	9	1507	5	0.97	11116	8	2171	4	0.96	22497	8
SST 124	1150	13	0.81	13015	7	1331	8	0.90	6653	5	2013	8	0.92	14334	4
Letaba	1384	5	1.05	60575	13	1520	3	1.04	39261	12	2059	7	1.08	114334	12
Scheepers 69	1264	9	0.83	7374	2	1366	7	0.92	7883	7	1811	13	0.73	55870	11
Caritha	1390	4	1.30	26369	11	1400	6	1.17	26852	10	2108	5	1.06	54347	10
Carina	1532	1	1.36	17475	8	1581	2	1.09	39403	13	2481	1	1.22	22425	7
Carol	1522	2	1.13	31611	12	1611	1	1.18	2074	3	2396	2	1.21	19809	5
Tugela-DN	1312	6	0.97	8620	5	1517	4	1.03	21294	9	2281	3	0.98	20765	6

* R = Rank
** b = Regression coefficient
*** S^2d = Deviation from the regression

For the Western Free State the cultivars SST 102, Oom Charl and Tugela-DN showed the best stability, while Scheepers 69, Molopo, Betta and SST 124 also had S^2d values approaching zero, but regression coefficients considerably smaller than 1.0. Cultivars with the highest S^2d values were, in ranked order, Letaba, Carol, Caritha, Karee, Molen and Carina. The three hybrids, Carol (b = 1.13), Caritha (b = 1.13) and Carina (b=1.36) also all had regression coefficients considerably larger than 1.0, indicating instability. They were however ranked 2nd , 4th and 1st in mean grain yield respectively.

For the Central Free State, the cultivars Betta, Molopo, SST 102, Oom Charl, SST 124, Molen, Scheepers 69 and Carol all had relatively low S^2d values, but regression coefficients varied considerably from b = 0.90 for SST 124 and Molopo, to b = 1.18 for Carol. Theoretically, Oom Charl, Betta and SST 102 would thus have the best stability. The most unstable cultivars were Letaba, Carina, Caritha and Karee, with Tugela-DN having intermediate stability.

For the Eastern Free State, the most stable cultivars are SST 102, Betta, Oom Charl and SST 124. The cultivars Tugela-DN, Molen, Molopo and the hybrids Carina and Carol indicated intermediate stability, even though the hybrids had regression coefficients > 1.20. The most unstable cultivars were Karee, Letaba, Scheepers 69 and Caritha in descending order.

Over the Free State as a whole, the most stable cultivars were SST 102, Oom Charl and Betta, all three being Betta-types. Molopo, Molen, SST 124, Scheepers 69 and Tugela-DN indicated reasonable stability, while Letaba, Karee, Caritha, Carina and Carol can be classified as generally unstable according to the procedure proposed by Eberhart & Russel.

4.7 *Wricke's ecovalence concept*

Wricke's ecovalence value was determined for each of 13 genotypes evaluated over a total of 120 environments in the Western, Central and Eastern Free State, and the results are presented in Table 4.9.

Table 4.9 Wricke's ecovalence values (WEV) for 13 genotypes over 120 environments across the Western, Central and Eastern Free State wheat production regions respectively

Cultivar	Western Free State		Central Free State		Eastern Free State	
	WEV	R	WEV	R	WEV	R
Betta	1 209 267	6	368 309	1	815 959	1
Molopo	902 564	4	676 608	4	2 678 060	7
SST 102	511 846	1	645 953	3	943 246	2
Karee	1 953 933	10	1 696 986	12	6 725 694	13
Oom Charl	744 782	2	473 792	2	1 523 126	3
Molen	1 322 334	7	770 028	7	1 979 079	6
SST 124	1 429 592	8	764 198	6	1 750 462	4
Letaba	2 737 372	12	1 644 425	10	6 323 544	12
Scheepers 69	1 125 696	5	751 105	5	5 508 342	11
Caritha	2 625 846	11	1 658 132	11	3 505 764	10
Carina	2 800 731	13	1 153 308	13	3 266 789	9
Carol	1 861 282	9	942 296	8	3 028 572	8
Tugela-DN	801 743	3	1 083 973	9	1 864 330	5

For the Western Free State, the cultivars with the lowest ecovalence and thus the best stability, according to Wricke (1962), were SST 102, Oom Charl, Tugela-DN and Molopo, while Scheepers 69, Betta, Molen and SST 124 indicated intermediate stability. The cultivars showing the greatest instability were Carina, Letaba, Caritha, Karee and Carol (Table 4.9).

In the Central Free State, the genotypes Betta, Oom Charl, SST 102, Molopo, Scheepers 69, SST 124 and Molen showed the best stability in that order, with the first four genotypes all being Betta-types. Carol and Tugela-DN have intermediate stability, while Carina, Karee, Caritha and Letaba indicated the greatest instability.

In the Eastern Free State, the most stable genotypes were again Betta, SST 102, Oom Charl, SST 124, Tugela-DN and Molen, while Molopo, Carol, Carina and Caritha indicated intermediate stability. The most unstable genotypes by far were Karee, Letaba and Scheepers 69.

Over the whole Free State region, the most stable genotypes, according to Wricke's procedure, thus appear to be SST 102, Oom Charl, Betta, Molopo, Tugela-DN, SST 124 and Molen, with the first four mentioned genotypes and Molen all being so-called Betta-types. The most unstable genotypes generally were Karee, Carina, Letaba and Caritha, while Carol and Scheepers 69 had intermediate stability. Remarkably similar results were found over all three regions. However, genotypes such as Betta, Molopo, Scheepers 69, Carina and Tugela-DN, showed fairly diverse reaction over the regions, confirming field observations of adaptability and stability. Of particular note is firstly Betta's superior stability in the Eastern and Central Free State in contrast to the inferior stability in the Western Free State. The converse was however true for Molopo which performed relatively better in the Central and Western Free State, as did Scheepers 69. Tugela-DN again performed well in the Western and Eastern Free State, but showed inferior stability in the lower potential Central Free State.

4.8 Additive main effects and multiplicative interaction (AMMI) model

The AMMI analyses of variance (ANOVA's) of the cultivar evaluation trials for respectively the Western, Central and Eastern Free State, according to the best AMMI model fit, are presented in Table 4.10. The best fit for the Western Free State was the AMMI 2 model, while for both the Central and Eastern Free State, the AMMI 3 model was the most suitable. For the Western Free State IPCA 1 declared over 40 per cent

of the G x E interaction sum of squares, while IPCA 2 declared 20 per cent of the interaction, with the remaining 39 per cent residual (noise) being uninterpretable and is thus discarded. The IPCA 2 declaring 20 per cent is relatively small and it could be difficult to draw meaningful conclusions from this principal component factor. In the Central Free State, IPCA 1 and IPCA 2 respectively explain 26 per cent and 25 per cent of the total G x E interaction sum of squares, while IPCA3 accounts for 15 per cent. In this case both the first two principal component factors would need to be interpreted and discussed. In the Eastern Free State, 41 per cent of the interaction sum of squares is attributable to IPCA 1, with 18 per cent and 11 per cent attributable to IPCA 2 and IPCA 3 respectively. While IPCA 2 and IPCA 3 will be investigated to elucidate meaningful and interpretable pattern, they may have to be discarded in the interpretation due to their relatively small contribution to the G x E sum of squares, as well as to the fact that they may not be associated with some identifiable characteristic, for example growth period, disease, susceptibility to lodging, etc., to explain the specific principal component factor. The AMMI 3 model for the Central and Eastern Free State does however indicate that more than one factor is fundamental to the G x E interaction in these production regions.

The IPCA scores of a genotype in the AMMI analysis are an indication of the stability of a genotype over environments. The greater the IPCA scores, either negative or positive as it is a relative value, the more specifically adapted a genotype is to certain environments. The more the IPCA scores approximate to zero (0), the more stable the genotype is over all environments sampled. It is important that not only the IPCA 1 score be used for stability analysis, but that IPCA 1 scores also be plotted against IPCA 2 scores at least, as will become evident in the following discussion.

Table 4.10 ANOVA of the cultivar evaluation trials for the Western Free State (Model AMMI 2), Central Free State (Model AMMI 3) and Eastern Free State (AMMI 3) over the period 1991 to 1994

Source	Western Free State				Central Free State				Eastern Free State			
	df	SS X 1 000 000	MS X 1 000 000	Prob	df	SS X 1 000 000	MS X 1 000 000	Prob	df	SS X 1 000 000	MS X 1 000 000	Prob
Total	2027	874	0.431		1715	872	0.508		2495	1847	0.740	
Treatment	506	789	1.559	***	428	803	1.875	***	623	1718	2.757	***
Genotype (G)	12	28	2.347	***	12	29	2.381	***	12	87	7.273	***
Environment (E)	38	681	17.934	***	32	722	22.548	***	47	1471	31.306	***
G x E	456	79	0.174	***	384	53	0.137	***	564	159	0.282	***
IPCA1	49	32	0.661	***	43	14	0.361	***	58	65	1.130	***
IPCA2	47	16	0.333	***	41	13	0.309	***	56	29	0.522	***
IPCA3	-	-	-		39	8	0.202	***	54	18	0.336	***
Residual	360	31	0.087	***	261	18	0.070	**	396	46	0.117	***
Error	1521	85	0.056		1287	69	0.053		1872	129	0.069	

If the IPCA scores of a genotype are interpreted in conjunction with the IPCA 1 scores of the individual environments, the adaptability of the genotype can largely be determined by characterisation of the environments, for example whether they be low potential (unfavourable) environments, high potential (favourable) environments, etc, due to drought conditions, high temperature conditions, or whatever the limiting production factor may be.

Figure 4.4 indicates the AMMI model 2 biplot for the Western Free State trials. Distinct patterns are identifiable with the higher potential environments predominating in quadrant III, such as Bultfontein plantings 1, 2, 3 and 4 of 1991 (BU11, BU12, BU13 and BU14) as examples, and the lower potential environments predominating in quadrant I, such as Petrusburg plantings 1 and 2 of 1992 and 1994 (PB21, PB22, PB41 and PB42) as examples. Considerably less variation around the mean yield of 1319 kg ha^{-1} is noted for the genotypes. The IPCA 1 scores indicate clearly that the hybrids, vizably Caritha, Carina and Carol, are specifically adapted to high potential or favourable conditions, as is Molen to a lesser extent. It must however be kept in mind that these are also the genotypes with relatively longer growth periods. On the other hand, the relatively shorter growth period genotypes, vizably SST 124, Karee, Betta, Scheepers 69 and Molopo, appear to be specifically adapted to lower potential or more unfavourable conditions. By just considering the IPCA 1 scores, Oom Charl, Tugela-DN, SST 102 and Letaba appear to be the most stable genotypes cultivars over the range of environments. However, since IPCA 2 also plays a significant role (20 per cent) in the G x E interaction, the IPCA 1 scores were plotted against the IPCA 2 scores to further explore stability (Figure 4.5). Of specific importance is the subsequent outlier and isolated position of Letaba, indicating a specifically strong reaction to the 2nd principal component factor. On the IPCA 1 score only, Letaba was previously classified as stable, which would obviously now be incorrect. Other genotypes indicating considerable reaction to the 2nd principal component factor, are Karee and Carina. According to Figure 4.5, the cultivars with the best yield stability over the range of environments sampled, would be Oom Charl, Tugela-DN, SST 102 and Molen.

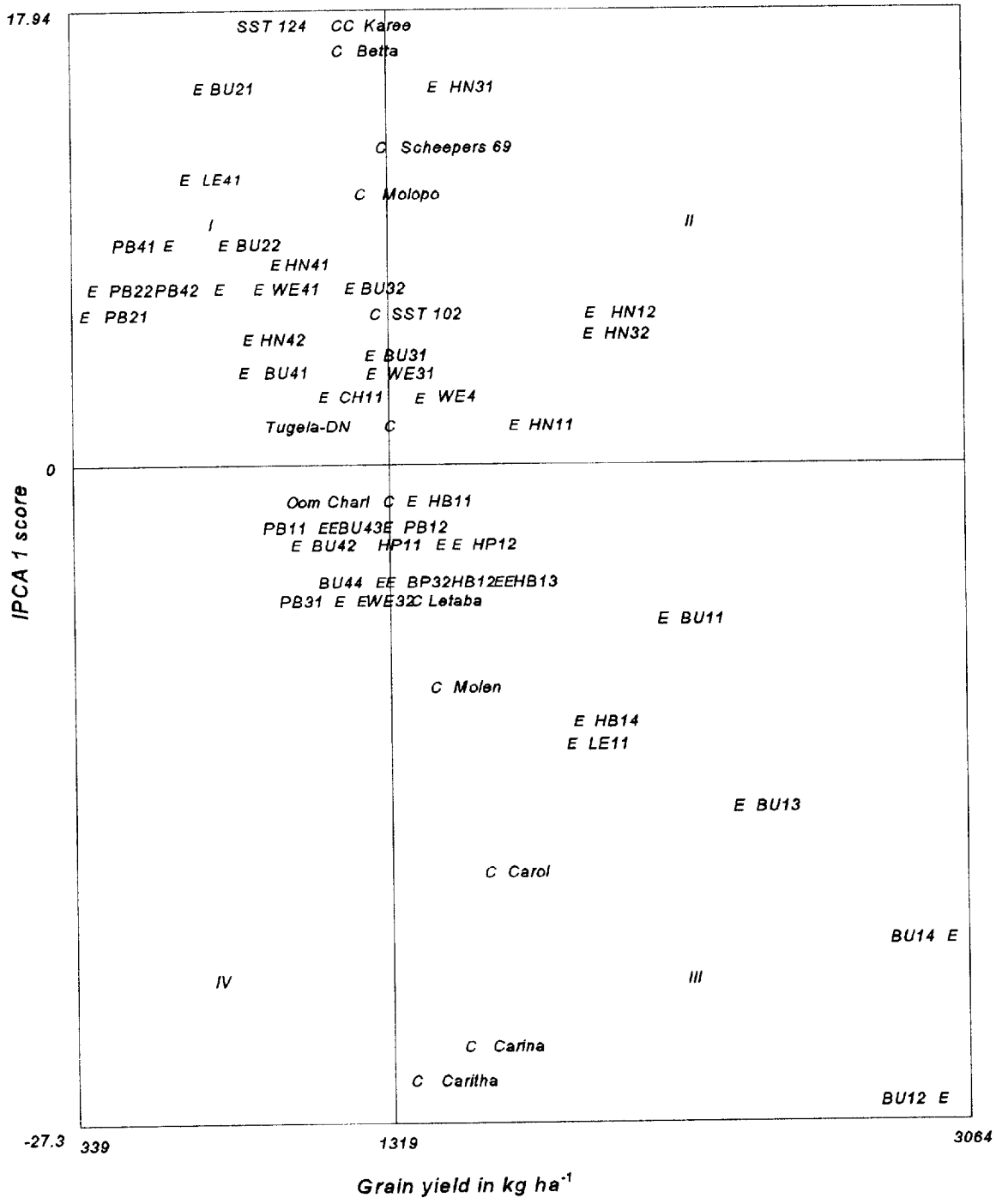

Figure 4.4 **AMMI model 2 biplot for 13 genotypes and 39 environments included in the Western Free State wheat cultivar evaluation trials from 1991 to 1994.**

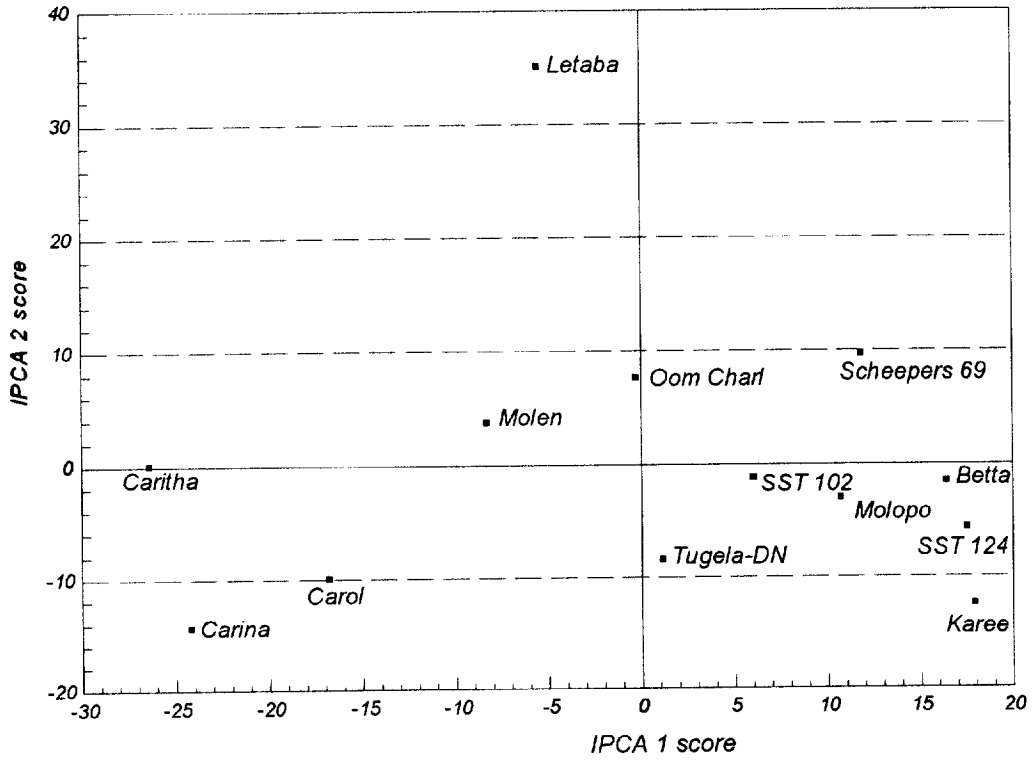

Figure 4.5 Plotted IPCA 1 and IPCA 2 scores of wheat genotypes included in the Western Free State cultivar evaluation trials over the period 1991 to 1994.

Figure 4.6 indicates the AMMI model 3 biplot of the Central Free State trials. Again a distinct pattern is discernible with the majority of high potential (favourable) environments, such as Ladybrand Plato plantings 1 and 2 of 1993 (LP31 and LP32) as examples, positioned in quadrant III and the lower potential (unfavourable) environments, such as Excelsior plantings 1 and 2 of 1994 (EX41 and EX42) as examples, positioned in quadrant I. Considerable variation in yield was noted over environments, but considerably less so over genotypes, as can also be deduced from the ANOVA. The hybrids Caritha and Carol, and to a lesser extent Letaba, appear to be specifically adapted to the higher potential conditions, while Karee, SST 124 and Scheepers 69 are specifically adapted to lower yield potential conditions. According to the biplot (mean yield vs IPCA 1 scores), the most stable genotypes appear to be Carina, Oom Charl, Molen, Tugela-DN, Betta, Molopo and SST 102.

Central Free State

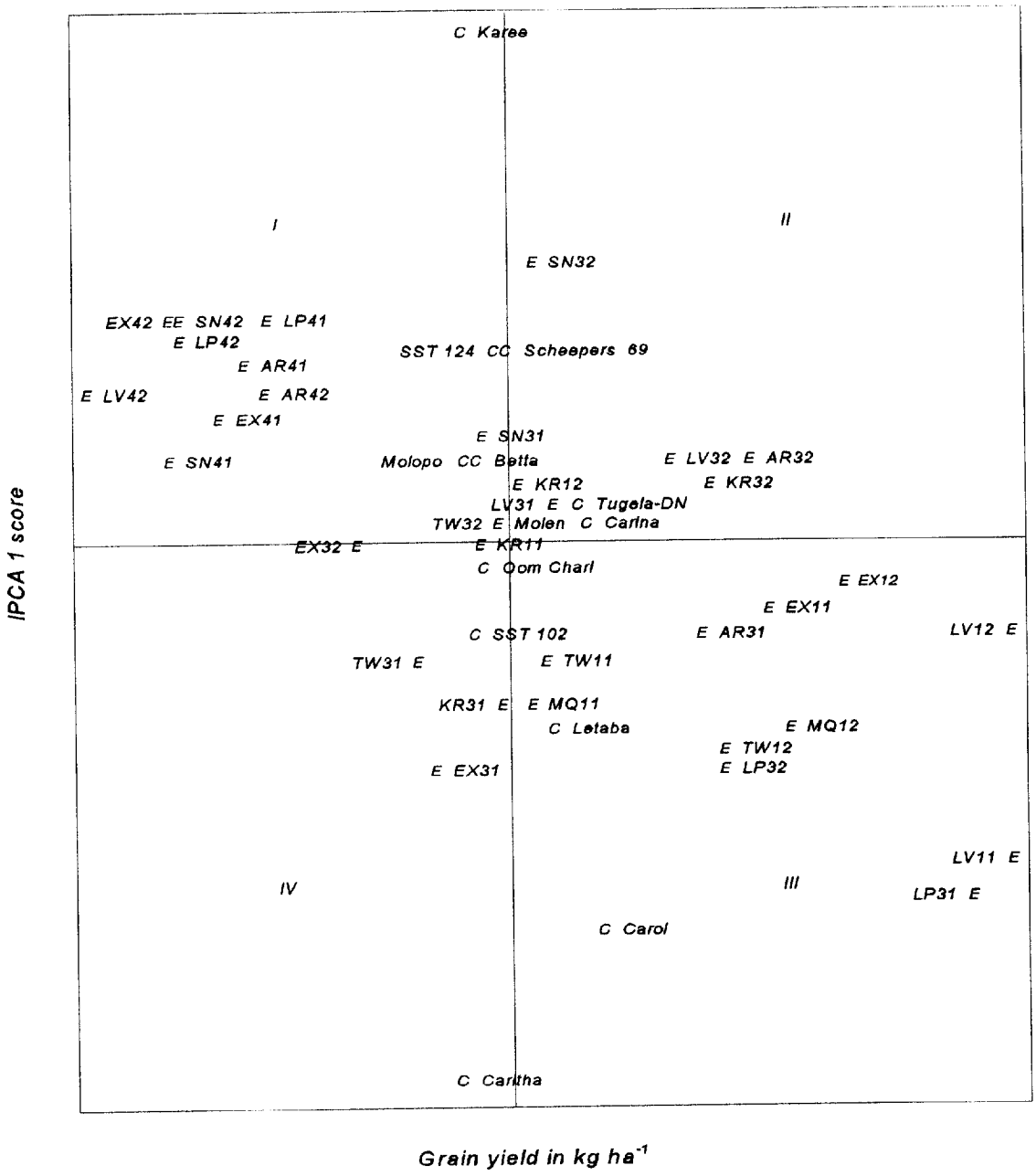

Figure 4.6 **AMMI model 3 biplot for 13 wheat genotypes and 33 environments included in the Central Free State cultivar evaluation trials from 1991 to 1994.**

However when the IPCA 1 scores are plotted against the IPCA 2 scores, the picture changes dramatically (Figure 4.7) (remember IPCA 1 contributes 26 per cent to G x E sum of squares, while IPCA 2 contributes 25 per cent). It is especially Carina, but also Molen and Tugela-DN, and again Letaba, that indicate specific reaction to the 2nd principal component factor and thus greater instability over all environments. From Figure 4.7, the genotypes with the best yield stability appear to be Betta, Oom Charl, SST 102, Molopo and Scheepers 69. The most unstable genotypes are thus the hybrids, Caritha, Carol and Carina, as well as Karee, Letaba and to a lesser extent Tugela-DN and Molen.

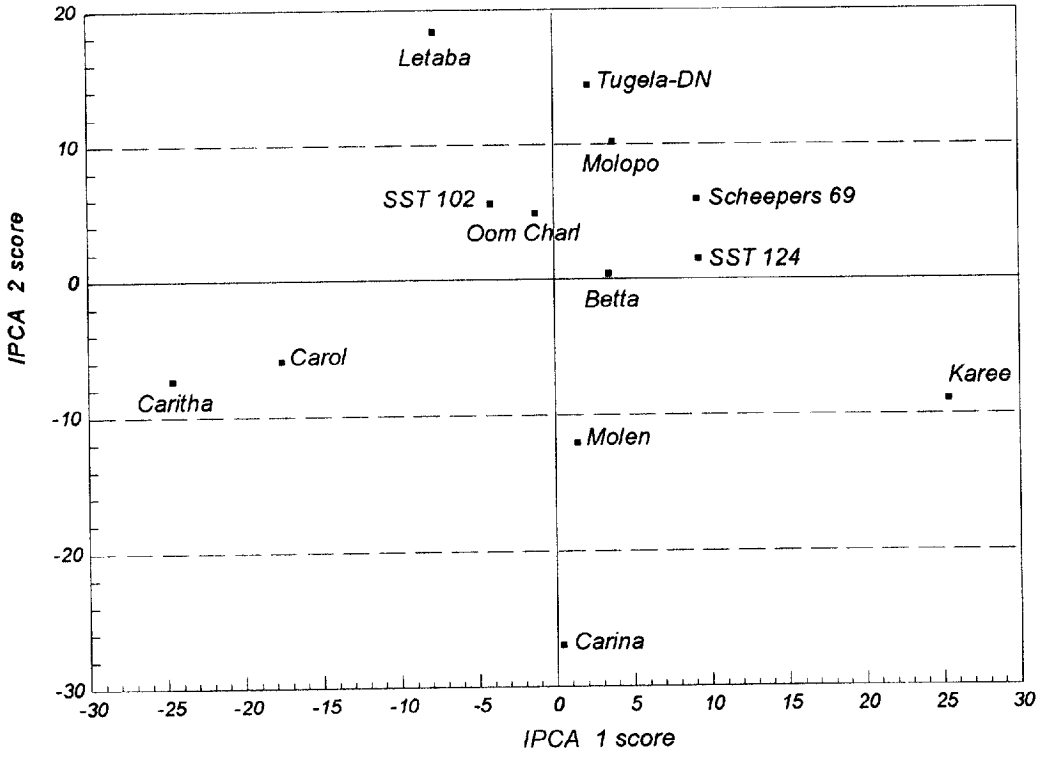

Figure 4.7 IPCA 1 and IPCA 2 scores of genotypes in the Central Free State trials plotted against one another.

The AMMI model 3 biplot of the Eastern Free State cultivar evaluation trials is presented in Figure 4.8.

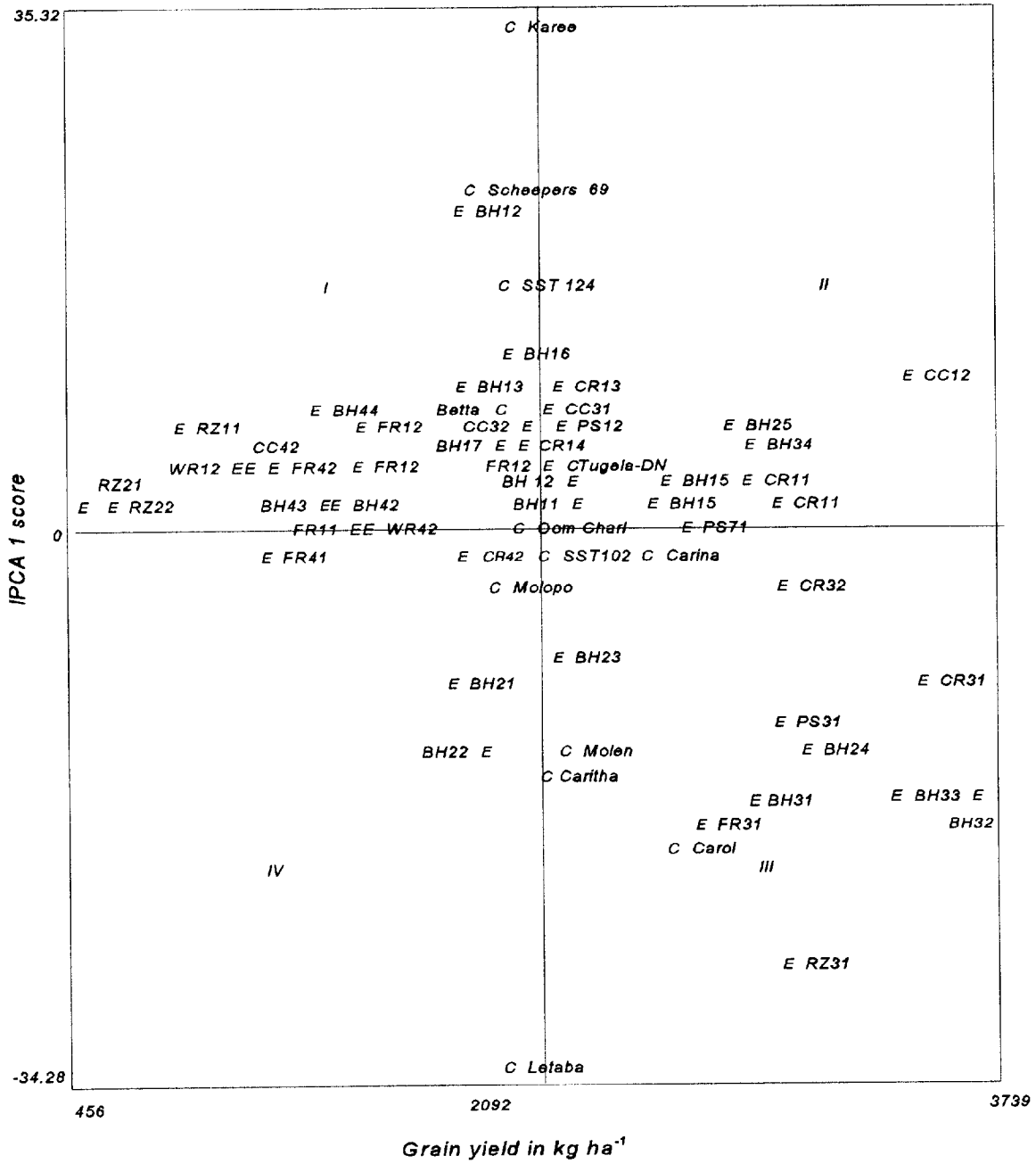

Figure 4.8 **AMMI model 3 biplot for 13 wheat genotypes and 48 environments included in the Eastern Free State cultivar evaluation trials from 1991 to 1994.**

A slightly different pattern to the two previous biplots was observed. High potential environments, such as Bethlehem plantings 1, 2, 3 and 4 of 1993 (BH31, BH32, BH33 and BH34) as examples, were fairly evenly distributed across quadrants II and III, even through the distribution in quadrant III was wider than in quadrant II. However the low potential environments, such as Reitz plantings 1 and 2 of 1992 (RZ21 and RZ22) as examples, were predominantly distributed in a band just above the IPCA 1 score of zero in quadrant I. According to the biplot (yield plotted against IPCA 1), Letaba, Carol, Caritha and Molen are specifically adapted to certain favourable environments, while Karee, Scheepers 69 and SST 124 are better adapted to unfavourable environments in general, but also to specific or certain higher potential environments. The biplot indicates that Oom Charl, SST 102, Carina, Molopo, Tugela-DN and Betta are the more stable genotypes over environments.

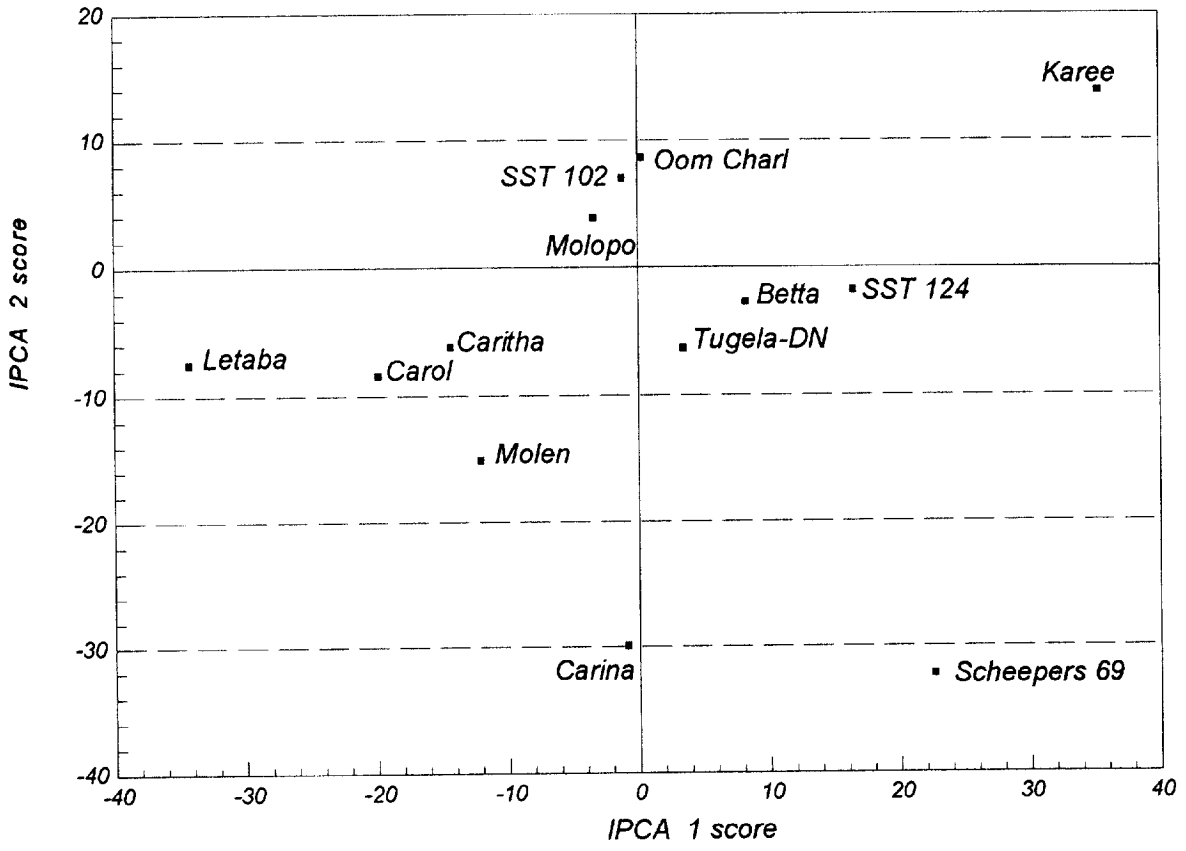

Figure 4.9 Plotted IPCA 1 and IPCA 2 scores of genotypes included in the Eastern Free State trials over the period 1991 to 1994.

However, when the IPCA 1 scores are plotted against the IPCA 2 scores (Figure 4.9), it is especially Carina's position which now indicates great instability. Other cultivars also significantly affected by the 2nd principal component factor are Scheepers 69, Molen and Karee. From Figure 4.9 the most stable varieties appear to be Oom Charl, SST 102, Molopo, Betta and Tugela-DN. The first four mentioned varieties are all so-called Betta-types.

From the respective AMMI biplots for the Western, Central and Eastern Free State, it is clear that the genotypes are arranged in a fairly specific and similar order, according to the IPCA 1 scores. The genotypes generally occur on the IPCA 1 axis in order from longer to shorter growth period, with the intermediate growth period genotypes positioned in the middle around the zero IPCA 1 score. The short growth period genotypes, such as Karee, Scheepers 69 and SST 124, are best adapted to unfavourable conditions, while the longer growth period genotypes, vizably the hybrids, and Letaba and Molen, are better adapted to the high potential or favourable environments.

In the interpretation of the AMMI analysis, the genotype main effect (yield) should also be considered and a rather remarkably similar ranking order pattern in mean yield response over all three regions was noted (Table 4.11). The hybrids Carina and Carol were ranked either first or second over all three regions. Molen and Tugela-DN were the next best yield performers and were also the purelines with the highest mean yield. The hybrid Caritha followed, but at this yield level it can not compete economically with pureline genotypes due to a seed price 4-5 times more expensive than for pureline seed. Other purelines with a generally good mean yield were Letaba, SST 102, Oom Charl, Scheepers 69 and SST 124. The purelines Molopo and Betta were the worst performers in this regard.

Despite discernible differences in adaptation over regions, it generally appears that the hybrids are specifically adapted to favourable conditions, Karee, Scheepers 69 and SST 124 to unfavourable conditions, and the Betta-types and Tugela-DN can

Table 4.11 **Mean yield (kg ha^{-1}), rank, IPCA 1 and IPCA 2 scores and an AMMI stability value (ASV) of wheat genotypes analysed according to the AMMI model over 120 environments in the Western, Central and Eastern Free State respectively, for the period 1991 to 1994**

Cultivar	Western Free State						Central Free State						Eastern Free State					
	Yield (kg ha^{-1})	R	IPCA 1 score	IPCA 2 score	ASV	R	Yield (kg ha^{-1})	R	IPCA 1 score	IPCA 2 score	ASV	R	Yield (kg ha^{-1})	R	IPCA 1 score	IPCA 2 score	ASV	R
Betta	1170	12	16.4	-1.5	32.8	7	1243	11	3.5	0.4	3.8	1	1911	12	8.2	-2.7	16.6	5
Molopo	1245	10	10.7	-3.0	21.6	5	1229	13	3.8	10.2	11.3	5	1950	11	-3.4	3.9	8.6	3
SST 102	1281	8	6.0	-1.2	12.1	3	1300	10	-4.1	5.6	7.1	3	2077	6	-1.2	7.0	7.5	1
Karee	1196	11	17.9	-12.4	37.9	11	1242	12	25.4	-8.9	28.8	13	1973	9	35.3	13.8	80.6	13
Oom Charl	1289	7	-0.3	7.7	7.7	1	1326	9	-1.2	4.9	5.1	2	1970	10	0.3	8.6	8.6	2
Molen	1415	3	-8.3	3.8	17.0	4	1506	5	2.2	14.4	14.6	8	2170	4	-12.1	-15.1	31.1	7
SST 124	1148	13	17.5	-5.6	35.4	9	1330	8	9.3	1.5	10.2	4	2013	8	16.4	-1.8	36.9	9
Letaba	1384	5	-5.5	35.1	36.8	10	1520	3	-7.7	18.4	20.2	10	2059	7	-34.3	-7.5	77.5	12
Scheepers 69	1264	9	11.8	9.7	25.5	6	1365	7	9.2	5.9	11.6	6	1811	13	22.6	-32.2	60.2	11
Caritha	1390	4	-26.4	0.1	52.8	13	1399	6	-24.6	-7.3	27.6	12	2108	5	-14.4	-6.2	33.0	8
Carina	1528	1	-24.2	-14.3	50.5	12	1581	2	0.4	-26.9	26.9	11	2481	1	-0.9	-29.9	30.1	6
Carol	1519	2	-16.8	-9.9	35.0	8	1611	1	-17.6	-5.9	19.9	9	2396	2	-19.9	-8.4	45.6	10
Tugela-DN	1312	6	1.1	-8.4	8.7	2	1517	4	1.4	-12.0	12.1	7	2281	3	3.4	-6.3	9.9	4

be classified as genotypes with good stability over environments. Letaba is highly unstable and has unique adaptation, a real dark horse, while the similar but dramatic sensitivity of Carina to the second principal component factor in both the Central and Eastern Free State warrants further attention. It is clear that adaptation and yield stability of genotypes in the Free State can not be ascribed to one factor only, namely soil water supply/drought, but that other factors, possibly temperature, also affect adaptation and stability significantly and should be investigated further.

4.9 Comparison of analyses

Tables 4.12, 4.14 and 4.16 indicate the ranking orders for stability of the 13 wheat genotypes, according to the six different genotype x environment interaction 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 pairwise comparisons of the different stability analysis procedures for the respective production regions (Tables 4.13, 4.15 and 4.17). Subsequently Student's *t* test was performed to determine the significance of Spearman's rank correlation coefficients and the results are indicated in Tables 4.18, 4.19 and 4.20 for the Western, Central and Eastern Free State production regions respectively.

Remarkable and total correspondence of significance for Spearman's rank correlation coefficients between analysis procedures was noted over the three production regions. Over all three regions Shukla's stability analysis procedure correlated highly significantly (P0.01) with those of Eberhart & Russel, Wricke and the AMMI model, while the same held true for Eberhart & 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 & Binns' and Finlay & Wilkenson's procedures with the other procedures, nor in the comparison between the two above-mentioned procedures. This indicates that the Lin & Binns procedure, as well as the Finlay & Wilkenson procedure, certainly differ

Table 4.12 Values and ranking order for stability according to six different G x E stability analysis procedures on 13 wheat cultivars evaluated over 39 sites in the Western Free State

Cultivar	G x E stability analysis procedure											
	Shukla		Lin & Binns		Finlay & Wilkenson		Eberhart & Russel		Wricke		AMMI	
	δ^2_i	R	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.

Table 4.13 Spearman's coefficients of rank correlation for six G x E stability analysis procedures conducted on 13 cultivars evaluated over 39 sites in the Western Free State

Statistical procedure	Shukla	Lin & Binns	Finlay & Wilkenson	Eberhart & Russel	Wricke	AMMI
Shukla	-					
Lin & Binns	-0.38	-				
Finlay & Wilkenson	0.37	-0.90	-			
Eberhart & 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 0,01 level (see Table 4.18)

Table 4.14 Values and ranking order for stability analysis, according to six different G x E stability analysis procedures, on 13 wheat cultivars evaluated over 33 sites in the Central Free State

Cultivar	G x E stability analysis procedure											
	Shukla		Lin & Binns		Finlay & Wilkenson		Eberhart & Russel		Wricke		AMMI	
	δ^2_i	R	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

Table 4.15 Spearman's (19) ranking order correlation coefficient matrix for six G x E stability analysis procedures conducted on 13 cultivars evaluated over 33 sites in the Central Free State

Statistical procedure	Shukla	Lin & Binns	Finlay & Wilkenson	Eberhart & Russel	Wricke	AMMI
Shukla	-					
Lin & Binns	-0.46	-				
Finlay & Wilkenson	0.33	-0.82	-			
Eberhart & 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 0,01 level (see Table 4.19)

Table 4.16 Values and ranking order for stability analysis, according to six different G x E stability analysis procedures, on 13 wheat cultivars evaluated over 48 sites in the Eastern Free State

Cultivar	G x E stability analysis procedure											
	Shukla		Lin & Binns		Finlay & Wilkenson		Eberhart & Russel		Wricke		AMMI	
	δ^2_i	R	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	3	8.6	2
Molen	173 322	6	147 885	4	0.96	6	22 497	8	1 979 079	6	31.1	7
SST 124	150 328	4	225 845	8	0.92	3	14 334	4	1 750 462	4	36.9	9
Letaba	610 290	12	221 577	7	1.08	11	114 334	12	6 323 544	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

Table 4.17 Spearman's (19) ranking order correlation coefficient matrix for six G x E stability analysis procedures conducted on 13 cultivars evaluated over 48 sites in the Eastern Free State

Statistical procedure	Shukla	Lin & Binns	Finlay & Wilkenson	Eberhart & Russel	Wricke	AMMI
Shukla	-					
Lin & Binns	0.11	-				
Finlay & Wilkenson	0.05	-0.80	-			
Eberhart & 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 0,01 level (see Table 4.20)

Table 4.18 Student's *t* test for significance[a] of Spearman's rank correlation coefficient for the Western Free State

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

a. $t \geq t(0.01; 11df) = *$

Table 4.19 Student's *t* test for significance[a] of Spearman's rank correlation coefficient for the Central Free State

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

a. $t \geq t(0.01; 11df) = *$

Table 4.20 Student's *t* test for significance[a] of Spearman's rank correlation coefficient for the Eastern Free State

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

a. $t \geq t(0.01; 11df) = *$

significantly from the other procedures in stability determination and definition.

The Lin & Binns procedure showed the greatest deviation from the other procedures, generally having negative rank correlation coefficients over all three the regions concerned. Lin & Binns define stability as the deviation of a specific genotype's performance from the performance of the best 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 it's 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 & Binns procedure thus appears to be considerably more of a genotype performance measure, rather than a stability measure over sites. The genotype mean yield (main effect) could then rather be used to identify a superior yield performing genotype. 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 x environment interaction in the Free State.

Finlay & Wilkenson's procedure also shows limited correspondence to the procedures of Shukla, Eberhart & Russel, Wricke and the AMMI model, but appears to be an improvement on the method of Lin & Binns. Finlay & Wilkenson's 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 & Léon (1988), as well as to Type I stability as defined by Lin *et al.* (1986). Further limitations of this technique are those generally associated with joint linear regression of genotype

yield on trial site mean, vizably (1) that the trial site mean is not independent of the data being analysed, (2) that regression coefficients are biased because of a critical assumption of regression analysis, that the independent variable is measured without error, could not be met, and (3) 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 X E interaction and determining stability of wheat genotypes in the Free State.

The Eberhart & 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 the first two mentioned procedures. 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 & 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 & Russel's stability can be aligned to Becker & Léon's 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 & Wilkenson procedure). While this type of stability analysis may be useful due to its simplicity and certain biological relevance, it must be used with caution and the limitations noted with this analysis approach should be considered when interpreting results. The use of this model in describing G X E interaction and stability of genotypes is recommended on condition that it is used in conjunction with other, preferably multivariate, methods of analyses. Becker & Léon (1988) also 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 4.13, 4.15 and 4.17 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 & Weber (1980) also noted. The procedures of Wricke and Shukla are statistically similar and are based on using the G X 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 also have Type II stability, according to Lin *et al.* (1986), and fall into the dynamic stability concept of Becker & 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, or preferably with the AMMI model in identifying and recommending superior genotypes for wheat producers in the Free State.

The AMMI model can be described as the only multivariate analysis method used in this study as it integrates analysis of variance and principal components analysis into a unified approach. The more holistic approach of AMMI is particularly effective in clarifying genotype x environment interactions. The study has clearly indicated that it

can summarise patterns and relationships of genotypes and environments successfully, as well as offers a valuable prediction assessment. While other multivariate analysis procedures (such as cluster analysis) are often difficult to interpret in relation to genotype x environment interaction, the AMMI model offers very relevant biological information (principal component factors can be described according to environmental and/or biological factors) and is statistically fairly simple. From the study it would appear that if a single method of describing G X E interaction and the stability of a genotype had to be selected, the AMMI model would be the most appropriate. Becker & 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 method has been proposed in this study, using IPCA1 and IPCA2 scores to determine an AMMI stability value (ASV), 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 & 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, and since it has considerable predictive value, it is recommended that this model form the basis of analysing genotype x environment interaction 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.

Chapter 5

SUMMARY

1. The study was undertaken to compare various statistical (parametric) methods of analysis to determine the most suitable procedure to evaluate wheat genotype performance under the variable and high-risk dryland conditions in the Free State province of South Africa, as well as to assess the suitability of these statistical procedures for characterising yield stability. The principal objective of the study is thus to recommend the most appropriate statistical procedure(s) to estimate wheat genotype performance and stability more accurately, to select superior wheat genotypes for this highly variable production region, and to understand and characterise the interaction of these genotypes with the environment in order to make reliable recommendations to producers and identify superior lines in breeding programmes for commercial classification.

2. Thirteen wheat genotypes were planted at 39 sites in the Western Free State, 33 sites in the Central Free State and 48 sites in the Eastern Free State over the period 1991 to 1994. Grain yield, and other parameters (not discussed), were determined and genotypes were evaluated for performance and yield stability in all three wheat production regions according to six statistical procedures, vizably the procedures of (i) Shukla, (ii) Wricke, (iii) Lin & Binns, (iv) Finlay & Wilkenson, (v) Eberhart & Russel and (vi) the AMMI model. A procedure is also proposed to determine an absolute genotype stability measure for the AMMI model. Subsequently the different procedures were compared using Spearman's rank correlation coefficient and the significance of the correlation coefficients were determined by means of Student's *t* test.

3. Shukla's stability variance procedure generally indicated good yield stability for the Betta group of genotypes, vizably Betta, SST 102, Oom Charl and Molopo, over all three regions. On the other hand the hybrids, vizably Carina, Caritha

and to a lesser degree Carol, as well as the purelines Karee and Letaba, generally showed poor stability over all three regions. Cultivars with intermediate stability were Molen, SST 124, Scheepers 69 and Tugela-DN. Differential responses over the three regions of especially Betta, Tugela-DN and Scheepers 69 emphasize the different adaptation of these genotypes to the respective regions.

4. Lin & Binns' cultivar performance measure indicated good yield stability, according to their definition and procedure, for especially the two hybrids, Carina and Carol, while the purelines Molen, Letaba and Tugela-DN also performed satisfactorily. The Betta group of genotypes, together with Karee, showed the worst stability. Again there was considerable correspondence of the performance of the genotypes over the three production regions. However, differential responses over regions of especially SST 124 and Scheepers 69 indicate that SST 124 is not well adapted to the Western Free State, nor Scheepers 69 to the Eastern Free State conditions.

5. Finlay & Wilkenson's regression analysis procedure generally indicated Scheepers 69, Karee and SST 124 to have above average stability ($b \leq 0,90$), but also specific adaptability to low-yielding or unfavourable environments. The Betta group, together with Molen, Letaba and Tugela-DN had average yield stability, while the hybrids Carina, Carol and to a lesser degree Caritha had below average stability ($b \geq 1.10$), but specific adaptation to high-yielding or favourable environments.

6. Eberhart & Russel's procedure, based on deviation from the regression in regression analysis, showed Oom Charl, SST 102 and Betta to have superior stability in all three regions, while Karee, Letaba and the hybrid Caritha were the most unstable. Molopo, Molen, SST 124 and Tugela-DN showed intermediate or average stability over all three regions. Scheepers 69 showed poor stability in the Eastern Free State, but very good stability in the Western Free State.

Both Carina and Carol also indicated a considerable differential yield stability response over the three production regions.

7. Wricke's ecovalence procedure showed the Betta group of genotypes, vizably Oom Charl, SST 102, Betta and to a lesser degree Molopo, to be the most stable genotypes over all three production regions, although Betta in the Western Free State and Molopo in the Eastern Free State tended to be more unstable. The most unstable genotypes over the three regions were Karee, Letaba, Caritha, Carina and to a lesser degree Carol. Again Tugela-DN, Molen, SST 124 and Scheepers 69 showed intermediate yield stability over the regions, except for Scheepers 69 which showed poor stability in the Eastern Free State.

8. For the AMMI method, a procedure combining IPCA1 and IPCA2 scores was used to determine an absolute AMMI stability value. According to this analysis, Oom Charl and SST 102 have the best stability over all three regions, while Tugela-DN, Molopo, Betta, Molen, SST 124 and Scheepers 69 all had average stability. However SST 124 showed good stability in the Central Free State specifically, as did Tugela-DN in the Western and Eastern Free State. Scheepers 69 again showed poor stability in the Eastern Free State. The hybrids Carina, Carol and Caritha, as well as the purelines Karee and Letaba, showed the greatest instability. According to the AMMI method, Carina and Carol did however show average stability in the Eastern Free State.

9. Spearman's rank correlation coefficient was used to compare the six different statistical procedures and significance was tested using Student's *t* test. Lin & Binns' procedure showed no correspondence whatsoever to any of the other five stability analysis procedures. Examination of its definition reveals it to rather indicate genotype performance over environments (similar to main effect) than to be a stability measure. Finlay & Wilkenson's procedure similarly showed a total lack of correspondence to all the other procedures. Shukla's stability variance and Wricke's ecovalence procedures are similar in definition, with the

result that rank correlation coefficients of 1.0, indicating total equivalence between the two procedures, were found for all three regions. Both procedures also indicated highly significant (P=0.01) rank correlation coefficients with both Eberhart & Russel's procedure and the AMMI method. Eberhart & Russel's procedure of deviation from the regression also had highly significant rank correlation coefficients over all three regions when compared with the AMMI model, the only multivariate procedure evaluated.

RECOMMENDATION

Since the procedure of Lin & Binns rather indicates genotype performance, and since it is also based on the performance relative to the single best performer in a trial, the procedure should preferably not be used for describing G X E interaction and stability of genotypes. The Finlay & Wilkenson procedure is primarily based on Type I or the static/biological stability concept, and is thus also not suitable for describing G X E interaction and especially the stability of genotypes. Both the procedures of Shukla and Wricke can be useful in supplying additional information on the stability of genotypes, but have limited or no value in describing the response patterns of genotypes to varying environmental conditions. Of the regression techniques, Eberhart & Russel's procedure of deviation from the regression appears to be the most useful in that the regression coefficient also gives additional information describing the genotypes response to different environments. However, the regression approach has several statistical and biological limitations which must be considered carefully when using this procedure. Finally the AMMI model, while statistically more complex, appears to more accurately describe both G X E interaction and stability analysis by means of response patterns which can easily be elucidated from either the biplot or from a scattergram of IPCA1 scores on IPCA2 scores.

The procedures of Shukla and Wricke, as well as of Eberhart & Russel, are useful in characterising wheat genotype stability. However the AMMI method provides considerably more information, not only in terms of a stability measure, but also in

terms of describing response and spatial patterns, clarifying genotypic effects and having an inherent predictive value. For this reason the AMMI model should be the principal statistical method to be used to describe genotype x environment interaction and stability of wheat genotypes grown under dryland conditions in the Free State province of South Africa.

OPSOMMING

1. Die studie is onderneem om verskeie statistiese (parametriese) metodes van genotipe x omgewingsinteraksie-analise te vergelyk om sodoende die mees geskikte prosedure om koringgenotipes se prestasie onder die wisselende en hoë risiko droëlandtoestande in die Vrystaat-provinsie van Suid-Afrika te beskryf, en veral om die geskiktheid van hierdie statistiese prosedures te ondersoek om die opbrengsstabiliteit van hierdie winterkoringgenotipes te karakteriseer. Die doel van hierdie studie is dus om die mees geskikte statistiese prosedure(s), wat koringgenotipes se prestasie en opbrengsstabiliteit die akkuraatste beskryf, aan te beveel om verbeterde koringgenotipes uit die teeltprogramme vir hierdie hoogs wisselende produksiegebied te selekteer en vir kommersiële vrystelling te identifiseer, asook om die interaksie van hierdie genotipes met die omgewing te verstaan en te karakteriseer om sodoende betroubare en sinvolle aanbevelings aan produsente te maak.

2. Dertien winterkoringgenotipes, wat algemeen in die Vrystaat verbou word, is by 39 lokaliteite in die Wes-Vrystaat, 33 lokaliteite in die Sentraal-Vrystaat en 48 lokaliteite in die Oos-Vrystaat oor die periode 1991 tot 1994 in cultivarevaluasieproewe getoets. Graanopbrengs en ander parameters (nie bespreek nie) is bepaal en genotipes is vir graanopbrengsprestasie en opbrengsstabiliteit in al drie streke volgens ses statistiese prosedures, naamlik die prosedures van (i) Shukla, (ii) Wricke, (iii) Lin en Binns, (iv) Finlay en Wilkenson, (v) Eberhart en Russel en (vi) die AMMI-model evalueer. 'n Prosedure vir die bepaling van 'n absolute genotipestabiliteit-maatstaf vir die

AMMI-model word ook voorgestel. Daarna is die verskillende prosedures met mekaar vergelyk deur van Spearman se rangorde-korrelasiekoëffisiënt gebruik te maak en die betekenisvolheid van die korrelasiekoëffisiënte is deur middel van Student se *t*-toets bepaal.

3. Shukla se stabiliteitsvariansie-prosedure het oor die algemeen goeie opbrengsstabiliteit vir die Betta-groep cultivars, naamlik Betta, SST 102, Oom Charl en Molopo, in al drie produksiestreke getoon. Daarenteen het die basters, naamlik Carina, Caritha en tot 'n mindere mate Carol, asook die suiwertelende genotipes Karee en Letaba, oor die algemeen swak opbrengsstabiliteit in die drie produksiestreke getoon. Genotipes met intermediêre opbrengsstabiliteit was Molen, SST 124, Scheepers 69 en Tugela-DN. Gedifferensieerde reaksies van veral Betta, Tugela-DN en Scheepers 69 oor die drie streke beklemtoon die variërende aanpassing van elk van hierdie genotipes in die onderskeie streke.

4. Lin en Binns se cultivarprestasie-maatstaf het goeie opbrengsstabiliteit, volgens hulle definisie en prosedure, vir veral die basters Carina en Carol getoon, terwyl die suiwertelende genotipes Molen, Letaba en Tugela-DN ook bevredigend presteer het. Die Betta-groep van genotipes, asook Karee, het die swakste stabiliteit getoon. Weereens was daar aansienlike ooreenstemming tussen die cultivars se opbrengsstabiliteit oor die drie produksiestreke. Die gedifferensieerde reaksies van veral SST 124 en Scheepers 69 oor die drie streke het egter getoon dat SST 124 nie goed aangepas is in die Wes-Vrystaat nie en dat Scheepers 69 swak aangepas is in die Oos-Vrystaat.

5. Finlay en Wilkenson se prosedure van regressie-analise het oor die algemeen getoon dat Scheepers 69, Karee en SST 124 oor bogemiddelde opbrengsstabiliteit ($b \leq 0.90$) beskik, maar dat dié genotipes ook spesifiek by lae opbrengs- of ongunstige toestande aangepas is. Die Betta-groep, tesame met Molen, Letaba en Tugela-DN, het gemiddelde opbrengsstabiliteit vir al drie streke getoon, terwyl die basters Carina, Carol en tot 'n mindere mate Caritha

weer ondergemiddelde opbrengsstabiliteit ($b \geq 1.10$) het, maar weer spesifiek aangepas is by hoë opbrengs- of gunstige omgewingstoestande.

6. Eberhart en Russel se prosedure, wat gebaseer is op die afwyking vanaf die regressie in regressie-analise, het getoon dat Oom Charl, SST 102 en Betta oor die beste opbrengsstabiliteit in al drie produksiestreke beskik, terwyl Karee, Letaba en die baster Caritha weer die mees onstabiele cultivars was. Molopo, Molen, SST 124 en Tugela-DN het intermediêre of gemiddelde stabiliteit in die drie streke getoon. Scheepers 69 het swak opbrengsstabiliteit in die Oos-Vrystaat getoon, maar baie goeie stabiliteit in die Wes-Vrystaat. Beide Carina en Carol het ook aansienlik gedifferensieerde opbrengsstabiliteit oor die drie streke getoon.

7. Wricke se ekovalensie-maatstaf ("ecovalence measure") het getoon dat die Betta-groep van genotipes, naamlik Oom Charl, SST 102, Betta en tot 'n mindere mate Molopo, die mees opbrengsstabiele genotipes oor al drie produksiestreke was, alhoewel Betta in die Wes-Vrystaat en Molopo in die Oos-Vrystaat geneig was om onstabiel te wees. Die genotipes met die swakste opbrengsstabiliteit oor die streke was Karee, Letaba, Caritha, Carina en tot 'n mindere mate Carol. Weereens het Tugela-DN, Molen, SST 124 en Scheepers 69 gemiddelde opbrengsstabiliteit in al drie streke getoon, behalwe vir Scheepers 69 wat swak opbrengsstabiliteit in die Oos-Vrystaat getoon het.

8. Vir die AMMI-metode is 'n prosedure wat die IPCA 1-telling (eerste hoofkomponent van die interaksie) met die IPCA 2-telling kombineer, gebruik om 'n absolute AMMI-stabiliteitswaarde te bepaal. Volgens dié analise het Oom Charl en SST 102 die beste stabiliteit in al drie streke, terwyl Tugela-DN, Molopo, Betta, Molen, SST 124 en Scheepers 69 almal gemiddelde stabiliteit getoon het. SST 124 het egter in die Sentraal-Vrystaat spesifiek goeie opbrengsstabiliteit getoon, soos ook die geval met Tugela-DN in die Wes- en Oos-Vrystaat. Scheepers 69 het weer swak opbrengsstabiliteit in die Oos-Vrystaat getoon. Die basters Carina,

Vrystaat getoon. Die basters Carina, Carol en Caritha, asook die suiwertelende genotipes Karee en Letaba, het die swakste opbrengsstabiliteit getoon. Volgens die AMMI-metode beskik Carina en Carol egter oor gemiddelde opbrengsstabiliteit in die Oos-Vrystaat.

9. Spearman se rangorde-korrelasiekoëffisiënt is gebruik om die ses verskillende statistiese prosedures met mekaar te vergelyk en die betekenisvolheid daarvan is deur middel van Student se *t*-toets bepaal. Lin en Binns se prosedure het geen ooreenstemming met enige van die ander vyf stabiliteitsmetodes getoon nie. 'n Ondersoek na hul definisie toon dat hul maatstaf eerder gemiddelde genotipeprestasie oor omgewings beskryf (soortgelyk aan hoofeffek), as wat dit 'n opbrengsstabiliteit-maatstaf is. Finlay en Wilkenson se prosedure toon soortgelyk geen ooreenstemming met die ander prosedures nie. Shukla se stabiliteitvariansie- en Wricke se ekovalensie-prosedures is soortgelyk in definisie, met die gevolg dat rangorde-korrelasiekoëffisiënte van 1.0, wat totale ooreenstemming tussen die twee prosedures aandui, tussen die twee prosedures in al drie streke gevind is. Beide prosedures het ook hoogs betekenisvolle ($P = 0.01$) rangorde-korrelasiekoëffisiënte met beide Eberhart en Russel se prosedure en die AMMI-metode getoon. Eberhart en Russel se prosedure van afwyking vanaf die regressie het ook hoogs betekenisvolle rangorde-korrelasiekoëffisiënte met die AMMI-metode, wat die enigste meerveranderlike-prosedure is wat geëvalueer is, vir al drie produksiestreke gehad.

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