Genotype x Environment Interaction for Sunflower Hybrids in South Africa

by

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Dedicated to
My Father in Heaven,
My wife, Elsie
and my daughters, Elanie and Carina

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CHAPTER 1
INTRODUCTION

1.1) Importance of Sunflower

Sunflower, cultivated for agricultural purposes, belongs to the genus *Helianthus.* There are 67 species belonging to *Helianthus,* of which only two are exploited as food source (Heiser, 1978). This is *H. annuus*, produced mainly for its oil, as birdfood, meal supplement for animal feed and for human consumption as confectionery kernels (Dorrel, 1978; Lofgren, 1978) and *H. tuberosus,* Jerusalem artichoke, of which the tubers are consumed.

Sunflower has been exploited since the early 16th century by the Ozark Bluff Dwellers in North America (Fick, 1978). Selection for better yield has been practiced in the old USSR and by 1880 a large number of cultivars, all open-pollinated, were available. In 1910 breeding and selection commenced at official experimental stations in the USSR. Since then research on sunflower has expanded dramatically in the world and most developed, as well as a number of developing countries have established government funded breeding programmes and private breeding programmes.

The worldwide sunflower production has increased from 3.6 million tons during the period 1965-1974 (Putt, 1978), to 24,067 million metric tons in 2003 (NSA, 2003) with a world price of 328US$ per ton (SAGIS, 2003a), and a brute value of 7.9billionUS$ or R52billion.

In South Africa the sunflower crop for the 2002/2003 season was 642 075 metric ton on 605 750 hectares. The total crop production for maize for the same period was 9.4million ton on 3.2million hectares (SAGIS, 2003b), while wheat produced 2.3 million ton on 941 100 hectares (SAGIS, 2003c) and approximately 413 000 hectares under production for other crops (SAGIS, 2003b; SAGIS, 2003c). Sunflower has therefore not been the major product of seed companies in South Africa, but is still a very important source of income. In contrast to maize, the tendency is to limit the number of sunflower hybrids in a company's product range for logistical reasons. In order to do this it is important to select varieties that perform relatively well in all regions. This leads to one or two cultivars per company being commersialised in the whole sunflower production region in South Africa. If there is relatively little interaction between genotype and environment, thismay be an acceptable practice, but if the genotype and environment interaction is of such magnitude that it contributed a significant amount to the performance of a genotype, companies would have to revise their marketing strategies in order to make region specific recommendations.

1.2) Sunflower Research and Breeding

Sunflower research is based on two basic structures, namely the breeding programme and multi-location yield trials. The breeding programme focuses on the development of new inbred lines, on the female side both cytoplasmic male sterile (CMS) and maintainer lines, and on the male side, restorer lines. The CMS and restorer lines are crossed in various combinations to obtain hybrids for evaluation in the multi-location yield trials. The yield trials serve three basic objectives: 1) to accurately estimate and predict yield based on limited experimental data, 2) to determine the yield stability and pattern of response of genotypes across environments, and 3) to provide a reliable guidance in selecting genotypes for breeding in future years (Crossa, 1990). To make significant progress in breeding, it is therefore necessary to obtain reliable data from these yield trials.

Yield trials usually consists of G genotypes tested in E environments with R replications. The environments are normally regarded as location and year combinations, such as Delmas in 1995, or Delmas in 1996 being two different environments. This result in GxExR or GER observations. This type of testing and research helps breeders and agronomists to make estimates of a genotype's yield potentialover environments and thus permit recommendations of cultivars for commercial use to be made, while also assisting in selecting lines for breeding. The more GER observations are made, i.e. more replications or more environments, the more reliable the data become. Although the ideal is to have as many locations and replications as possible, there are always financial and logistical restrictions on the number of each used. Increasing replications normally is less costly than increasing locations, therefore the careful selection of locations is of utmost importance.

When testing a diversity of genotypes in a number of dissimilar environments, it is often observed that the ranking of genotypes differs between environments. This can be described as an interaction between genotypes and environments. Bailey (1983) gives the following definition for interaction:

"In some experiments or processes the yield measured is affected by two or more factors. If the yield is not just the sum of the effects of the separate factors, the factors are said to *interact*. If there are two factors, the difference between the yield and the sum of the effects of the two factors is called the *interaction* of the two factors."

Because of this interaction it is often difficult to make recommendations of sunflower genotypes to be planted in specific regions.

The aim of this study is to establish whether interaction in sunflower testing in South Africa is of any significance, and if so, how this would affect the recommendation of cultivars for marketing purposes, as well as the method of testing, i.e. the location of sites for testing.

CHAPTER 2
LITERATURE REVIEW

The genotype x environment (GxE) interaction in several crops has been studied widely worldwide. In South Africa, Laubscher*, et al.* (2000) found that minimum night temperature, which determines the rate of development of certain physiological stages in maize, was a major contributor to GxE interaction. GxE interactions in potatoes (Steyn, *et al*. 1993), lucerne (Smith & Smith, 1992) and soybean (Smit & de Beer, 1991) have been found. GxE interaction in wheat in South Africa was reported by Purchase, *et al*. (2000 a & b). They found that the wheat hybrids and long growth period pureline cultivars had a superior adaptation to high yield potential conditions, while the short and medium growth period pureline cultivars were better adapted to lower yield potential conditions.

In Canada,May and Kozub (1993) did research on barley to establish whether the selection of genotypes based on GxE interactionand main effects would differ from those made on main effects alone. They found that no single genotype was superior over all nine test sites used, and the grouping of genotypes for similarity of response at locations was not consistent over years. This indicated that genotypes selected on main effect alone, may differ from those selected when the GxE interaction is taken into account.

Some studies on sunflower have also been done. Fick and Zimmer (1976) found that the stability of yield performance of cultivars is under genetic control. They also found that some inbred lines tend to contribute more to the stability of hybrids than other, which shows that the genotype contributes to some extent to yield stability.

De la Vega, *et al.*(2000) investigated whether the daily linear harvest index increase (DHI), used in crop simulation models, was stable for sunflower across genotypes and environments, as was generally believed. The slope of the DHI provides a simple means to predict grain growth and yield in field crops. Using principal components analysis, they showed that a significant GxE interaction for DHI does exist and it is not a stable attribute across genotypes and environments.

According to Robinson, *et al* (1967), latitude affects the number of days from planting to flower. They compared plantings from Texas (31°N. Lat) to Manitoba (49°N. Lat), all done on 14 May and found that there was an average increase of 1.9 days to flower for each degree latitude increase, from south to north. These effects can be ascribed to GxE interaction.

Foucteau, *et al*. (2001) studied two sunflower networks in France. They determined an interaction for yield between genotypes' growing length and the length of the season. A correlation between earliness of sunflower cultivars and earliness of season exists and they found a positive correlation between these two factors for yield. Early cultivars performed much better in early environments, while later cultivars were superior in late environments, because of their ability to fully utilise the longer growing season. The interaction variance component was much larger than the genotypic variance component and led to multiple genotypic rank changes across locations. They also found that each genotype's oil content wasaffected by water deficit during flowering period and that this was a repeatable interaction in both testing networks.

De la Vega, *et al*. (2001) reported GxE interaction in sunflower in Argentina for oil yield and biomass. It was shown that differences between the northern and central regions of Argentina, in photoperiod and minimum temperature, played a significant interaction role on oil yield. Because most of the breeding programmes in Argentina are situated in the central region, it would be more cost effective if selection for cultivars for both the central and northern regions could be done only in the central region. It was found that due to the strong interaction effects between photoperiod and oil yield, that it would be possible to identify cultivars for the northern region making use of late planting dates in the central region. When photoperiod was artificially increased to 15.5 hours per day in the north, oil yield response of cultivars were similar to that of normal planting dates in the central region. They identified a way to exploit the interaction effect to the advantage of their breeding programme.

Nel & Loubser (2000) reported GxE interaction effects on yield and certain seed traits of sunflower in South Africa. Grain yield, hectolitre mass, thousand seed weight, hullability, hull content and fine material in the sample were all affected by the genotype, environment and GxE interaction. For hectolitre mass and hull content, the environment had the greatest effect, while for the thousand seed weight and hullability, the genotype had the dominant effect. In all cases the GxE interaction played a significant role.

Various statistical techniques are available to determine this GxE interaction as described by the above authors, but not all give easily interpretable results. Crossa (1990) compared a number of techniques, including analysis of variance (ANOVA), joint linear regression, additive main effect and multiplicative interaction analysis (AMMI) and different multivariate analyses like principal components analysis (PCA), principal coordinates analysis, factor analysis and cluster analysis. Crossa concludes that linear regression analysis is mathematically simple and results obtained are biologically interpretable, but there are major disadvantages, like: 1) it is uninformative when linearity fails. One of the assumptions of the linear regression is that there exists a linear relationship between interaction and environmental means. When this linearity does not exist, results could be misleading. The analysis requires that a high proportion of the genotype by environment effects should be attributable to linear regression; 2) it is highly dependant on the set of genotypes and environments included in the study. In the regression model, the genotype mean (x variable) is not independent of the marginal means of the environments (y variable). Regressing one set of variables on another that is not independent, violates one of the assumptions of regression analysis. This interdependence might be a major problem when working with smaller numbers of genotypes, but not when the number is large. If the standard set for stable yield is based on very few genotypes (let's say 9, as in this study), each estimated stability coefficient involves regressing one genotype on an average to which it contributes one ninth, or 11.1%. The smaller the number of genotypes, the bigger the discrepancy; and 3) it tends to oversimplify the different response patterns by explaining the interaction variation in one dimension (regression coefficient), when in reality it may be highly complex.

The multivariate methods on the other hand, overcome some of the problems of linear regression, but the results are difficult to interpret in relation to GxE interaction. According to Crossa (1990) multivariate analyses have three main purposes: 1) to eliminate noise from data pattern; 2) to summarise data; and 3) to reveal a structure in the data. Multivariate analyses are best suited for analysing two-way matrices of G genotypes and E environments, the aim being to evaluate the response of any genotype in E environments. This response can then be conceived as a pattern in E-dimensional space, with the coordinate of an individual axis being the yield or other metric of the genotype in one environment. Principal components analysis is one of the more commonly used multivariate analyses, but it's shortcoming is the fact that it ignores the additive main effects (Zobel, *et al*., 1988; Gauch, 1992). The combination of analysis of variance and principal components analysis in the AMMI model is however a valuable tool for better understanding GxE interaction and obtaining better yield estimates, while taking both the additive main effects and multivariate effects into account.

Gauch (1992) also compared different methods of analysing multilocation yield trial data. He describes the ANOVA, linear regression, PCA, AMMI and shifted multiplicative model (SHMM). AMMI is the only model that distinguishes clearly between the main and interaction effects and this is usually desirable in order to make reliable yield estimations.

CHAPTER 3
GENOTYPE x ENVIRONMENT INTERACTION:
Introduction, Materials and Methods

This chapter gives a brief introduction to the importance of GxE interaction in sunflower testing and its utilisation in selection of genotypes for commercialisation and selecting locations as test sites. The materials and methods used to conduct the study are also discussed.

3.1) Introduction

Multi-location trials are crucial for selecting the best cultivar for specific environments, before any recommendations can be made for future commercialisation. Cultivars react differently to environmental factors due to GxE interaction. In describing this GxE interaction, the AMMI model is more parsimonious than the analysis of variance (ANOVA) model and allows a more complete interpretation of the interaction, than the linear regression model, because the interaction can be modeled in more than one dimension (Vargas, *et al*., 1999; Crossa, 1990; Gauch, 1992)It also takes the main effects , neglected in principal components analysis, into account (Crossa, 1990; Gauch, 1992).

When performing an analysis of variance (ANOVA) on a set of data, the following equation is applicable:

$$Y_{ger} = \mu + \alpha_g + \beta_e + \theta_{ge} + \varepsilon_{ger} \qquad \textbf{(1)}$$

where

Y_{ger}	is the yield of genotype g in environment e, with r replications,
μ	is the grand mean,
α_g	is the genotype deviation (genotype mean minus grand mean),
β_e	is the environment deviation,
θ_{ge}	is the interaction deviation,

ε_{ger} is the error term.

It is important to remember that when talking about an environment, it is always a location x year combination, and not just thelocation . This also applies for GxE interaction, which includes genotype x location x year interaction.

From equation 1 it is clear that interaction is the non-additive residual in the ANOVA model. From the ANOVA analysis the sum of squares (SS) for treatments is partitioned into three sources: genotypes (G), environments (E) ad genotype x environment interaction (GxE). The relative magnitude of each of these SS sources varies from trial to trial (Gauch, 1992).

In some cases the interaction, regarded as the non-additive residual of the ANOVA with (G-1)(E-1) degrees of freedom, contributes more to treatment differences, than does the genotype. Even though the interaction contains such a large number of degrees of freedom and often contributes a significant amount to the treatment SS, its nature is not explained by the ANOVA, though identified (Zobel, *et al.*1988).

AMMI combines the ANOVA, which compute the genotype and environment additive effects, with principal components analysis (PCA), which is a multiplicative model, analysing the non-additive interaction effects (Gauch, 1988; Gauch & Zobel, 1996). The results can be presented in an easily interpretable and informative biplot graph which shows both the additive main effects and the multiplicative interaction effects.

The equation used to predict the yield of a cultivar in a specific environment according to AMMI*N* is as follows (Gauch, 1992):

$$\hat{Y}_{ger} = \mu + \alpha_g + \beta_e + \sum_n \lambda_n \gamma_{gn} \delta_{en} + \rho_{ge} + \varepsilon_{ger} \text{ with n=1,...,N} \qquad \textbf{(2)}$$

where μ is the grand mean, α_g is the genotype deviation estimated as $\bar{Y}_g - \bar{Y}$, β_e is the environment deviation estimated as $\bar{Y}_e - \bar{Y}$ and $\sum_n \lambda_n \gamma_{gn} \delta_{en}$ is the multiplicative fraction, with multiplicative parameters λ_n , the characteristic value for IPCA axis *n*, γ_{gn}, the genotype eigenvector for axis *n*, and δ_{en}, the environment eigenvector for axis *n*. If not all axes are used, a residual ρ_{ge} remains. ε_{ger} is the error term.

As with PCA, a convenient scaling for the multiplicative parameters is $\left(\lambda^{0.5}\gamma_g\right)$ and $\left(\lambda^{0.5}\delta_e\right)$, because their product gives the interaction's expected value directly, without needing further multiplication by the singular value. These AMMI multiplicative parameters are termed the interaction PCA scores, or IPCA scores.

The member of the AMMI family with 1 interaction principal component analysis (IPCA) axis, while all higher axes are relegated to the residual, is denoted as AMMI1. In the same manner, when retaining 2 IPCA axes, it is denoted as AMMI2. In general, AMMI*N* denotes the AMMI model with IPCA axes 1 to N.

An alternative to equation 2can be used (Gauch, 1992). In the additive part of the equation the genotype and environment deviations can be substituted by the genotype and environment means, respectively π_g and τ_e. When this is done the grand mean should however be deducted, instead of added as was the case. The formula changes as follows:

$$Y_{ger} = \tau_e + \pi_g - \mu + \left(\lambda^{0.5}\gamma_g\right)\left(\lambda^{0.5}\delta_e\right) + \rho_{ge} + \varepsilon_{ger} \qquad \textbf{(3)}$$

where $\left(\lambda^{0.5}\gamma_g\right)$ is the IPCA score for genotype *g* and $\left(\lambda^{0.5}\delta_e\right)$ is the IPCA score for environment *e*.

When none of the IPCA axes are significant, AMMI simply implies a normal ANOVA analysis, or AMMI*0,* where the 0 indicates that none of the interaction principal component axes were significant (Gauch, 1992).

General experience indicates that there must be a considerable amount of interaction affecting the yield of sunflower cultivars grown under South African conditions.

Testing cultivars over a wide range of environments each year, reveals that it is impossible to identify a superior genotype for the whole range of environments tested, because cultivar rankings vary across environments. This implies interaction between genotype and environment (Gauch, 1992). If one could exploit this interaction, instead of ignoring it, advances in the breeding programme can be achieved in a much shorter time (de la Vega, *et al*., 2001) and better recommendations can be made.

In plantbreeding, efficiency is critical, that is, maximizing agricultural progress and benefits per unit of cost. In developed countries research cost equals about 2% of the value of the agricultural products and in developing countries, only 0.5% (Gauch, 1992). For sunflower in South Africa the unofficial required volume during the early 2000's, was approximately 800,000 tons per annum with an average price of about R1,900 per ton (estimated figures). Regarded as a developing country, the research cost amounts to about R7.6million per annum. This is no small amount spent on the development of new cultivars.

Since yield trials are the primary experiment in plant breeding, it is important to design and analyse these trials in a manner that extracts as much information as possible from this costly data. It is expensive to increase the number of locations, but relatively cheap to better examine and more accurately analyse data to obtain more reliable results. It is therefore important to better manage the costly aspects of research, specifically the selection of locations for testing, as this is a key aspect in containing costs and obtaining meaningful data.

Therefore, this study was based on the following questions:

1. Is the relative magnitude of the GxE interaction on yield for sunflower under South African conditions small enough to be ignored, or large enough to be exploited?
2. How does the observed GxE interaction influence cultivar selection and recommendation for the whole testing area, or target environments within the testing area?

3. How does the observed GxE interaction influence the selection of locations for testing sunflower cultivars?

3.2) Materials and Methods

Three different sets of trials were planted over a three year period, one set per year, each containing 36 cultivars. All trials were Lattice designs (6x6) with three replications. A different randomization was used at each location. The two row plots, with 0.91meter row spacing, were 6 meters long with a 1.5 meter alley between ranges. The plant population for all trials was approximately 36,000 plants per hectare.

Only nine sunflower cultivars were included in all three consecutive years, seven of Pannar (Pty) Ltd., one long season (SF8), five medium season (SF3 to SF7) and one short season (SF9) and two of other companies, one long (SF1) and one medium season (SF2) (Table 4). These nine cultivars were evaluated in 16 different locations (table 1) from the 1995/1996 to the 1997/1998 season. Not all locations wereused each year and a total of 32 environments (location x year combinations listed in table 1) are included in this study.

At the Delmas location planting dates were divided into early, medium and late plantings, asmultiple trials were planted each year at this location, varying only in planting dates. Each planting date at this site was regarded as a separate environment (table 1).

Table 1. Summary of the locations included in the study, including the environment codes assigned to each environment.

Site (Region)	Location Code	Regional orientation	Coordinates	Climatic Region	Relative Planting Date	Environment Code		
						95/96	96/97	97/98
Balfour	BA	East	26°38'S 28°35'E	Moist Highveld Grassland		BA95		BA97
Bethal	BE	East	26°27'S 29°27'E	Moist Highveld Grassland				BE97
Bloemfontein	BL	West	29°06'S 26°12'E	Dry Highveld Grassland			BL96	
Delmas	DE	East	26°08'S 28°41'E	Moist Highveld Grassland	Early		DE96	DE97
	DM	East	26°08'S 28°41'E	Moist Highveld Grassland	Medium	DM95		DM97
	DL	East	26°08'S 28°41'E	Moist Highveld Grassland	Late		DL96	DL97
Dwaalboom	DW	North	24°43'S 26°48'E	Northern Arid Bushveld		DW95		DW97
Kinross	KI	East	26°25'S 29°05'E	Moist Highveld Grassland			KI96	
Klerksdorp	KL	West	26°51'S 26°39'E	Dry Highveld Grassland		KL95	KL96	KL97
Kroonstad	KR	West	27°39'S 27°14'E	Dry Highveld Grassland		KR95		KR97
Leandra	LE	East	26°22'S 28°55'E	Moist Highveld Grassland				LE97
Lichtenburg	LI	West	26°08'S 26°09'E	Dry Highveld Grassland			LI96	LI97
Makokskraal	MA	West	26°20'S 26°37'E	Dry Highveld Grassland		MA95		
Rysmierbult	RY	West	26°28'S 26°58'E	Dry Highveld Grassland			RY96	RY97
Senekal	SN	East	28°19'S 27°37'E	Moist Highveld Grassland		SN95	SN96	
Settlers	SE	North	24°57'S 28°32'E	Central Bushveld		SE95	SE96	SE97
Standerton	ST	East	26°55'S 29°14'E	Moist Highveld Grassland		ST95		
Tweespruit	TW	East	29°11'S 27°01'E	Moist Highveld Grassland		TW95	TW96	

The climatic regions, coordinates and regional orientation (East, West or North) for each location are also listed in table 1. The testing region coincides with four different climatic regions, as described by the South African Weather Service (SAWS, 2003). The 24 different regions in South Africa are shown in figure 1 and the four of interest are described in table 2. For the purposeof this study the Northern

Arid Bushveld and Central Bushveld are considered as one climatic region and regarded as Northern sites, as conditions are very similar and each region only encompass one testing location. The locations in the Moist Highveld Grassland and Dry Highveld Grassland are regarded as Eastern and Western locations respectively.

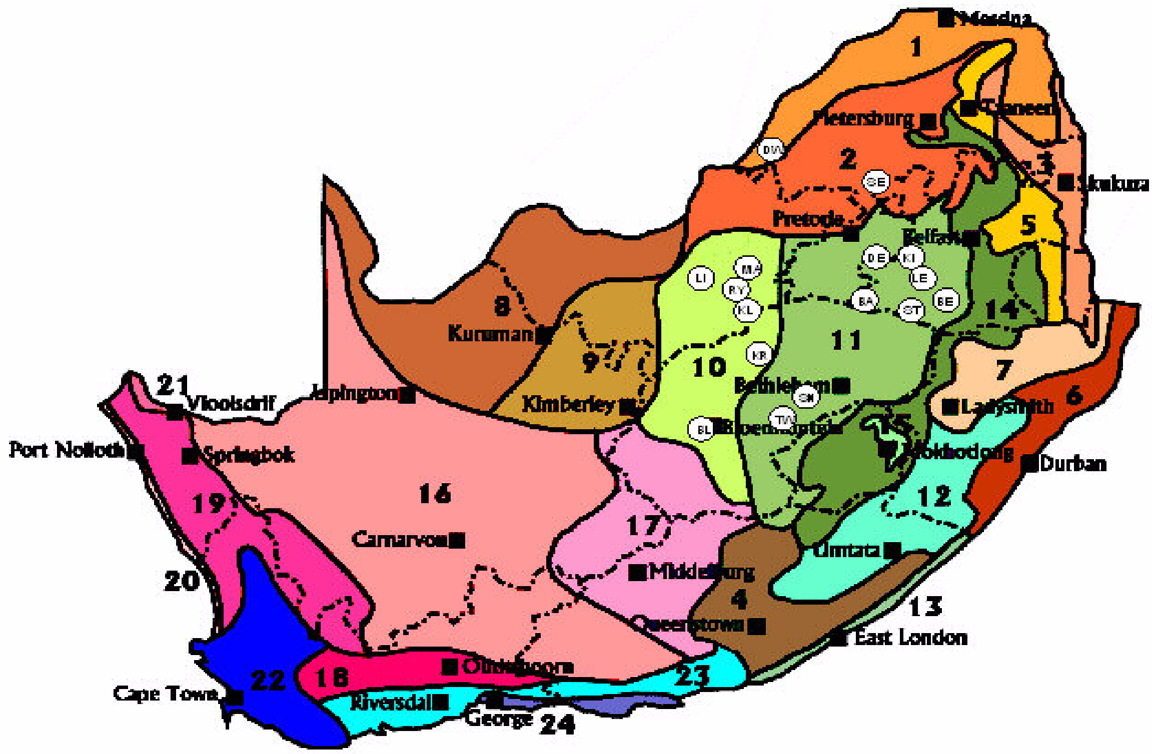

Figure 1. The Climatic Regions of South Africa and approximate location of trial sites.

1. Northern Arid Bushveld, 2. Central Bushveld, 3. Lowveld Bushveld, 4. South-Eastern Thornveld, 5. Lowveld Mountain Bushveld, 6. Eastern Coastal Bushveld, 7. KwaZulu-Natal Central Bushveld, 8. Kalahari Bushveld, 9. Kalahari Hardveld Bushveld, 10. Dry Highveld Grassland, 11. Moist Highveld Grassland, 12. Eastern Grassland, 13. South-Eastern Coast Grassland, 14. Eastern Mountain Grassland, 15. Alpine Heath land, 16. Great and Upper Karoo, 17. Eastern Karoo, 18. Little Karoo, 19. Western Karoo, 20. West Coast, 21. North-Western Desert, 22. Southern Cape Forest, 23. South-Western Cape, 24. Southern Cape.

Table 2. Description of the climatic regions included in this study.

Regional Orientation	Climatic Region	Properties
West	Dry Highveld Grassland	Precipitation ranges from about 450mm in the west to about 700mm at its northern border. The rainy season reaches its maximum during December and January in the north, but February to March in the west and south. Winds are highly variable, but tend to be more from the north and north-east.
East	Moist Highveld Grassland	Similar to the previous region, but cooler and wetter due to higher elevation and position relative to rain bearing systems. Precipitation, which ranges from 600-800mm p.a., has its maximum during December and January, but February in the south. Winds are highly variable, but easterly and westerly winds are more prevalent.
North	Northern Arid Bushveld	Lower than average rainfall (300-500mm p.a.) for the savanna regions. Rainy season lasts from about November to March, with the peak falling in January.
	Central Bushveld	Precipitation, somewhat erratic, ranges from 500-750mm p.a.. Rainy season lasts from about November to March, with peak falling in January. Winds blow mostly from the north-east.

All the plots, of the 9 entries included in this study, were harvested and weighed, resulting in 864 yield measurements with 287 degrees of freedom for treatments, 64 for the block effect, and 512 for error (table 3). All weights were converted to tons per hectare.

An AMMI analysis was performed on the data using the Genstat computer programme (Genstat 5, Release 4.2).

CHAPTER 4
GENOTYPE x ENVIRONMENT INTERACTION:
Results, Discussion and Conclusions

4.1) Results and Discussion

4.1.1) GxE Interaction

This section deals with the first question asked, namely:" Is the relative magnitude of the GxE interaction on yield for sunflower in South African conditions small enough to be ignored, or large enough to be exploited?"

The AMMI2 analysis of variance is given in table 3. The model captures 34% of the interaction sum of squares (SS) with the first IPCA axis(IPCA1) , with only 15.3% of the interaction degrees of freedom (df), and 22.5% of the interaction SS with the second IPCA axis (IPCA2), with 14.5% of the interaction degrees of freedom. Both IPCA1 and IPCA2 are statistically highly significant ($P<0.001$). The partitioning of the interaction SS was effective, with the mean square (MS) of the first IPCA axis 3.5 times that of the residual MS, and the second IPCA axis MS 2.5 times that of the residual MS. The combined MS for the two IPCA axes are 6.1 times that of the residual MS. In total, AMMI2 contained 89.9% of the treatment SS, while the residual contained only 10.1%. The treatment and block SS combined make up 81.4% of the total SS, with only 40.7% of the total df, while the error term's SS make up 18.6% of the total SS, while containing 59.3% of the total df. These results indicates that the AMMI model fits the data well, and justifies the use of AMMI2

Table 3. The analysis of variance table, for AMMI2, of the nine sunflower cultivars tested over 32 environments.

Source	df	SS	MS	F
Total	863	488.3	0.566	
Treatment	287	378.6	1.319	7.418**
Environment	31	279.7	9.024	30.951**
Genotype	8	10.6	1.322	7.437**
Interaction	248	88.3	0.356	2.001**
IPCA1	38	30.0	0.790	4.442**
IPCA2	36	19.9	0.553	3.107**
Residual	174	38.3	0.220	1.239*
Block	64	18.7	0.292	1.640**
Error	512	91.0	0.178	

*, ** Significant at P=0.05 and P=0.01 respectively.

Tables 4 and 5 give the IPCA1 and IPCA2 scores for genotypes and environments respectively,as derived from the multiplicative terms, $\left(\lambda^{0.5}\gamma_g\right)$ and $\left(\lambda^{0.5}\delta_e\right)$ in equation 3. When considering the multiplicative term, $\left(\lambda^{0.5}\gamma_g\right)\left(\lambda^{0.5}\delta_e\right)$ in equation 3, it can be clearly seen that when both the genotypic and environmental IPCA scores have the same signs, either both negative or both positive, the biggest advance wil be made in Y, while having opposite signs will bring about a reduction in Y. Therefore, the sign of the IPCA score does not reflect a negative or positive interaction effect on yield, but simply shows that cultivars will perform better in environments with similar signs, and worse in environments with opposite signs.

Table 4. Summary of the mean yields and Genotypic IPCA scores, GIPCA1 and GIPCA2 for the 9 cultivars, together with a classification of cultivars based on length of growing period.

Hybrid Code	Mean Yield (Y_g) (t/ha)	GIPCA1 Score	GIPCA2 Score	Classification
SF1	2.207	0.681	-0.551	Long season
SF2	2.122	-0.510	-1.257	Medium season
SF3	2.249	0.310	0.476	Medium season
SF4	2.301	0.124	0.485	Medium season
SF5	2.201	-0.098	0.132	Medium season
SF6	2.392	0.329	0.204	Medium season
SF7	2.155	0.184	0.145	Medium season
SF8	2.202	-1.420	0.385	Long season
SF9	1.971	0.400	-0.019	Short season

Table 5. Summary of the mean yields and Environmental IPCA scores, EIPCA1 and EIPCA2 for the 32 environments.

Location	Year	Env Code	Mean Yield (Y_e) (t/ha)	EIPCA1	EIPCA2
Balfour	1995	BA95	3.063	-0.801	-0.367
Balfour	1997	BA97	2.878	-0.190	-0.233
Bethal	1997	BE97	2.085	-0.230	-0.032
Bloemfontein	1996	BL96	2.180	0.285	-0.190
Delmas Early	1996	DE96	2.432	-0.005	0.238
Delmas Early	1997	DE97	2.280	0.131	0.314
Delmas Late	1996	DL96	1.368	0.136	0.100
Delmas Late	1997	DL97	2.316	0.148	0.027
Delmas Medium	1995	DM95	1.268	-0.040	-0.680
Delmas Medium	1997	DM97	2.699	0.078	-0.201
Dwaalboom	1995	DW95	3.841	-0.136	0.055
Dwaalboom	1997	DW97	2.306	-0.393	0.099
Kinross	1996	KI96	1.540	-0.015	-0.040
Klerksdorp	1995	KL95	2.046	0.431	-0.072
Klerksdorp	1996	KL96	1.483	0.144	-0.161
Klerksdorp	1997	KL97	1.818	0.121	-0.095
Kroonstad	1995	KR95	1.892	0.231	-0.268
Kroonstad	1997	KR97	1.468	0.213	-0.433
Leandra	1997	LE97	2.500	0.040	0.113
Lichtenburg	1996	LI96	2.187	0.048	-0.349
Lichtenburg	1997	LI97	2.047	-0.055	0.162
Makokskraal	1995	MA95	2.310	-0.178	0.333
Rysmierbult	1996	RY96	3.358	-0.566	0.750
Rysmierbult	1997	RY97	2.137	-0.054	-0.175
Senekal	1995	SN95	2.621	0.292	0.056
Senekal	1996	SN96	2.327	-0.365	0.021
Settlers	1995	SE95	2.810	0.168	0.064
Settlers	1996	SE96	1.817	-0.452	0.151
Settlers	1997	SE97	1.638	0.342	-0.186
Standerton	1995	ST95	1.779	0.677	0.350
Tweespruit	1995	TW95	1.988	0.584	0.552
Tweespruit	1996	TW96	1.912	-0.254	0.096

With equations 2 and 3 we can now estimate the expected yield value of any of the cultivars in any of the environments for AMMI2.

Taking cultivar SF1 in environment BA95 as an example, the expected AMMI1 yield is given by $\tau_e + \pi_g - \mu + \left(\lambda^{0.5}\gamma_g\right)\left(\lambda^{0.5}\delta_e\right)$ or 3.063t/ha+2.207t/ha- 2.200t/ha+[(0.681)(-0.801)] t/ha = 2.525t/ha. SF1 is thus expected to give a yield of 2.525t/ha in BA95. The difference between the observed yield and this AMMI1 estimate is included in the residual. When using AMMI2 for estimation, the expected yield should be closer to the observed yield and the residual will not be as large. For this we need to make use of equation 2. The expected yield of SF1 in BA95with the AMMI2 estimation is 2.727t/ha. Because both IPCA1 and IPCA2 are significant, the AMMI2 estimation gives us a more accurate prediction of the expected performance of cultivars in different environments. Table 6 gives the AMMI2 estimations of all 9 cultivars in the 32 environments with the grand mean of 2.200t/ha.

Table 6. The AMMI2 estimated yield (t/ha) for the each of the 9 cultivars in the 32 environments

	Cultivars									
Environments	**SF1**	**SF2**	**SF3**	**SF4**	**SF5**	**SF6**	**SF7**	**SF8**	**SF9**	**Env. Mean**
BA95	2.727	3.854	2.689	2.887	3.093	2.917	2.817	4.060	2.521	**3.063**
BA97	2.885	3.190	2.758	2.843	2.867	2.960	2.765	3.060	2.578	**2.878**
BE97	1.954	2.165	2.048	2.143	2.104	2.195	1.993	2.401	1.765	**2.085**
BL96	2.486	2.196	2.227	2.225	2.128	2.427	2.160	1.704	2.069	**2.180**
DE96	2.304	2.057	2.593	2.648	2.465	2.671	2.420	2.532	2.196	**2.432**
DE97	2.204	1.741	2.519	2.550	2.310	2.579	2.305	2.217	2.097	**2.280**
DL96	1.413	1.094	1.507	1.535	1.369	1.625	1.363	1.215	1.192	**1.368**
DL97	2.409	2.129	2.424	2.449	2.306	2.562	2.302	2.119	2.146	**2.316**
DM95	1.623	2.065	0.980	1.034	1.182	1.308	1.116	1.064	1.036	**1.268**
DM97	2.870	2.834	2.677	2.713	2.666	2.876	2.639	2.513	2.505	**2.699**
DW95	3.725	3.763	3.874	3.953	3.863	3.999	3.779	4.058	3.557	**3.841**
DW97	1.991	2.303	2.280	2.406	2.358	2.388	2.203	2.904	1.918	**2.306**
KI96	1.560	1.520	1.566	1.621	1.537	1.719	1.487	1.548	1.306	**1.540**
KL95	2.386	1.838	2.195	2.166	1.995	2.365	2.070	1.408	1.991	**2.046**
KL96	1.676	1.533	1.500	1.524	1.448	1.689	1.441	1.218	1.314	**1.483**
KL97	1.960	1.797	1.860	1.889	1.795	2.031	1.782	1.612	1.640	**1.818**
KR95	2.205	2.033	1.885	1.893	1.835	2.106	1.851	1.462	1.761	**1.892**
KR97	1.859	1.825	1.377	1.386	1.391	1.642	1.399	1.001	1.332	**1.468**
LE97	2.472	2.259	2.615	2.661	2.511	2.727	2.478	2.488	2.284	**2.499**
LI96	2.419	2.523	2.085	2.126	2.137	2.324	2.101	1.987	1.984	**2.187**
LI97	1.927	1.793	2.156	2.220	2.075	2.254	2.015	2.186	1.793	**2.047**
MA95	2.012	1.904	2.463	2.551	2.372	2.511	2.281	2.693	2.004	**2.310**
RY96	2.567	2.626	3.589	3.753	3.514	3.517	3.318	4.453	2.889	**3.358**
RY97	2.204	2.306	2.086	2.147	2.120	2.275	2.057	2.148	1.890	**2.137**
SN95	2.796	2.324	2.787	2.786	2.600	2.920	2.638	2.229	2.508	**2.621**
SN96	2.075	2.408	2.274	2.394	2.367	2.404	2.218	2.855	1.952	**2.327**
SE95	2.668	2.737	2.838	2.922	2.836	2.960	2.744	3.075	2.513	**2.810**
SE96	1.433	1.778	1.798	1.936	1.882	1.891	1.711	2.518	1.404	**1.817**
SE97	1.981	1.619	1.705	1.692	1.581	1.905	1.629	1.082	1.549	**1.638**
ST95	2.054	0.916	2.205	2.135	1.760	2.265	1.910	0.955	1.814	**1.779**
TW95	2.088	0.918	2.481	2.429	2.004	2.484	2.130	1.373	1.981	**1.988**
TW96	1.693	1.842	1.928	2.028	1.950	2.040	1.834	2.311	1.579	**1.912**
Cultivar Mean	**2.207**	**2.122**	**2.249**	**2.301**	**2.201**	**2.392**	**2.155**	**2.202**	**1.971**	**2.200**

Figure 2 shows the cultivar yields, scaled as the genotype average, τ_g in t/ha, on the abscissa and the genotype IPCA1 score on the ordinate. The data are provided in table 4. From figure 2 it is clear that SF3, SF6 and SF9 differ only in main effect and not in interaction effect, while SF1, SF5 and SF8 are similar for main effect, but differ in GxE interaction effect. Cultivars SF3, SF4, SF5, SF6, SF7 and SF9 (grouped) all show relative little GxE interaction on IPCA1 and group together along the abscissa, although they differ dramatically in main effect. SF8's interaction is clearly the highest of all cultivars, as it is farthest from the abscissa. It is not clear what factor causes this interaction explained by IPCA1 from figure 2. From this figure a confused pattern emerges, with the two long season cultivars having the highest and lowest IPCA1 scores respectively, while the medium and short season cultivars group around the abscissa. This indicates that length of growing season is not the only factor contributing to the GxE interaction explained by IPCA1, but another factor might be involved.

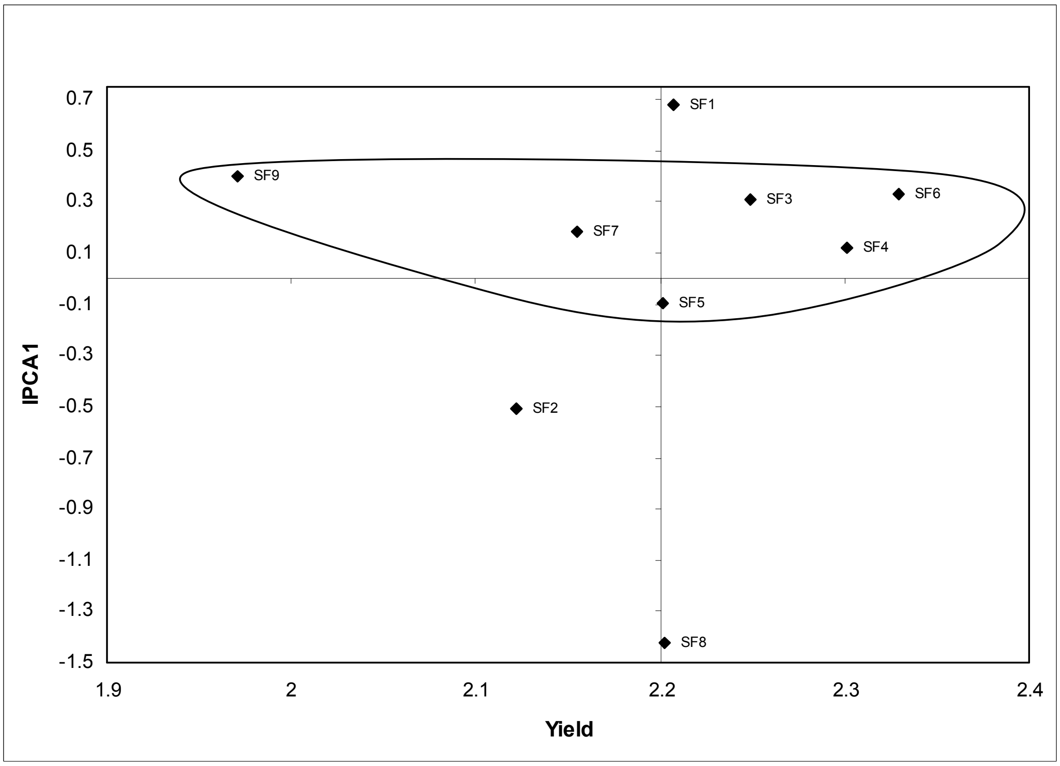

Figure 2. A plot of the IPCA1 scores against the mean yield (t/ha) of the 9 cultivars.

When considering IPCA2 also, which explains a significant amount of the GxE interaction ($P<0.01$), a clearer pattern becomes evident, but it is not until the IPCA1 versus IPCA2 biplot for genotypes and environments (discussed later) is considered, that some explanation of GxE interaction is possible.

In the explanation of figure 2, a decision has been made that cultivars SF3, SF4, SF5, SF6, SF7 and SF9 show little GxE interaction because of the relatively small distance from the coordinates to the abscissa. If however IPCA2 is also taken into consideration, it can be clearly seen in figure 3 that SF3 and SF4 show considerably more GxE interaction due to the factor or factors explained by IPCA2. The only cultivars showing relatively little GxE interaction now, are SF5, SF6, SF7 and SF9, with SF5 having the least, in terms of both axes. From figure 3 it is also evident that SF2 show considerable reaction to the second interaction principal component factor. Now a more distinct grouping is evident, as the unrelated long growing season cultivars, SF8 and SF1, group in opposite quadrants 1 and 3, while most of the medium growing season cultivars related to each other, SF3, SF4, SF6 and SF7 group in quadrant 2 and the unrelated medium growing season cultivar, SF2 lie in the opposite quadrant 4.

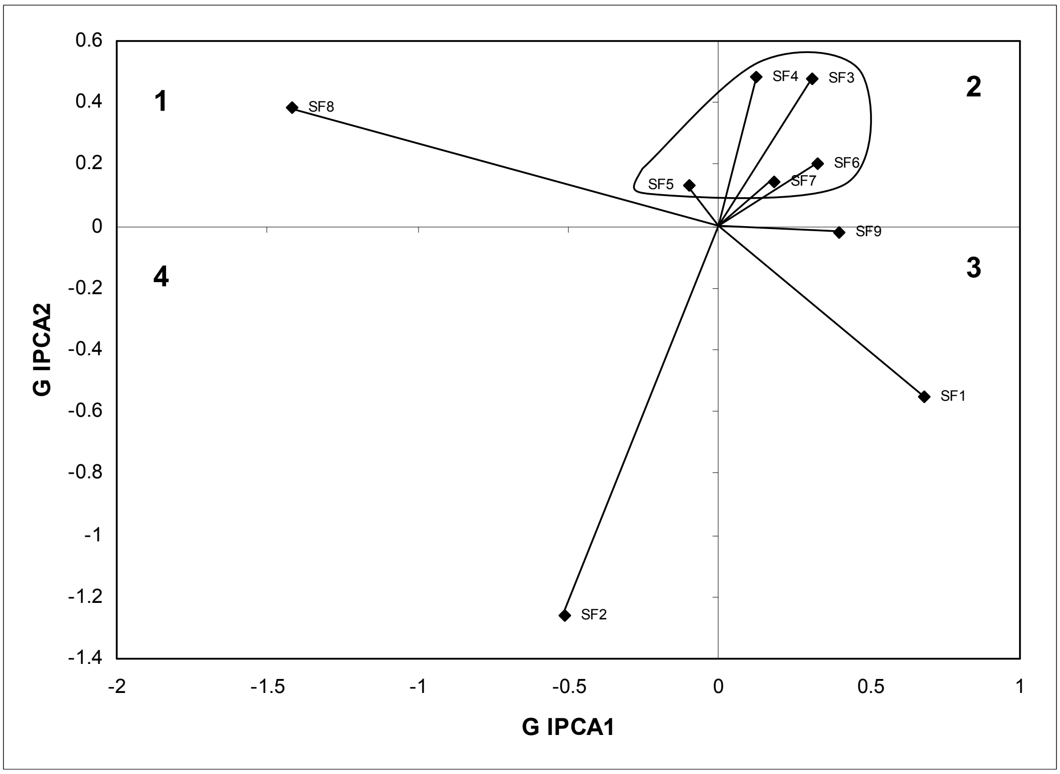

Figure 3. The IPCA1 and IPCA2 scores plotted for cultivars, those with least total interaction close to the origin. Cultivars grouped based on a hierarchical cluster analysis at 70%.

The genotypically related cultivars, SF3 to SF7, together with the unrelated SF9, are also located closely around the origin, indicating that the genotypic background of these cultivars show the least amount of GxE interaction, while all the rest of the genotypically unrelated cultivars, SF1, SF2 and SF8 show the most GxE interaction and are not grouped with any other cultivars. When performing a hierarchical cluster analysis of genotypes over environments, a perfect grouping at 70% becomes apparent (figure 3) where all closely related cultivars are in the same cluster, and all unrelated cultivars are ungrouped.

For the environments, similar graphs to figures 2 and 3 can be drawn, using the data provided in table 5. In figure 4 the IPCA1 score for each environment is plotted on the ordinate and the mean yield, in ton per hectare, on the abscissa. No clear groupings of environments are evident. The information from this figure is however limited and again we need to consider both IPCA axes. In figure 5 the IPCA1 scores are plotted on the abscissa and the IPCA2 scores on the ordinate. In this figure the grouping of the environments are clearer with most environments clustering around the origin, but with the exclusion of ST95, TW95, DM95, BA95 and RY96.

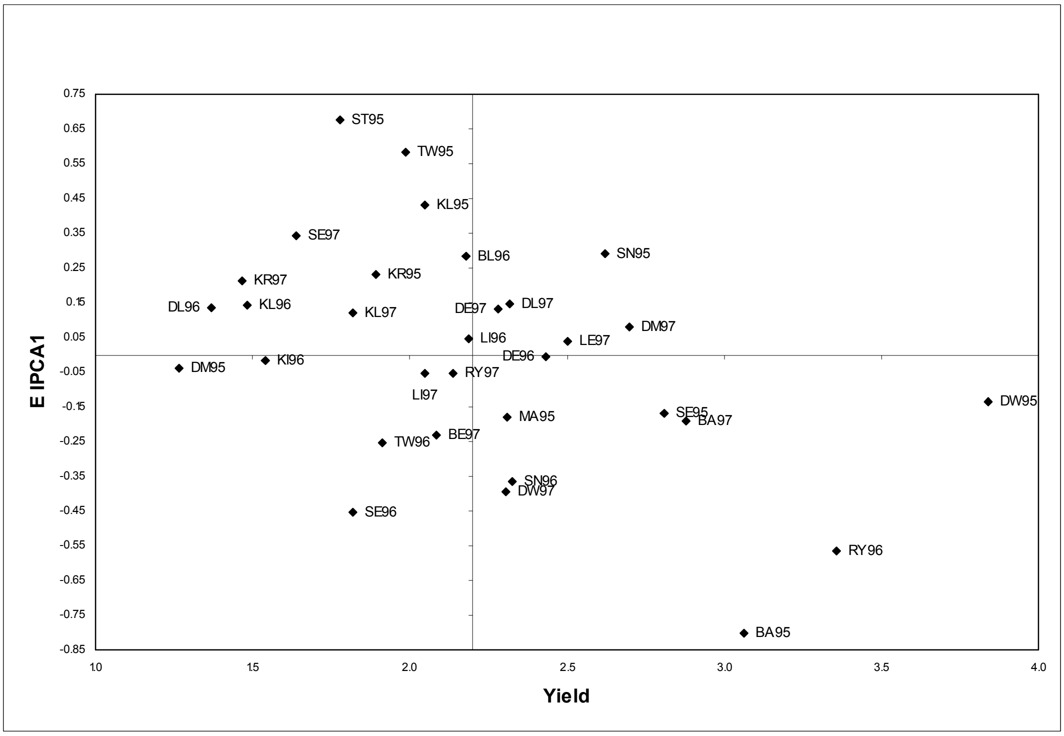

Figure 4. IPCA1 scores for environments plotted against the mean yield (t/ha) for each environment.

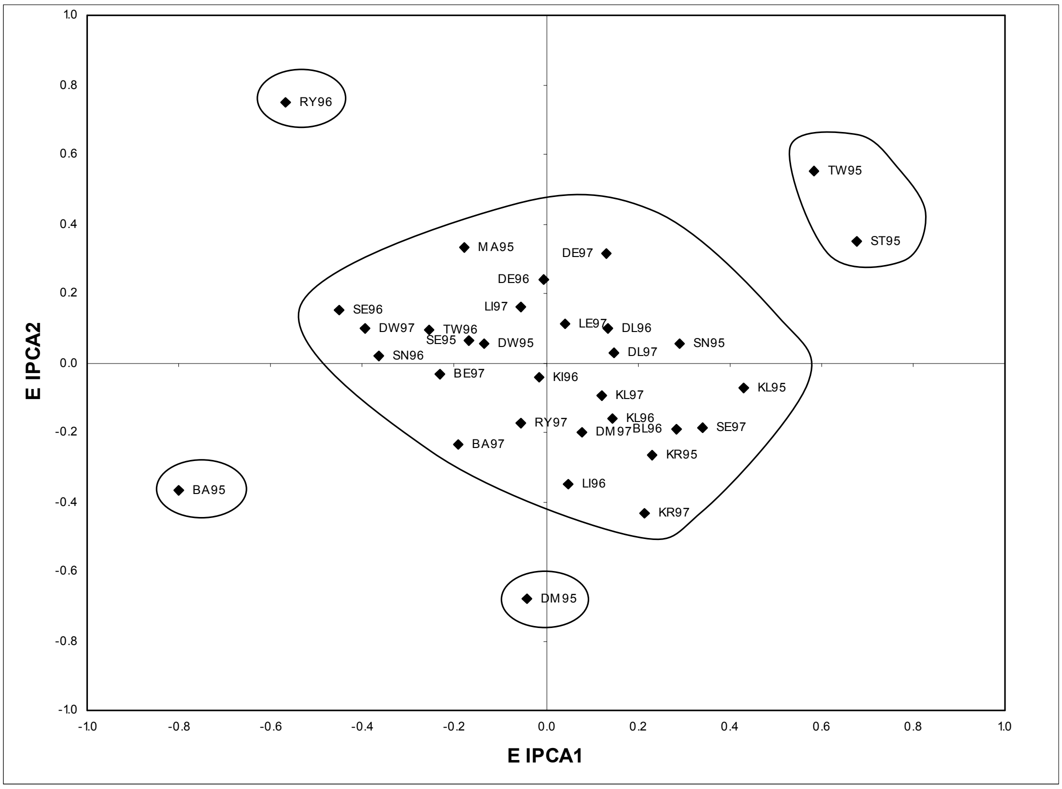

Figure 5. Environments grouping closely around the origin based on both IPCA axes.

From figures 4 and 5 it is evident that there was much more interaction during the 1995/1996 season than in other seasons, as the environments for that year are more scattered, while the 1996/1997 and 1997/1998 seasons' environments are more closely grouped around the origin, indicating less GxE interaction during those seasons. To find the cause of this one needs to look at how factors like average temperature, maximum day and minimum night temperatures, rainfall, etc. differed between seasons. Only then can a deduction be made on what factors are causal for this higher GxE interaction during the 1995/1996 season.

Using figure 5 as basis, grouping environments with similar regional orientation together in figure 6, a distinct pattern can be observed. The Northern and Western environments, all situated in the Dry Highveld Grassland, Northern Arid Bushveld and Central Bushveld, tend to cluster in quadrants 1 and 3. The Eastern environments, of the Moist Highveld Grassland, cluster in quadrants 2 and 4. Although no data are available for rainfall or minimum and maximum temperature, and a precise reason for the grouping cannot be given, a reasonable accurate assumption can be made from the description of the different climatic regions involved. The main difference between the environments in quadrants 1 and 3, to those of quadrants 2 and 4, is the location of the sites. Referring to tables 1 and 2, the localities from regions with higher temperatures and lower rainfall, plot in quadrants 1 and 3, the only exception being RY97 which plots close to quadrant 3. Similarly, the localities from the cooler climatic regions with higher rainfall tend to plot in quadrants 2 and 4. The exceptions in this case are DM97, DE96, TW96 and SN96. It seems as if temperature or growing degree units (GDU's), as explained by Laubscher *et al*. (2000), and rainfall might play a role in the grouping of environments. However, no single environmental factor contributes to a simple grouping of environments or cultivars, but only when IPCA1 and IPCA2 are considered in conjunction, can groupings be distinguished. This indicates that cultivars and environments group together based on multiple environmental factors, contributing to a complex GxE interaction. This needs to be further investigated in a later study.

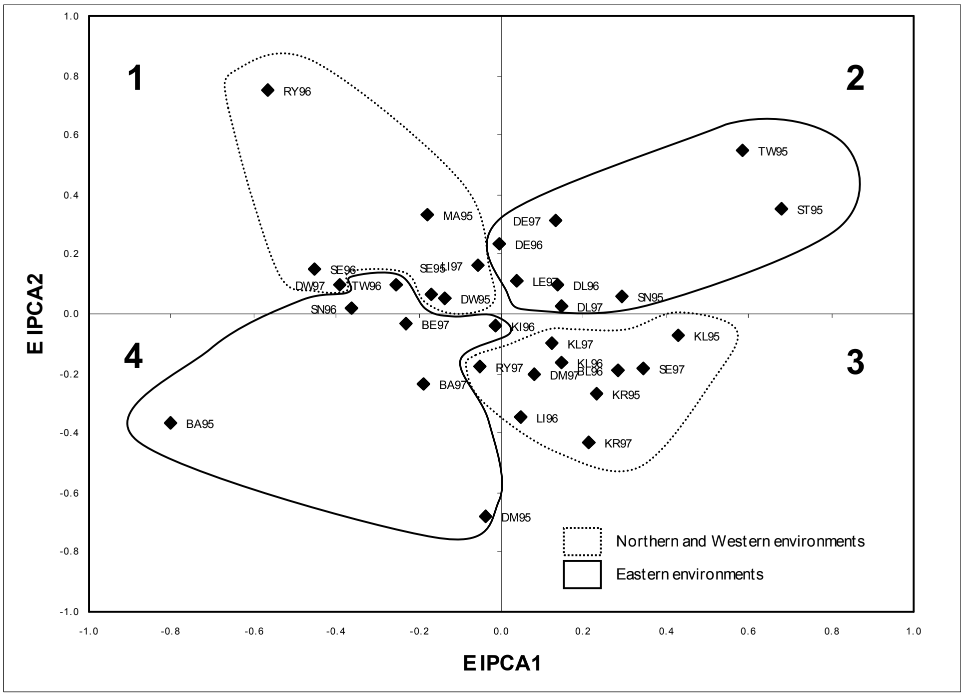

Figure 6. Grouping of environments based on regional orientation, with Northern and Western environments predominantly in quadrants 1 and 3, and Eastern environments predominantly in quadrants 2 and 4.

If the causal factors of the observed GxE interaction could be identified, the use of this type of cluster graph, as in figure 6, could give valuable information on why certain environments group together. In this figure, each quadrant is representative of a specific set of environmental conditions. The environmental conditions of each quadrant will correspond with those of the different quadrants in figure 3, where cultivars were plotted.

A discussion on the practical implications of this clustering of environments for cultivar selection and recommendation will be done in a later section of this study.

From the above discussion it is clear that meaningful GxE interaction exists in the testing of sunflower cultivars in different environments. If the environments could be classified, selections could be made for specific environments, both for breeding and commercial recommendation.

In summary, answering the first question about the importance of the GxE interaction in sunflower testing, it is therefore clear that different genotypes, or genotypic backgrounds interact differently to the environmental factors ruling IPCA1 and IPCA2 and that the GxE interaction is of such a magnitude that it holds potential to be used for cultivar and environmental classification and selection. GxE interaction can therefore not be ignored, but has to be utilised in selection and recommendation.

In the next section, means of using this to the advantage of breeders and agronomists will be discussed.

4.1.2) Cultivar Recommendations

This section deals with the second question asked, namely:" How does the observed GxE interaction influence cultivar selection and recommendation for the whole testing area, or target environments within the testing area?"

In this study it is not the aim to make cultivar recommendations based on the few cultivars used, but rather to study and understand the mechanisms of GxE interaction, upon which, methods can be devised to assist in future selection for breeding programmes. Due to the sometimes elusiveness of an identifiable pattern in the data, a more illustrative approach could be useful to researchers and breeders. Therefore the aim of the following section is to make use of graphical and tabular representations, showing the pattern of GxE interaction, to accomplish this task.

412.1) Cultivar Superiority Zones

Using equation 2, an estimated yield, based on AMMI2 estimates, for each cultivar in every environment can be calculated, as was done in table 6. Accordingly a good estimate of cultivar performance for specific environments can be made. In table 7 the first five cultivar recommendations, based on these estimated yields, are shown for each environment.

From this table it can be seen thatfive groups of environments emerg e, based on the cultivar recommendations. Firstly, SF6 is prominent in the top two environments, followed by SF1 being the cultivar of choice in environments 3 through 8. From environment 9 through 18, SF6 is again prominent, while SF2 is in environments 19 and 20. Lastly, SF8 is the preferred cultivar from environment 21 to the end. Note how this transition in cultivar recommendation changes with decreasing IPCA1 scores.

Table 7. Environments ranked on IPCA1 scores, including the first 5 recommended cultivars for each environment, based on the AMMI2 estimates.

	Environment	Dominant Cultivar	Mean Yld (t/ha)	EIPCA1 Score	EIPCA2 Score	AMMI2 Cultivar Recommendations				
						1st	2nd	3rd	4th	5th
1	ST95	SF6	1.779	0.677	0.350	**SF6**	SF3	SF4	SF1	SF7
2	TW95		1.988	0.584	0.552	**SF6**	SF3	SF4	SF7	SF1
3	KL95	SF1	2.046	0.431	-0.072	**SF1**	SF6	SF3	SF4	SF7
4	SE97		1.638	0.342	-0.186	**SF1**	SF6	SF3	SF4	SF7
5	SN95		2.621	0.292	0.021	SF6	**SF1**	SF3	SF4	SF7
6	BL96		2.180	0.285	-0.190	**SF1**	SF6	SF3	SF4	SF2
7	KR95		1.892	0.231	-0.268	**SF1**	SF6	SF2	SF4	SF3
8	KR97		1.468	0.213	-0.433	**SF1**	SF2	SF6	SF7	SF5
9	DL97	SF6	2.316	0.148	0.027	**SF6**	SF4	SF3	SF1	SF5
10	KL96		1.483	0.144	-0.161	**SF6**	SF1	SF2	SF4	SF3
11	DL96		1.368	0.136	0.100	**SF6**	SF4	SF3	SF1	SF5
12	DE97		2.280	0.131	0.314	**SF6**	SF4	SF3	SF5	SF7
13	KL97		1.818	0.121	-0.095	**SF6**	SF1	SF4	SF3	SF2
14	DM97		2.699	0.078	-0.201	**SF6**	SF1	SF2	SF4	SF3
15	LI96		2.187	0.048	-0.349	SF2	SF1	**SF6**	SF5	SF4
16	LE97		2.500	0.040	0.113	**SF6**	SF4	SF3	SF5	SF8
17	DE96		2.432	-0.005	0.238	**SF6**	SF4	SF3	SF8	SF5
18	KI96		1.540	-0.015	-0.040	**SF6**	SF4	SF3	SF1	SF8
19	DM95	SF2	1.268	-0.040	-0.680	**SF2**	SF1	SF6	SF5	SF7
20	RY97		2.137	-0.054	-0.175	**SF2**	SF6	SF1	SF8	SF4
21	LI97	SF8	2.047	-0.055	0.162	**SF6**	SF4	SF8	SF3	SF5
22	DW95		3.841	-0.136	0.055	**SF8**	SF6	SF4	SF3	SF5
23	SE95		2.810	-0.168	0.064	**SF8**	SF6	SF4	SF3	SF5
24	MA95		2.310	-0.178	0.333	**SF8**	SF4	SF6	SF3	SF5
25	BA97		2.878	-0.190	-0.233	SF2	**SF8**	SF6	SF1	SF5
26	BE97		2.085	-0.230	-0.032	**SF8**	SF6	SF2	SF4	SF5
27	TW96		1.912	-0.254	0.096	**SF8**	SF6	SF4	SF5	SF3
28	SN96		2.327	-0.365	0.021	**SF8**	SF2	SF6	SF4	SF3
29	DW97		2.306	-0.393	0.099	**SF8**	SF4	SF6	SF5	SF2
30	SE96		1.817	-0.452	0.151	**SF8**	SF4	SF6	SF5	SF3
31	RY96		3.358	-0.566	0.750	**SF8**	SF4	SF3	SF6	SF5
32	BA95		3.063	-0.801	-0.367	**SF8**	SF2	SF5	SF6	SF4

Table 7 gives valuable information regarding cultivar performance and adaptation. From this table it becomes evident that SF6 was the first recommendation in 13 out of 32 times, second in 9 out of 32 times, third in 8 out of 32 times and fourth in only 2 out of 32 times, being in the top four recommendations 32 out of 32 times. No other cultivar matches the performance of SF6.

When these cultivar recommendations are superimposedon to figure 4, it is easy to see a grouping of environments according to cultivar performance. For the sake of simplicity, only the first cultivar recommendation at each environment, e.g. SF6 at ST95, is plottedat the coordinates for that environment. If this is done for all the environments, a grouping of environments can be done, as shown in figure 7. It is evident that specific cultivars are superior in distinct areas in this graph. It is much easier to visualise this grouping of environments when plotted, as in figure 7.

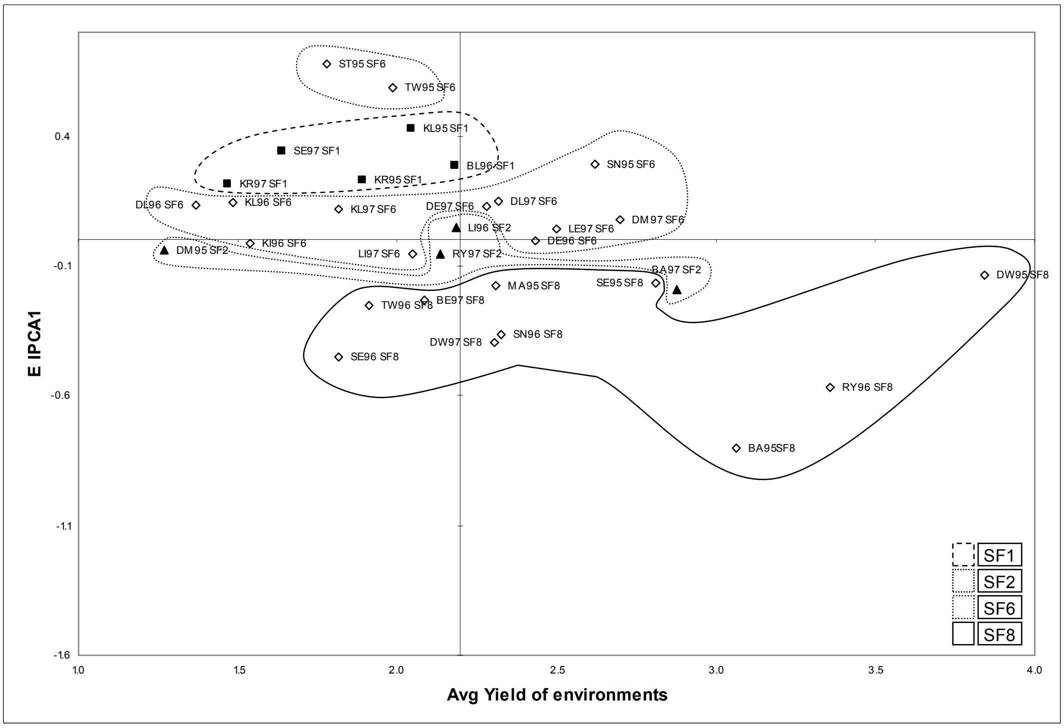

Figure 7. Grouping of environments according to the superior cultivar as determined by the AMMI2 estimates at each environment.

When plotting these AMMI2 recommendations onto figure 6, where we have environment IPCA1 scores versus IPCA2 scores, an interesting pattern evolves. In figure 8 it can be seen that SF8 is the predominant cultivar in quadrant 1, which encompass mostly Northern and Western environments, while SF1 dominates quadrant 3, also mostly Northern and Western environments.In q uadrant 2, with only Eastern environments, SF6 is always the cultivar of choice. Likewise, in quadrant 4, also mostly with Eastern environments, with only RY97 being a Western environment, SF2 dominates all, but two of the environments. In general, it seems as if the longer growing season cultivars, SF8 and SF1 are better adapted in the Northern and Western environments, while the medium growing season cultivars are better adapted to the Eastern environments. A possible explanation of this might be that the longer season cultivars have a longer cycle, or slower growth rate, to exploit the more GDU's of these environments, as was found by Laubscher, *et al* (2000) in maize. Foucteau's (2001) findings in France supports this viewpoint, as they also found the longer season sunflower cultivars to perform better in the long season environments and shorter season cultivars to be better for yield in short season environments. In South African conditions the longer season cultivars might also perform better in warmer, longer season environments due to their ability to photosynthesize over a longer period and have more time to recover after short periods of stress due to heat or drought, as this is often the case in the Northern and Western environments. This assumption leads the way to further research on the correlation between growth rate of sunflower cultivars and both the GDU's of the environment and the availability of moisture during the various growth stages of the plant.

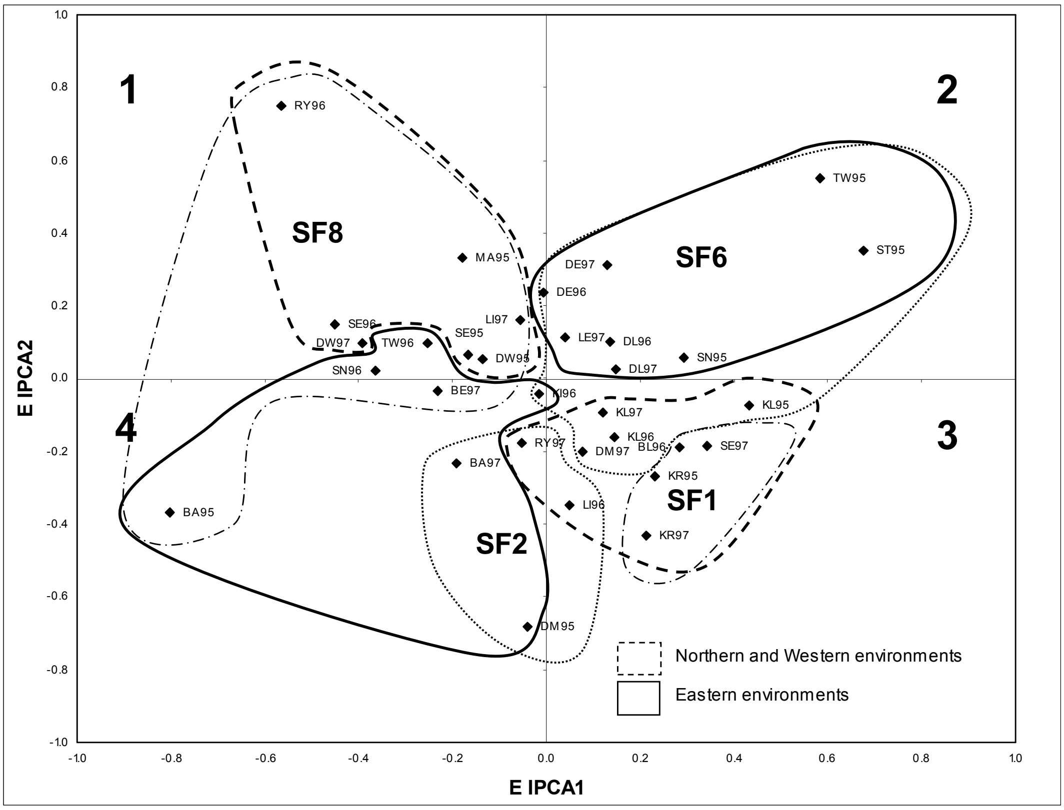

Figure 8. Cultivar superiority zones superimposed onto the regional groupings to indicate which cultivars are the first recommendation by the AMMI2 model for each environment.

It is therefore clear that cultivars are adapted to a specific set of environmental conditions, as each quadrant in figure 8 represents such a set of conditions. If those conditions could be identified and described, it would be possible to make a recommendation of cultivars for all the environments that satisfies those conditions. For all the environments in quadrant 1, SF8 would be recommended and SF1 most of the time in quadrant 3, but with the present knowledge of the environments we cannot distinguish between environments in quadrants 1 and 3, as both mainly consist of

Northern and Western environments. Referring to table 7, it is evident that in all the cases where SF8 was the first recommendation, SF1 was not even in the first five cultivars recommended. The same applies to all the environments where SF1 was the first recommendation, SF8 was not under the first five recommendations. Therefore, neither SF8, nor SF1 can be recommended for the Northern and Western environments, as in some cases it would be the correct choice, but in other cases the completely incorrect choice. Unless the distinguishing factors can be determined between the two quadrants, no single cultivar can be recommended for these environments. The same apply for quadrants 2 and 4, as they both enclose Eastern environments, but their cultivar recommendations differ.

To illustrate the importance of choice of cultivar, table 8 gives the improvement on the average yield and overall yield, if only the first AMMI2 recommended cultivar for each environment was planted for all 32 environments. An increase of 385kg/ha, 18% on the grand mean yield would have been achieved.

Table 8. Yield improvement on the trial average if only the first AMMI2 recommendation was planted at each environment.

Environment		AMMI2 Recommendation		Improvement (t/ha)
Code	Mean Yield	Cultivar	Yield (t/ha)	
BA95	3.063	**SF8**	4.060	0.997
BA97	2.878	**SF2**	3.190	0.312
BE97	2.085	**SF8**	2.401	0.316
BL96	2.180	**SF1**	2.486	0.306
DE96	2.432	**SF6**	2.671	0.239
DE97	2.280	**SF6**	2.579	0.299
DL96	1.368	**SF6**	1.625	0.257
DL97	2.316	**SF6**	2.562	0.246
DM95	1.268	**SF2**	2.065	0.797
DM97	2.699	**SF6**	2.876	0.177
DW95	3.841	**SF8**	4.058	0.217
DW97	2.306	**SF8**	2.904	0.598
KI96	1.540	**SF6**	1.719	0.179
KL95	2.046	**SF1**	2.386	0.340
KL96	1.483	**SF6**	1.689	0.206
KL97	1.818	**SF6**	2.031	0.213
KR95	1.892	**SF1**	2.205	0.313
KR97	1.468	**SF1**	1.859	0.391
LE97	2.500	**SF6**	2.727	0.227
LI96	2.187	**SF2**	2.523	0.336
LI97	2.047	**SF6**	2.254	0.207
MA95	2.310	**SF8**	2.693	0.383
RY96	3.358	**SF8**	4.453	1.095
RY97	2.137	**SF2**	2.306	0.169
SN95	2.621	**SF6**	2.920	0.299
SN96	2.327	**SF8**	2.855	0.528
SE95	2.810	**SF8**	3.075	0.265
SE96	1.817	**SF8**	2.518	0.701
SE97	1.638	**SF1**	1.981	0.343
ST95	1.779	**SF6**	2.265	0.486
TW95	1.988	**SF6**	2.484	0.496
TW96	1.912	**SF8**	2.311	0.399
Average	**2.200**		**2.585**	**0.385**

Table 9 lists all the environments where either SF1 or SF8 was recommended by the AMMI2 model. This table compares the two scenarios where the correct choice of cultivar was made with that of where the wrong choice was made. In the first case an overall improvement of 479kg/ha was made and where the incorrect choice was made, a decline of 370kg/ha occurred. This is a total difference of 849kg/ha between the correct and incorrect choice of cultivars.

Table 9. Yield improvement or decline on the trial when the correct or wrong selection between SF8 and SF1 would have been made.

Environment		SF1 and SF8 Recommendations				
			Correct choice		Wrong choice	
Code	Mean Yld	AMMI2 First Recommendation	Yield (t/ha)	Difference (t/ha)	Yield (t/ha)	Difference (t/ha)
BA95	3.063	**SF8**	4.060	0.997	2.727	-0.336
BE97	2.085	**SF8**	2.401	0.316	1.954	-0.131
BL96	2.180	**SF1**	2.486	0.306	1.704	-0.476
DW95	3.841	**SF8**	4.058	0.217	3.725	-0.116
DW97	2.306	**SF8**	2.904	0.598	1.991	-0.315
KL95	2.046	**SF1**	2.386	0.340	1.408	-0.638
KR95	1.892	**SF1**	2.205	0.313	1.462	-0.430
KR97	1.468	**SF1**	1.859	0.391	1.001	-0.467
MA95	2.310	**SF8**	2.693	0.383	2.012	-0.298
RY96	3.358	**SF8**	4.453	1.095	2.567	-0.791
SE95	2.810	**SF8**	3.075	0.265	2.668	-0.142
SE96	1.817	**SF8**	2.518	0.701	1.433	-0.384
SE97	1.638	**SF1**	1.981	0.343	1.082	-0.556
SN96	2.327	**SF8**	2.855	0.528	2.075	-0.252
TW96	1.912	**SF8**	2.311	0.399	1.693	-0.219
Average	**2.337**		**2.816**	**0.479**	**1.967**	**-0.370**

Clearly this illustrates the importance of correctly characterising the environments by identifying the factors responsible for the GxE interaction in order to facilitate cultivar selections and recommendations. If however a better understanding of the mechanisms and patterns of GxE interaction is not possible, a different approach may have to be taken in the selection of cultivars. Then cultivars cannot be reliably advised for specific environments, simply because we cannot classify those environments correctly.

If, with the current knowledge, we might be unable to recommend cultivars with specific adaptation for specific environments, and not even make the assumption that all long season cultivars will perform better in all Northern and Western, or warm dry environments, nor will all medium season cultivars perform well in all Eastern , or cool moist environments, on what basis can we make recommendations?

To answer this question the breeder needs to look at the general adaptation of cultivars. If certain environments within the testing area cannot be targeted with specific cultivars, the breeder has to look for cultivars that are reasonably well adapted to as large a part of the production area as possible.

Purchase, *et al* (2000b) tested for yield stability in wheat in the Orange Freestate Province in South Africa, using various tests. Because AMMI does not make provision for a quantitative stability measure, they developed their own test based on the AMMI model's IPCA1 and IPCA2 values for each cultivar. They called it the AMMI Stability Value (ASV). This ASV is in effect the distance from the coordinate point to the origin in a two dimensional scattergram of IPCA1 scores against IPCA2 scores, as shown in figure 3. Because the IPCA1 score contributes more to the GxE sum of squares, a weighted value is needed.This weight is calculated according to the relative contribution of IPCA1 to IPCA2 to the interaction SS.

$$(ASV) = \sqrt{\left[\left(\frac{SS_{IPCA1}}{SS_{IPCA2}}\right)(GIPCA1score)\right]^2 + (GIPCA2score)^2} \qquad \textbf{(4)}$$

where

$\frac{SS_{IPCA1}}{SS_{IPCA2}}$ is the weight given to the IPCA1 value by dividing the IPCA1 sum of squares by the IPCA2 sum of squares,

$GIPCA1score$ is the IPCA1 score for that specific hybrid, and

$GIPCA2score$ is the IPCA2 score for that specific hybrid.

The smaller the ASV value, the more stable the cultivar. Using this equation, the ASV for each cultivar can now be calculated. These values are listed in table 10.

Table 10. Cultivars ranked according to their AMMI Stability Values (ASV).

Hybrid Code	Genotype Mean (Y_g)	GIPCA1 Score	GIPCA2 Score	**ASV**	**Rank**
SF5	2.201	-0.098	0.132	**0.198**	**1**
SF7	2.155	0.184	0.145	**0.313**	**2**
SF4	2.301	0.124	0.485	**0.520**	**3**
SF6	2.392	0.329	0.204	**0.536**	**4**
SF9	1.971	0.400	-0.019	**0.603**	**5**
SF3	2.249	0.310	0.476	**0.667**	**6**
SF1	2.207	0.681	-0.551	**1.165**	**7**
SF2	2.122	-0.510	-1.257	**1.473**	**8**
SF8	2.202	-1.420	0.385	**2.175**	**9**

No significant correlation (r = -0.111) exists between the genotype mean, Y_g and the genotype ASV. In figure 9 all the cultivars are plotted with their ASV on the ordinate and their average yield on the abscissa. The graph is divided into quadrants by the vertical and horisontal lines representing the grand mean and the average value for ASV's respectively. Quadrant 1 includes less stable cultivars with below average yield. Quadrant 4 includes stable, but below average yielders. Quadrants 2 and 3 include the higher yielding cultivars, with the more stable ones in quadrant 3.

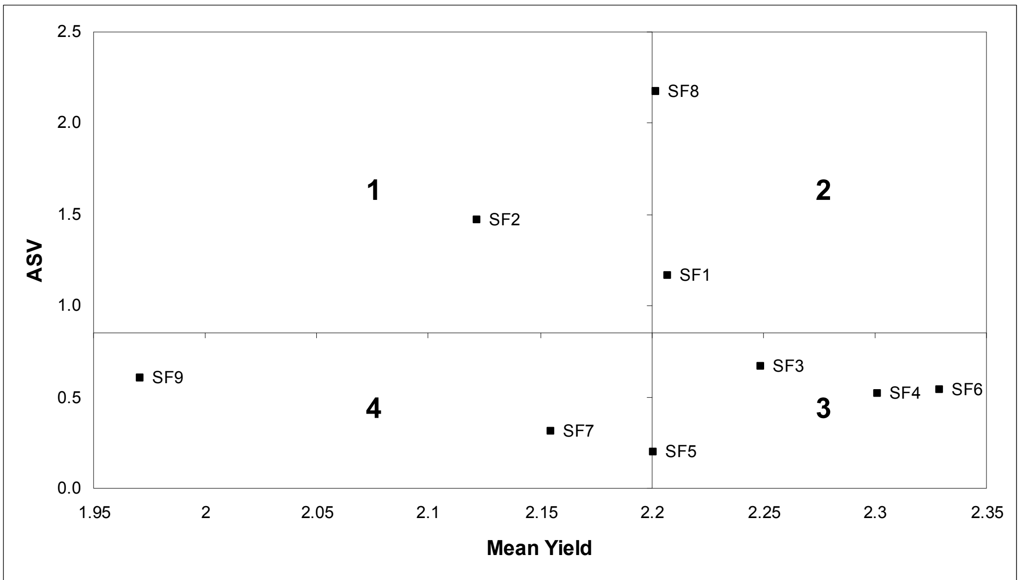

Figure 9. Cultivars sorted into quadrants based on their ASV and yield performance.

It is clear that, if ASV, together with the yield was used, different selections for recommendation would be made than in our previous discussion, where four cultivars, SF1, SF2, SF6 and SF8 each had its environments of recommendation according to table 7. Observing the ASV's and average yields in figure 9, SF1, SF2 and SF8 would not have been considered for recommendation, as their average yields are not the highest and their stability are the lowest of all nine cultivars. It is however important to realise that the stability of a cultivar is a function of interactions in all the environments that it has been tested in. A cultivar like SF8 was tested both in environments suited for it, and in environments not suited for it. If it was only tested in environments where it was adapted, and excluded from the rest, a drastic improvement in the ASV of that cultivar would be achieved. A cultivar like SF6 on the contrary, also had specific environments where it outperformed the rest, but in all other environments also performed reasonably well. It can be said that SF6 is adapted to a wider range of conditions than SF8. SF8 however, still has its area of adaptation where it is the cultivar of choice, although this area cannot be properly defined with the current knowledge.

Stability in itself should however not be the only parameter for selection, as the most stable cultivar wouldn't necessarily give the best yield performance. As example, consider SF5, which has the lowest ASV. If SF5 was selected as cultivar of choice because of its stability, a mean yield of 2.201t/ha would have been reached (table 11). This is no real improvement on the grand mean of 2.200t/ha. Referring to table 7, SF5's best estimated performance according to AMMI2 would be a third place in BA95. It appears only once in the third place, seven times in the fourth place and 11 times in the fifth place. This performance does not match that of a cultivar like SF6, with reasonably good ASV and good average yield. If SF6 was planted in all 32 environments, an increase in average yield from 2.200t/ha to 2.392t/ha would be achieved. Only at one environment the average yield of SF6 was below that of the environment mean.

Clearly, the ASV is a parameter that needs to be considered together with the recommendations of table 7. It is impossible to only make use of a stability estimate like ASV for cultivar selection, but the focus needs to be on a performance summary, as depicted in table 7.

Table 11. Comparison between changes in mean yield when either SF5, with the lowest ASV, or SF6, with higher ASV, but better average yield performance, was recommended.

Environment	Mean Yield	Recommended Cultivar	
		SF5	SF6
BA95	3.063	3.093	2.917
BA97	2.878	2.867	2.960
BE97	2.085	2.104	2.195
BL96	2.180	2.128	2.427
DE96	2.432	2.465	2.671
DE97	2.280	2.310	2.579
DL96	1.368	1.369	1.625
DL97	2.316	2.306	2.562
DM95	1.268	1.182	1.308
DM97	2.699	2.666	2.876
DW95	3.841	3.863	3.999
DW97	2.306	2.358	2.388
KI96	1.540	1.537	1.719
KL95	2.046	1.995	2.365
KL96	1.483	1.448	1.689
KL97	1.818	1.795	2.031
KR95	1.892	1.835	2.106
KR97	1.468	1.391	1.642
LE97	2.500	2.511	2.727
LI96	2.187	2.137	2.324
LI97	2.047	2.075	2.254
MA95	2.310	2.372	2.511
RY96	3.358	3.514	3.517
RY97	2.137	2.120	2.275
SN95	2.621	2.600	2.920
SN96	2.327	2.367	2.404
SE95	2.810	2.836	2.960
SE96	1.817	1.882	1.891
SE97	1.638	1.581	1.905
ST95	1.779	1.760	2.265
TW95	1.988	2.004	2.484
TW96	1.912	1.950	2.040
Average	**2.200**	**2.201**	**2.392**

The breeder and farmer both want a cultivar that is stable and always yields best in every region and year. This describes the ideal cultivar, but because interaction nearly always is sizeable and significant, the ideal cultivar virtually never exists. Consequently, the selection of cultivars relate to the approach taken towards risk management or risk avoidance. If the environments could be sufficiently described, cultivars SF1, SF2, SF6 and SF8 could be recommended for certain environments, thus managing risk. Because the environments for specific locations change from year to year, and because the cultivar recommendation is based on environments, not locations, there is always a chance that the selected cultivar would not perform as intended. As example, refer back to table 7. For Settlers location, SE, SF8 performed very well in 1995 and 1996, but poorly in 1997. If SF8 was therefore selected for Settlers based on results from environments SE95 and SE96, the farmer would have been at risk to have a poor crop in 1997 with SF8. In most years however, SF8 would be the correct choice of cultivar for this location and deliver satisfying results.

But, with the present knowledge, we can however not classify environments and therefore the approach of risk avoidance should rather be taken. This is done by selecting the cultivar that performs good most of the time in most environments. This decision is facilitated by using table 7 as discussed previously.

4.1.3) GxE Interaction Influence on Location Selection

The third and last question we need to answer is: "How does the observed GxE interaction influence the selection of locations for testing sunflower cultivars?"

For yield trials, the same location is often being used for several years, causing it to be a part of several different environments, as each year by location represents another environment. Although cultivar recommendations are based on data from past years, it is applied for future decisions on the farm. Hence, from a perspective of yield prediction, the entity receiving the prediction or recommendation is the location, considered over years, and not the environment. Because the next seasons environmental conditions are unpredictable, future performance are best predicted by past years' sampling. It is important to keep in mind that the location comprises only the patch of soil where the trial was planted. It is not necessarily representative of the whole farm, but merely a sample of it.

Selection of cultivars are based on the performance of those cultivars in environments, but recommendations are made for locations The environment for a location for the next season cannot be predicted, therefore locations are a crucial unit in yield trial research. Accordingly, researchers and agronomists need effective analyses and methods of characterising locations.

In order to visualise the yield response of locations over years, an effective method is to group the coordinates for all the environments with similar locations. When both IPCA axes are significant, both IPCA1 and IPCA2 scores need to be plotted against the environmental mean yields. This can be done on a graph with environmental mean yields on the abscissa and environmental ASV scores, which combines the weighted IPCA1 and IPCA2 scores, on the ordinate. Table 12 gives the ASV scores for environments, as given by the following equation:

$$(ASV) = \sqrt{\left[\left(\frac{SS_{EIPCA1}}{SS_{EIPCA2}}\right)(EIPCA1score)\right]^2 + (EIPCA2score)^2} \qquad \textbf{(5)}$$

where

$\frac{SS_{EIPCA1}}{SS_{EIPCA2}}$ is the weight given to the IPCA1 value by dividing the environment IPCA1 sum of squares by the environment IPCA2 sum of squares,

$EIPCA1score$ is the IPCA1 score for that specific environment, and

$EIPCA2score$ is the IPCA2 score for that specific environment.

Table 12. Environments' ASV's as determined by equation 5.

Environment Code	Mean Yld(Y_e)	EIPCA1	EIPCA2	**ASV**
KI96	1.540	-0.015	-0.040	**0.046**
LE97	2.500	0.040	0.113	**0.128**
LI97	2.047	-0.055	0.162	**0.182**
RY97	2.137	-0.054	-0.175	**0.193**
KL97	1.818	0.121	-0.095	**0.206**
DW95	3.841	-0.136	0.055	**0.212**
DL97	2.316	0.148	0.027	**0.225**
DL96	1.368	0.136	0.100	**0.228**
DM97	2.699	0.078	-0.201	**0.233**
DE96	2.432	-0.005	0.238	**0.238**
SE95	2.810	0.168	0.064	**0.261**
KL96	1.483	0.144	-0.161	**0.270**
BE97	2.085	-0.230	-0.032	**0.348**
LI96	2.187	0.048	-0.349	**0.356**
TW96	1.912	-0.254	0.096	**0.365**
BA97	2.878	-0.190	-0.233	**0.369**
DE97	2.280	0.131	0.314	**0.371**
MA95	2.310	-0.178	0.333	**0.428**
KR95	1.892	0.231	-0.268	**0.439**
SN95	2.621	0.292	0.056	**0.444**
BL96	2.180	0.285	-0.190	**0.470**
KR97	1.468	0.213	-0.433	**0.539**
SE97	1.638	0.342	-0.186	**0.548**
SN96	2.327	-0.365	0.021	**0.551**
DW97	2.306	-0.393	0.099	**0.601**
KL95	2.046	0.431	-0.072	**0.654**
DM95	1.268	-0.040	-0.680	**0.683**
SE96	1.817	-0.452	0.151	**0.698**
TW95	1.988	0.584	0.552	**1.039**
ST95	1.779	0.677	0.350	**1.079**
RY96	3.358	-0.566	0.750	**1.136**
BA95	3.063	-0.801	-0.367	**1.262**
Avg	2.200			**0.463**

In figures 10to 12 the grouping of environments with the same location was respectively done for Eastern, Northern and Western regions, only where locations were used in more than one year of testing. This reveals interesting differences in yield responses over the years. It is important to note that two or three year's data is not enough for the following deductions. To make reliable deductions on a locations GxE response, the need arise for data over many years. The following discussion is therefore merely to establish a school of thought, and not to select locations based on the limited data available.

In figure 10, where only Eastern environments were included, it is clear that Senekal, SN and Delmas, DE, DM and DL, with the exception of DM95,are relatively stable for GxE interactions, meaning that the rankings of cultivars will not differ much from year to year. Senekal does not vary much for main effect either, while Delmas varies considerably for main effects. Locations like Balfour, BA and Tweespruit, TW hardly vary for main effects, giving more or less the same average yield from year to year, but they vary a lot in interaction effects, meaning that rankings of cultivars will differ from year to year.

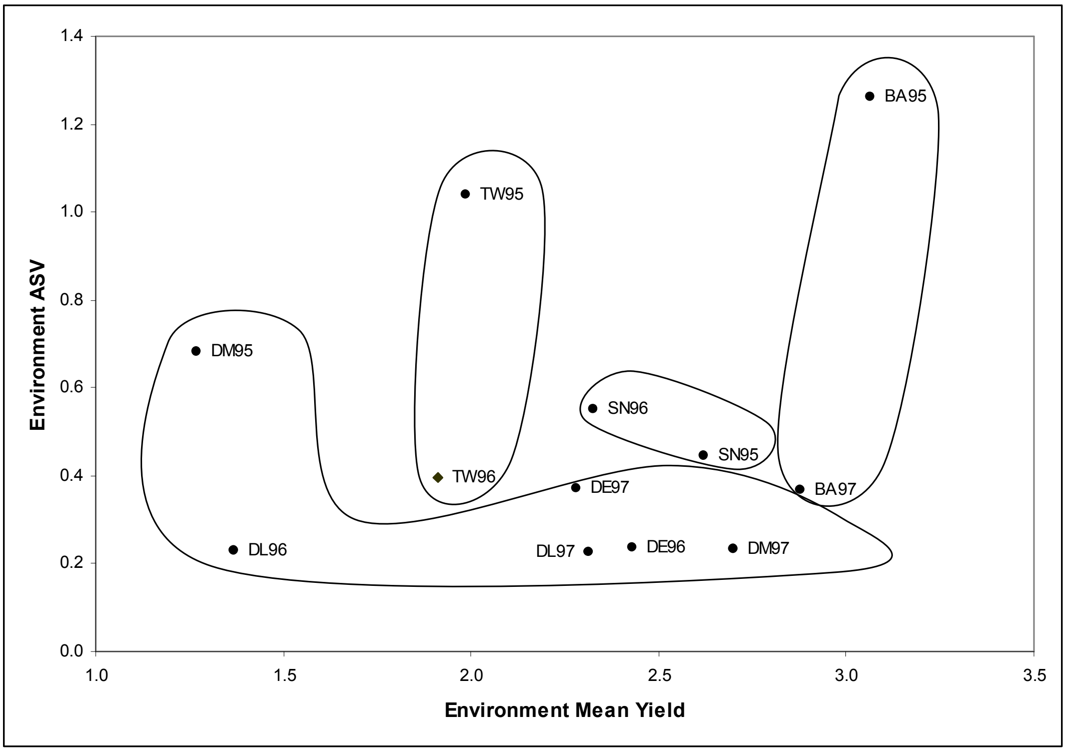

Figure 10. Grouping of the same locations in the Eastern region, where these locations have been included in more than one year of testing. Environment ASV scores are plotted against environment mean yields.

When considering the Northern environments in figure 11, it is clear that both these locations vary both in main and interaction effects and are thus very unpredictable from year to year, both for average yield and the ranking of cultivars.

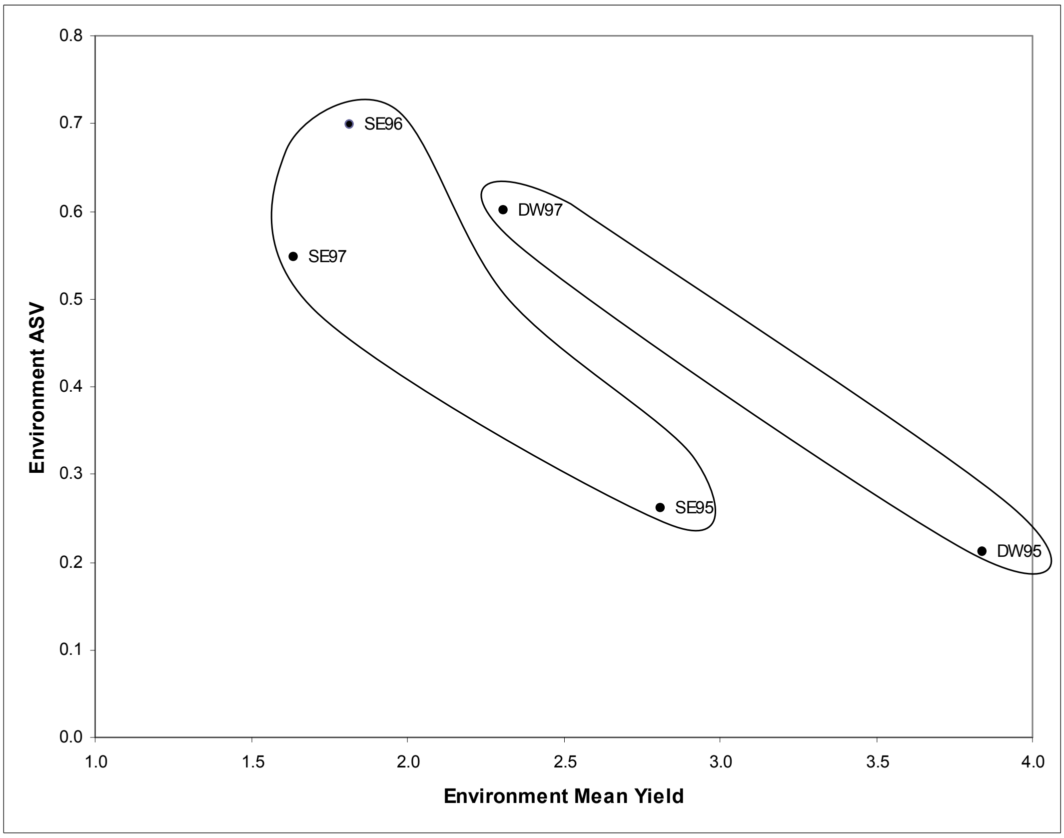

Figure 11. Grouping of the same locations in the Northern region, where these locations have been included in more than one year of testing. Environment ASV scores are plotted against environment mean yields.

Figure 12 includes all the Western environments. From this figure it is evident that Kroonstad, KR and Lichtenburg, LI are stable over years for both main and interaction effects. Klerksdorp, KL is rather stable for main,but not for interaction effects, while Rysmierbult, RY vary for both.

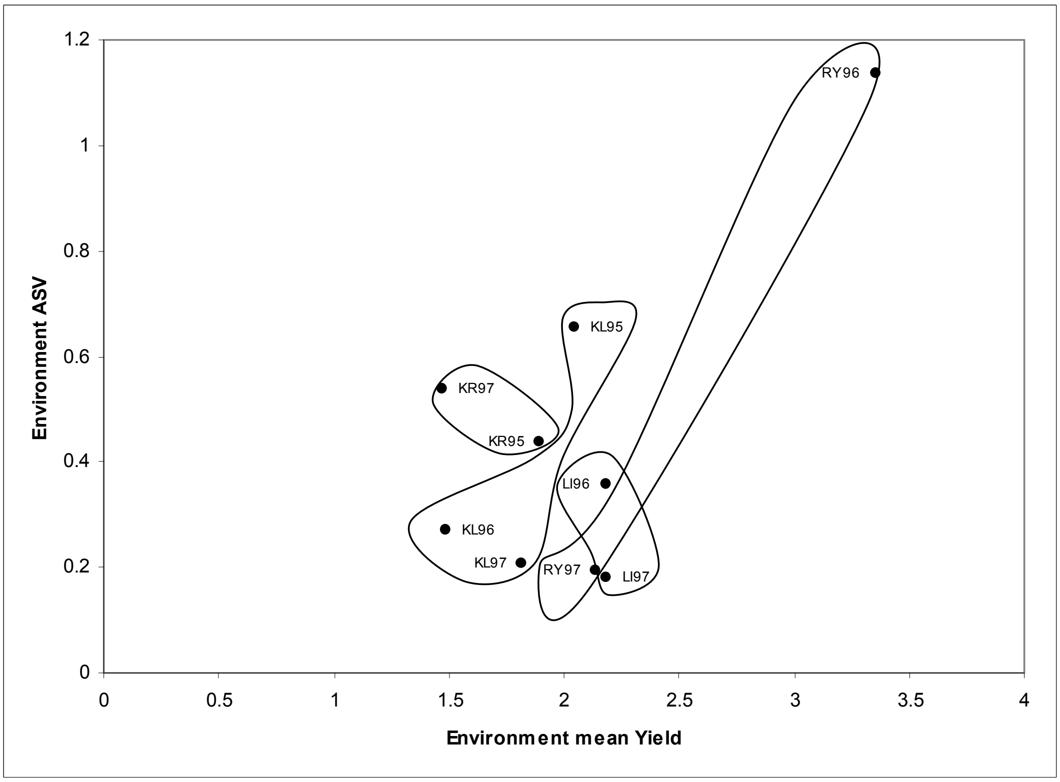

Figure 12. Grouping of the same locations in the Western region, where these locations have been included in more than one year to testing. Environment ASV scores are plotted against environment mean yields.

If these locations could be observed over more years, the implications of the observed patterns in variation of main and interaction effects would be far reaching. Based on this observed pattern, locations could be selected for various different trials, serving different purposes.

More often than not, it is true that trials that include hybrids in the initial stages of testing consist of many genotypes tested in only one or two locations. Mostly these initial trials consist of only one or two replications, because of a limitation on seed quantities. Because there is not much room for utilising interaction with just one location and one or two replications, the locations with greater stability and predictability, or less interaction will be better suited for these initial trials, as rankings will not differ much from year to year.

When testing more advanced cultivars, the number of genotypes decrease and the number of locations and replications normally increase. It is for these advanced trials that the utilisation of GxE interaction becomes more important. If only very stable and predictable locations were included in the trial network, it would be very difficult to identify cultivars with high variability in interaction. Distribution of trial locations across the whole spectrum of ASV scores would therefore be of utmost importance to identify both cultivars with higher interaction, as well as those that are stable across the whole array of locations, even in the unpredictable ones. At the same time it is important to include locations from low potential, medium potential and high potential regions (Kühn, 1975).

When choosing locations, the logistical implications sometimes are the most important. When deciding between two similar responding locations, choosing the one that is easier to access and take care of, because of shorter traveling distance, etc. might be the more effective option.

4.2) Conclusions

It has been established that the interaction between sunflower genotypes and environments is of such magnitude that it cannot be ignored in breeding and selection of cultivars for commercialisation. When doing a simple ANOVA on a set of data, this interaction, though identified as source, is not described sufficiently to be utilised in selections. However, with the multivariate analyses available, in this case the AMMI analysis, it might be possible to not only quantify the interaction, but also identify the sources of interaction. Because both the first two IPCA axes were significant, the AMMI2 model was used. Although environments, and to a certain extent cultivars, showed a distinct grouping when IPCA1 and IPCA2 scores were plotted against each other, the sources of interaction responsible for this grouping could not be completely identified. Evidence suggests the possibility exist that the growing length of cultivars, as well as the length of the season plays a role in the observed GxE interaction, but this needs to be confirmed by further investigation.

With the stability of cultivars quantified in table 10 and the AMMI2 recommendations in table 7, it is possible to identify the cultivars that are adapted only in a narrow range of environmental conditions, as well as those adapted to a wider range of conditions. No significant correlation exists between the ASV and the estimated AMMI2 yields of cultivars. ASV could therefore not be used on its own as a selection criteria. This is underlined by the comparison between the estimated yields of SF5, the cultivar with the lowest ASV, and SF6, with a higher ASV, but better yield, as depicted in table 11. In this case the cultivar with the best ASV was not the best selection for all environments.

When performing the hierarchical cluster analysis, it is also possible to identify cultivars with similar yield response. In this case all cultivars which clustered together at 70%, were closely related.

From the arrangement of environments according to their IPCA1 and IPCA2 scores, a distinct pattern evolved where Northern and Western environments grouped in opposite quadrants, 1 and 3, and Eastern environments grouped in quadrants 2 and 4 (figure 6). Each quadrant had its own cultivar/s dominating those environments, with longer season cultivars being superior in the warmer longer season environments and medium season cultivars outperforming the rest in the cool shorter season areas. Because the different quadrants could however not be uniquely described according to the environmental factors causing the GxE interactions, no cultivar can be recommended for any specific set of environments or locations. This forces the breeder and agronomist to select for cultivars adapted to a wider range of environmental conditions, not necessarily being the best cultivar in each environment, but having a good average yield and a small interaction component. The emphasis should therefore be on wide adaptation.

It is important to include both locations with large and small GxE interactions from each group of low, medium and high potential areas in the testing system when evaluating more advanced cultivars for commercialisation. By doing this, the variation in cultivar stability can be sufficiently observed and both cultivars with low stability, or large interaction, as well as cultivars with higher stabilityor small interaction can be identified. When only very stable locations are used, cultivar rankings would not differ much from environment to environment and all cultivars would also appear to be stable. It is very important that the ASV's of environments are established over many years. Only three years data are not sufficient to accurately determine the ASV of a location.

When testing large numbers of initial cultivars, with limited seed available, only one or two locations are normally used. It is then best to select locations with high stability for testing. In doing this, interaction would not play a big role in the ranking of cultivars, and cultivars can be selected purely on genotypic performance. Because only one or two locations are used, the GxE interaction cannot be sufficiently utilised for selections.

Finally, it can be said that the GxE interaction in sunflower is large enough to enable breeders to make better selections for adapted cultivars. If the environments can be classified in future studies, cultivars could be recommended for specific environments, and a dramatic increase in the average yield in sunflower can be achieved, as demonstrated in table 8.

CHAPTER 5
SUMMARY

When testing nine different sunflower cultivars in 32 South African environments (location x year), an Additive Main Effects and Multiplicative Interaction analysis (AMMI) identified sizeable genotype by environment (GxE) interaction. The first two Interaction Principal Components Axes (IPCA1 and IPCA2) were highly significant ($p<0.001$), but all the factors responsible for the GxE interaction could not be identified, as the causes of interaction seems to be of complex nature. IPCA1 captured 34% of the interaction SS with only 15.3% of the degrees of freedom, while IPCA2 captured 22.5% of the interaction SS with 14.5% of the degrees of freedom. This indicates that the AMMI2 model fits the data well and is parsimonious.

Both cultivars and environments grouped together in quadrants according to their length of season when their respective IPCA1 and IPCA2 scores were plotted against each other. Environments from the warmer dry Western and Northern regions, including the Dry Highveld Grassland, Northern Arid and Central Bushveld, grouped in opposite quadrants, 1 and 3, while environments from the cooler moist Eastern regions, including the Moist Highveld Grassland grouped in opposite quadrants, 2 and 4. The factors responsible for the division between quadrants 1 and 3, as well as those responsible for the division between quadrants 2 and 4 could not be identified. The long-season cultivars were better adapted to the Northern and Western environments, while the medium-season cultivars were better adapted to the Eastern environments. Each quadrant was dominated by a different cultivar. Because the environments and cultivars could not be sufficiently described according to the factors responsible for the observed GxE interaction, cultivars can not be advised for specific environments. It is therefore presently recommended that cultivars which are more widely adapted to South African conditions, be selected.

CHAPTER 6
OPSOMMING

Nege sonneblom kultivars is in 32 Suid Afrikaanse omgewings (lokaliteit x jaar) getoets.'n Additatiewe Hoofeffek en Multiplikatiewe Interaksie Analise (AMMI) het getoon dat noemenswaardige genotiep x omgewings (GxE) interaksie bestaan. Die eerste en tweede Interaksie Hoof Komponent asse (IPCA1 en IPCA2) is albei hoogs betekenisvol ($p<0.001$), maar die faktore verantwoordelik vir hierdie GxE interaksie kon nie geïdentifiseer word nie, omdat die oorsake van die waargenome interaksie kompleks blyk te wees. IPCA1 het 34% van die interaksie som van kwadrate (SS) in beslag geneem met slegs 15.3% van die vryheidsgrade (df), terwyl IPCA2 sowat 22.5% van die interaksie SS in beslag geneem het, met 14.5% van die df. Dit dui daarop dat die AMMI2 model die data goed omskryf.

Beide kultivars en omgewings het groepeer in kwadrante volgens hulle lengte van groeiseisoen, wanneer hul onderskeie IPCA1 en IPCA2 tellings teenoor mekaar geplot word. Omgewings in die warm Westelike en Noordelike gebiede, wat die Droë Hoëveld Grasland, Droë Noordelike Bosveld en Sentrale Bosveld insluit, het in teenoorgestelde kwadrante, 1 en 3 groepeer. Omgewings in die koeler Oostelike gebiede, wat die Vogtige Hoëveld Grasland insluit, het in teenoorgestelde kwadrante, 2 en 4 groepeer. Die faktore verantwoordelik vir die skeiding tussen kwadrante 1 en 3, asook diè verantwoordelik vir die skeiding tussen kwadrante 2 en 4, kon nie geïdentifiseer word nie. Die lang groeiseisoen kultivars was beter aangepas in die warm Westelike en Noordelike gebiede, terwyl die medium groeiseisoen kultivars beter aangepas was in die koeler Oostelike gebiede. In elke kwadrant het 'n ander kultivar domineer. Omdat die omgewings en kultivars nie voldoende beskryf kon word op grond van die faktore verantwoordelik vir die waargenome GxE interaksie nie, kan geen kultivar aanbeveel word vir spesifieke omgewings nie. Dit is dus huidiglik nodig om kultivars aan te beveel wat wyer aangepas is vir die Suid Afrikaanse toestande.

LIST OF ABBREVIATIONS

AMMI	**-**	**Additive Main effect and Multiplicative Interaction**
ANOVA	**-**	**Analysis of Variance**
ASV	**-**	**AMMI Stability Value**
CMS	**-**	**Cytoplasmic Male Sterility**
DHI	**-**	**Daily Linear Harvest Index**
E	**-**	**Environment**
EIPCA	**-**	**Environmental IPCA score**
G	**-**	**Genotype**
GxE or GE	**-**	**Genotype by Environment**
GxExR or GER	**-**	**Genotype by Environment by Replication**
GDU	**-**	**Growth Degree Unit**
GIPCA	**-**	**Genotypic IPCA score**
IPCA axis	**-**	**Interaction Principal Component axis**
MS	**-**	**Mean Square**
PCA	**-**	**Principal Components Analysis**
SAGIS	**-**	**South African Grain Information Services**
SAWS	**-**	**South African Weather Services**
SHMM	**-**	**Shifted Multiplicative Model**
SS	**-**	**Sum of Squares**
T/HA	**-**	**Ton per Hectare**
Y	**-**	**Yield**
$\overline{Y}$	**-**	**Average Yield**

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