

6147 982 7X



HIERDIE EKSEMPLAAR MAG ONDER
GEEN OMSTANDIGHEDE UIT DIE
BIBLIOTEK VERWYDER WORD NIE

University Free State



34300002275125

Universiteit Vrystaat

University Free State

**GENETIC VARIABILITY OF SOUTH AFRICAN SPRING WHEATS
FOR MILLING AND BREADMAKING QUALITY**

BY

FRANCOIS PETRUS KOEKEMOER

Submitted in the fulfilment of the requirements for the degree of *Philosophiae Doctor*, in the Department of Plant Sciences (Plant Breeding), Faculty of Natural and Agricultural Sciences

**UNIVERSITY OF THE FREE STATE
BLOEMFONTEIN
REPUBLIC OF SOUTH AFRICA
DECEMBER 2003**

SUPERVISOR: PROFESSOR C.S. VAN DEVENTER

Univorsiteit van die
Oranje-Vrystaat
BLOMPONTEIN

9 - JUL 2004

UOVS SABOL BIBLIOTEEK

I, hereby declare that this dissertation, prepared for the degree *Philosophiae Doctor*, which was submitted by me to the University of the Free State, is my own original work and has not previously in its entirety or in part had been submitted to any other University. All sources of materials and financial assistance used for the study have been duly acknowledged. I also agree that the University of the Free State has the sole right to the publication of this dissertation.

Signed on the 04 of March 2003 at the University of the Free State, Bloemfontein, Republic of South Africa.

Signature: 

Name: Francois Petrus Koekemoer

ACKNOWLEDGEMENTS

I wish to extend my sincere appreciation to the following people and organizations for their contribution towards the success of this study:

- Professor Charl Van Deventer as my mentor, without his supervision, encouragement, enthusiasm and dedication this study would not have been possible.
- My wife Carina and my children FP and Charisa for their support especially in the difficult times, when spending long hours before the books. My father and late mother who totally devoted and dedicated their lives in providing their children with a good education, financially as well as morally.
- My colleagues at Monsanto, especially Dr Danie Theunissen, for their encouragement and support, which made it easier for me to complete the study while working fulltime.
- The Chamber of Milling and Baking for providing the funds in order to complete this mammoth research project.
- Agricultural Research Council and particularly, the wheat quality laboratory at Small Grain Institute, with Mrs Chrissie Miles in charge of the laboratory, for generating and making the quality data available for utilization in this study.
- Mrs Juliëtte Kilian, the librarian at Small Grain Institute for her assistance in obtaining some of the literature.
- Dr Hugo van Niekerk, my former manager and colleague with his calm, patient, enthusiastic and unselfish manner in which he moulded many young inexperienced breeders into highly successful individuals.
- Ultimately, our heavenly Father for giving me the insight and perseverance to complete this study. Therefore, I dedicated this study to His honour.

TABLE OF CONTENTS

	Page
Declaration	i
Acknowledgements	ii
Table of Contents	iii
List of most commonly used abbreviations	viii
List of Tables	ix
List of Figures	xv
Chapter:	
1. Introduction	1
2. Literature review	6
2.1 Milling characteristics	7
2.1.1 Test weight	7
2.1.2 Thousand kernel mass	8
2.1.3 Vitreousness	10
2.1.4 Hardness	10
2.1.5 Break flour yield	11
2.1.6 Flour yield	12
2.1.7 Flour colour	14
2.1.8 Farinograph water absorption	15
2.1.9 Single Kernel Characterization system	16
2.2 Baking characteristics	17
2.2.1 Protein content	17
2.2.2 Protein quality	20
2.2.3 Falling number	22
2.2.4 SDS-sedimentation test	24
2.2.5 Wet gluten content	25
2.2.6 Mixograph	27
2.2.7 Alveograph	28

2.2.8	Loaf volume	29
2.3	References	31
3.	Effect of G x E interaction on milling and baking quality of irrigated spring wheat cultivars in South Africa	41
3.1	Abstract	41
3.2	Introduction	41
3.3	Materials and methods	45
3.3.1	Field trials	46
3.3.2	Quality analysis	49
3.3.3	Statistical analysis	50
3.4	Results and discussion	53
3.4.1	Cultivar comparisons	53
3.4.2	Location comparisons	55
3.4.3	Seasonal comparisons	58
3.4.4	Variance components	60
3.4.4.1	Genotypic effect	60
3.4.4.1.1	Milling characteristics	60
3.4.4.1.2	Baking characteristics	61
3.4.4.2	Genotypic x location interaction	62
3.4.4.3	Genotype x year interaction	63
3.4.4.4	Genotype x location x year interaction	64
3.5	Conclusions	65
3.6	References	67
4.	Optimal number of locations, years and replicates needed to screen South African spring wheat cultivars for milling and baking quality characteristics	74
4.1	Abstract	74
4.2	Introduction	74
4.3	Materials and methods	75
4.3.1	Field trials	76
4.3.2	Quality analysis	79

4.3.3	Statistical analysis	80
4.4	Results and discussion	82
4.5	Conclusions	84
4.6	References	85
5.	Stability analysis of South African spring wheats under irrigation for milling and baking characteristics	106
5.1	Abstract	106
5.2	Introduction	106
5.3	Materials and methods	111
5.3.1	Field trials	111
5.3.2	Quality analysis	114
5.3.3	Statistical analysis	116
5.3.3.1	Analysis of variance	116
5.3.3.2	Homogeneity of variances	116
5.3.3.3	Wricke's ecovalence	116
5.3.3.4	Eberhart and Russell's joint regression analysis	117
5.3.3.5	Shukla's procedure of stability variance	117
5.3.3.6	Lin and Binn's cultivar performance measurement	118
5.3.3.7	Additive Main Effects and Multiplicative Interaction method	119
5.3.3.8	Combined comparison of stability analysis procedures	119
5.4	Results and discussion	120
5.4.1	Stability analysis of the cultivars	120
5.4.1.1	Analysis of variance	120
5.4.2	Stability methods	125
5.4.2.1	Wricke's ecovalence concept	125
5.4.2.2	Eberhart and Russell's procedure	127
5.4.2.3	Shukla's procedure of stability variance	129
5.4.2.4	Lin and Binn's cultivar performance measurement	131
5.4.2.5	AMMI stability value	133
5.4.3	Combined comparison of stability analysis procedures	135
5.4.3.1	Milling characteristics	135

5.4.3.2	Baking characteristics	138
5.5	Conclusions	143
5.6	References	146
6.	Comparison between different selection methods to improve wheat quality	151
6.1	Abstract	151
6.2	Introduction	151
6.2.1	Tandem selection	154
6.2.2	Independent culling	155
6.2.3	Absolute limits of acceptability relative to a check	157
6.2.4	Index selection	157
6.2.4.1	Lukow's index selection	158
6.2.4.2	Howard's index selection	158
6.2.5	Multivariate selection	159
6.2.5.1	Canonical variate analysis	160
6.2.5.2	Cluster analysis	161
6.2.6	Objectives of this study	161
6.3	Materials and methods	162
6.3.1	Field trials	162
6.3.2	Quality analysis	165
6.3.3	Statistical analysis	167
6.3.3.1	Combination of independent culling method with absolute limits of acceptability regarding to a relative check	167
6.3.3.2	Index selection	169
6.3.3.2.1	Lukow's index selection	169
6.3.3.2.2	Howard's milling and baking worth index	170
6.3.3.2.2.1	Milling worth calculations	170
6.3.3.2.2.2	Baking worth calculations	173
6.3.3.3	Multivariate analysis	175
6.3.3.3.1	Canonical correlations and variate analysis	175
6.3.3.3.2	Cluster analysis	176

6.4	Results and discussion	177
6.4.1	Combination of independent culling method with absolute limits of acceptability regarding to a relative check	177
6.4.2	Index selection	180
6.4.2.1	Lukow's index selection	180
6.4.2.2	Howard's milling and baking worth index	181
6.4.3	Multivariate analysis	183
6.4.3.1	Canonical correlations and variate analysis	183
6.4.3.2	Cluster analysis	190
6.4.4	Evaluation of new test lines	191
6.5	Conclusions	196
6.6	References	200
7.	Summary/Opsomming	209
8.	Recommendations	215

LIST OF FREQUENTLY USED ABBREVIATIONS

AD	Alveograph distensibility
AS	Alveograph strength
ASTAB	Alveograph stability
BFLY	Break flour yield
FABS	Farinograph water absorption
FCL(C76)	Kent Jones flour colour at 76% extraction level
LFV	Loaf volume
LFV-12	Loaf volume standardized at 12% protein content
FLN	Falling number
FLY	Flour yield
FPC-Leco	Flour protein content determined with Leco apparatus
GPC-Leco	Grain protein content determined with Leco apparatus
HLM	Hectolitre mass
MDT	Mixograph mixing time
P/L	Alveograph P/L index
SDSS	SDS-sedimentation test
SKCS-DIA	Single Kernel Characterization System, kernel diameter
SKCS-G	Single Kernel Characterization System, kernel weight
SKCS-HI	Single Kernel Characterization System, hardness index
TKM	Thousand kernel mass
VK	Vitreousness kernels
WGC-12	Wet gluten content at 12% protein content

LIST OF TABLES

	Page
Table 3.1. Genotypes and their pedigrees, year of release, status and origin	46
Table 3.2. Regions with representative localities and the number of trials from 1997 until 1999	47
Table 3.3. Combined variance analysis regarding years, localities and genotypes	52
Table 3.4. Means for milling characteristics of spring wheat cultivars under irrigation (1997-1999)	54
Table 3.5. Means for baking characteristics of spring wheat cultivars under irrigation (1997-1999)	56
Table 3.6. Environment means for milling characteristics of spring wheat cultivars under irrigation (1997-1999)	57
Table 3.7. Environment means for baking characteristics of spring wheat cultivars under irrigation (1997-1999)	58
Table 3.8. Year means for milling characteristics of spring wheat cultivars under irrigation (1997-1999)	59
Table 3.9. Year means for baking characteristics of spring wheat cultivars under irrigation (1997-1999)	59
Table 3.10. Expected variance components for the milling characteristics regarding spring wheat cultivars under irrigation	71
Table 3.11. Expected variance components for the baking characteristics regarding spring wheat cultivars under irrigation	72
Table 3.12. Percentage contribution for each variance component in relation to the total variance for milling characteristics	73
Table 3.13. Percentage contribution for each variance component in relation to the total variance for baking characteristics	73
Table 4.1. Genotypes and their pedigrees, year of release, status and origin	77
Table 4.2. Regions with representative localities and the number of trials from 1997 until 1999	77

Table 4.3.	Optimal number of localities, years and replicates for milling Characteristics	83
Table 4.4.	Optimal number of localities, years and replicates for baking Characteristics	84
Table 4.5.	Theoretic variances (V_x) for hectolitre mass (HLM) for varying localities, years and replicates	96
Table 4.6.	Theoretic variances (V_x) for thousand kernel mass (TKM) for varying localities, years and replicates	96
Table 4.7.	Theoretic variances (V_x) for SKCS kernel weight (SKCS-G) for varying localities, years and replicates	97
Table 4.8.	Theoretic variances (V_x) for SKCS diameter (SKCS-DIA) for varying localities, years and replicates	97
Table 4.9.	Theoretic variances (V_x) for vitreous kernels (VK) for varying localities, years and replicates	98
Table 4.10.	Theoretic variances (V_x) for SKCS hardness index (SKCS-HI) for varying localities, years and replicates	98
Table 4.11.	Theoretic variances (V_x) for break flour yield (BFLY) for varying localities, years and replicates	99
Table 4.12.	Theoretic variances (V_x) for flour yield (FLY) for varying localities, years and replicates	99
Table 4.13.	Theoretic variances (V_x) for falling number (FLN) for varying localities, years and replicates	100
Table 4.14.	Theoretic variances (V_x) for grain protein content (GPC) for varying localities, years and replicates	100
Table 4.15.	Theoretic variances (V_x) for flour protein content (FPC) for varying localities, years and replicates	101
Table 4.16.	Theoretic variances (V_x) for wet gluten content (WGC) for varying localities, years and replicates	101
Table 4.17.	Theoretic variances (V_x) for SDS sedimentation (SDSS) for varying localities, years and replicates	102
Table 4.18.	Theoretic variances (V_x) for alveograph stability (ASTAB) for varying	

localities, years and replicates	102
Table 4.19. Theoretic variances (V_x) for mixograph developing time (MDT) for varying localities, years and replicates	103
Table 4.20. Theoretic variances (V_x) for alveograph strength (AS) for varying localities, years and replicates	103
Table 4.21. Theoretic variances (V_x) for alveograph distensibility (AD) for varying localities, years and replicates	104
Table 4.22. Theoretic variances (V_x) for alveograph P/L value (P/L) for varying localities, years and replicates	104
Table 4.23. Theoretic variances (V_x) for bread loaf volume (LFV) for varying localities, years and replicates	105
Table 4.24. Theoretic variances (V_x) for bread loaf volume standardized at 12% protein (LFV-12) for varying localities, years and replicates	105
Table 5.1. Genotypes and their pedigrees, year of release, status and origin	112
Table 5.2. Regions with representative localities and the number of trials from 1997 until 1999	113
Table 5.3. Combined analysis of variance results for the milling characteristics regarding spring wheat cultivars under irrigation	150
Table 5.4. Combined analysis of variance results for the baking characteristics regarding spring wheat cultivars under irrigation	150
Table 5.5. Means for milling characteristics regarding spring wheat cultivars under irrigation	122
Table 5.6. Ranks for milling characteristics regarding spring wheat cultivars under irrigation	123
Table 5.7. Means for baking characteristics regarding spring wheat cultivars under irrigation	124
Table 5.8. Ranks for baking characteristics regarding spring wheat cultivars under irrigation	125
Table 5.9. Wricke's ecovalence values regarding milling characteristics for spring wheat cultivars under irrigation	126

Table 5.10. Wricke's ecovalence values regarding baking characteristics for spring wheat cultivars under irrigation	127
Table 5.11. Eberhart and Russell's procedure values regarding milling characteristics for spring wheat cultivars under irrigation	128
Table 5.12. Eberhart and Russell's procedure values regarding baking characteristics for spring wheat cultivars under irrigation	129
Table 5.13. Shukla's procedure of stability variance values regarding milling characteristics for spring wheat cultivars under irrigation	130
Table 5.14. Shukla's procedure of stability variance values regarding baking characteristics for spring wheat cultivars under irrigation	131
Table 5.15. Lin & Binns' cultivar performance measurement values regarding milling characteristics for spring wheat cultivars under irrigation	132
Table 5.16. Lin & Binns' cultivar performance measurement values regarding baking characteristics for spring wheat cultivars under irrigation	133
Table 5.17. AMMI stability values regarding milling characteristics for spring wheat cultivars under irrigation	134
Table 5.18. AMMI stability values regarding baking characteristics for spring wheat cultivars under irrigation	135
Table 5.19. Spearman's ranking order correlation coefficient matrix for five G x E stability analysis procedures regarding hectolitre mass (HLM) and thousand kernel mass (TKM)	136
Table 5.20. Spearman's ranking order correlation coefficient matrix for five G x E stability analysis procedures regarding SKCS-weight (SKCS-G) and SKCS-diameter (SKCS-DIA)	136
Table 5.21. Spearman's ranking order correlation coefficient matrix for five G x E stability analysis procedures regarding vitreous kernels (VK) and SKCS-hardness index (SKCS-HI)	137
Table 5.22. Spearman's ranking order correlation coefficient matrix for five G x E stability analysis procedures regarding farinograph water-absorption (FABS) and break flour yield (BFLY)	138
Table 5.23. Spearman's ranking order correlation coefficient matrix for five	

	G x E stability analysis procedures regarding flour yield (FLY)	138
Table 5.24.	Spearman's ranking order correlation coefficient matrix for five. G x E stability analysis procedures regarding falling number (FLN) and grain protein content (GPC-Leco)	139
Table 5.25.	Spearman's ranking order correlation coefficient matrix for five G x E stability analysis procedures regarding flour protein content (fpc-Leco) and wet gluten content (WGC-12)	140
Table 5.26.	Spearman's ranking order correlation coefficient matrix for five G x E stability analysis procedures regarding SDS-sedimentation test (SDSS) and mixograph developing time (MDT)	141
Table 5.27.	Spearman's ranking order correlation coefficient matrix for five G x E stability analysis procedures regarding avleograph strength (AS) and alveograph distensibility (AD)	141
Table 5.28.	Spearman's ranking order correlation coefficient matrix for five G x E stability analysis procedures regarding avleograph stability (ASTAB) and alveograph P/L ratio (P/L)	142
Table 5.29.	Spearman's ranking order correlation coefficient matrix for five G x E stability analysis procedures regarding loaf volume (LFV) and loaf volume standardized at 12% protein content (LFV-12)	142
Table 6.1.	Milling and baking worth contributions developed by Howard (2003)	159
Table 6.2.	Genotypes and their pedigrees, year of release, status and origin	163
Table 6.3.	Regions with representative localities and the number of trials From 1997 until 1999	164
Table 6.4.	Quality standards for South Africa irrigation wheat cultivars	168
Table 6.5.	Means and limits for milling characteristics in comparison to the quality check Kariega	177
Table 6.6.	Means and limits for baking characteristics in comparison to the quality check Kariega	178
Table 6.7.	Standard deviations from the quality check Kariega for milling Characteristics	179

Table 6.8.	Standard deviations from the quality check Kariega for baking Characteristics	180
Table 6.9	Predicted loaf volume, baking strength and overall scores for five cultivars at five sites from 1997 until 1999	181
Table 6.10.	Milling worth values of five wheat cultivars from 1997-1999	181
Table 6.11.	Baking worth values of five wheat cultivars from 1997-1999	183
Table 6.12.	Canonical variate percentage variation and mean scores of the first two canonical variates regarding the milling characteristics for five cultivars	184
Table 6.13.	Correlation matrix for five cultivars at five localities from 1997 until 1999 for the milling characteristics	184
Table 6.14.	Canonical variate percentage variation and mean scores of the first two canonical variates regarding the baking characteristics for five cultivars	186
Table 6.15.	Correlation matrix for five cultivars at five localities from 1997 until 1999 for the baking characteristics	187
Table 6.16.	Canonical variate percentage variation and mean scores of the first two canonical variates regarding the both milling and baking characteristics for five cultivars	188
Table 6.17.	Correlation matrix for five cultivars at five localities from 1997 until 1999 for the both milling and baking characteristics	189
Table 6.18.	Independent culling levels set at absolute limits for milling characteristics in comparison to Kariega regarding BPT01/07 and BPT02/06	192
Table 6.19.	Independent culling levels set at absolute limits for baking characteristics in comparison to Kariega regarding BPT01/07 and BPT02/06	193
Table 6.20.	Individual milling worth values based on average values from the test lines included in this study	194
Table 6.21.	Individual baking worth values based on average values from the test lines included in this study	194

LIST OF FIGURES

	Page
Figure 4.1. Number of localities, years and replicates testing for hectolitre mass (HLM)	86
Figure 4.2. Number of localities, years and replicates testing for thousand kernel mass (TKM)	86
Figure 4.3. Number of localities, years and replicates testing for single kernel characterization kernel weight (SKCS-G)	87
Figure 4.4. Number of localities, years and replicates testing for single kernel characterization kernel diameter (SKCS-DIA)	.87
Figure 4.5. Number of localities, years and replicates testing for vitreous kernel (VK)	88
Figure 4.6. Number of localities, years and replicates testing for single kernel characterization kernel hardness (SKCS-HI)	88
Figure 4.7. Number of localities, years and replicates testing for break flour yield (BFLY)	.89
Figure 4.8. Number of localities, years and replicates testing for flour extraction (FLY)	89
Figure 4.9. Number of localities, years and replicates testing for falling number (FLN)	90
Figure 4.10. Number of localities, years and replicates testing for grain protein content (GPC-Leco)	90
Figure 4.11. Number of localities, years and replicates testing for grain flour protein content (FPC-Leco)	91
Figure 4.12. Number of localities, years and replicates testing for wet gluten content (WGC-12)	91
Figure 4.13. Number of localities, years and replicates testing for SDS sedimentation (SDSS)	92

Figure 4.14. Number of localities, years and replicates testing for mixograph developing time (MDT)	92
Figure 4.15. Number of localities, years and replicates testing for alveograph strength (AS)	93
Figure 4.16. Number of localities, years and replicates testing for alveograph distensibility (AD)	93
Figure 4.17. Number of localities, years and replicates testing for alveograph stability (ASTAB)	94
Figure 4.18. Number of localities, years and replicates testing for alveograph P/L value (P/L)	94
Figure 4.19. Number of localities, years and replicates testing for loaf volume (LFV)	95
Figure 4.20. Number of localities, years and replicates testing for loaf volume standardized at 12% protein content (LFV-12)	95
Figure 6.1. CVA analysis for the milling characteristics for five cultivars at five localities from 1997 until 1999	.204
Figure 6.2. CVA analysis for the baking characteristics for five cultivars at five localities from 1997 until 1999	205
Figure 6.3. CVA analysis for the milling and baking characteristics combined for five cultivars at five localities from 1997 until 1999	206
Figure 6.4. CVA analysis for the baking characteristics for five cultivars in comparison to two new test lines at five localities	207
Figure 6.5. CVA analysis for the baking characteristics for five cultivars in comparison to two test lines at five localities	208
Figure 6.6. Dendrogram depicting the clustering of 5 genotypes using average means at five localities over three years for milling characteristics	190
Figure 6.7. Dendrogram depicting the clustering of 5 genotypes using average means at five localities over three years for milling characteristics	191

CHAPTER 1

Introduction

The transition of the world's wheat industry in the past 10 years from a government driven, strategic commodity to a consumer driven, profit motivated industry is redefining the meaning of quality. As much as we might prefer the comfort of the known world of the past, change is upon us. We are not faced with the question of whether to change, but whether we are going to attempt to control the change, rather than be controlled by it. We can be part of the problem, or part of the solution (Dryan, 2001).

The South African wheat market cannot be isolated anymore from what is happening in the rest of the world, therefore classification of local wheat cultivars is an attempt to provide the South African wheat industry with new cultivars that perform well agronomical and possess suitable milling, rheological and baking characteristics. The analytical procedures and classification norms are compiled in conjunction with the wheat breeders, millers and bakers to ensure market-directed and quality-driven wheat production in the interest of the wheat producers and processors. The classification norms use cultivars as biological quality standards as a frame of reference against which new breeding lines are evaluated. Only cultivars that are successfully grown commercially and possess acceptable agronomical and quality characteristics may be considered as biological quality standards. As the breeding of wheat with the suitable quality characteristics is a long-term project, classification norms and quality standards are provided to breeders in an attempt to give them guidelines that should stand the test of time. Changing the classification norms and establishing new quality standards are for this reason thoroughly investigated and carefully considered to ensure that the long-term goals of breeding programmes are achieved. Currently South Africa is about the only country that is not taking hardness classes into consideration when evaluating new test lines. New test lines should be acceptable for the Chorleywood bread making process

which most of the processing industries are using. The Chorleywood process requires dough with short mixing times and protein contents in the order of 10%, because the Chorleywood was developed in Europe for weaker quality types. Therefore the current evaluation system in South Africa is actually producing wheats with stronger gluten strengths which can cause problems like increased dough temperature, increasing batch-batch cycle time and loaf volumes that exceed pan capacity (Van Lill and Purchase, 1995).

The effect of the climate, rainfall, environmental interaction, cultivation practices and other factors on wheat quality makes the use of fixed criteria or norms for classification purposes impractical. For this reason cultivars are used as biological quality standards, and acceptable deviations from the standard are established as classification norms. It is important that the agronomical performance and yield potential of the chosen quality standard should be comparable with those of the breeders' lines, as lower yields in some quality standards are often connected to higher protein content. Big differences in the protein content of breeders' lines and the quality standard cause deviations, especially in rheological analysis results, which complicates the interpretation and evaluation of breeders' lines. Each of the breeding companies conducts their own trials on which the quality analysis is being carried out. It is thus impossible to compare among test lines from different companies regarding the performance of their milling and baking characteristics. It is also thus very difficult to construct a long term data basis for a biological standard.

Kariega is the cultivar that represents the quality standard for the irrigation areas against which wheat breeders' lines are tested for the bread wheat class. The quality norms for classification are categorized in primary (P) and secondary (S) quality norms. The quality of new lines is judged by the primary criteria, which is non-negotiable. In borderline cases, a decisive answer is obtained by referring to secondary norms. Only red cultivars with medium hard to hard morphological characteristics will be allowed in the class. Currently the variation of the biological standard for a particular quality trait is not taken into consideration when comparing a new line against it. This means a test line can be rejected even though it shows better stability values than Kariega for the particular trait under consideration. Taking the stability values for quality traits into consideration will improve consistency of the milling and

baking characteristics dramatically. Furthermore, a lot emphasis is also being placed on characteristics that are mostly reflecting environmental influences therefore; it will be impossible to obtain proper genetic improvement for such traits.

A minimum of two years' analysed data from at least five localities per annum is required for provisional classification. If there is any doubt about any of the quality aspects, provisional classification is postponed. For final classification, analysed data over three years for the cultivar and the quality standards concerned from a minimum of five localities should be submitted. For classification in an area other than originally classified, two years' data from at least five localities is needed. The first year's data is valid for provisional classification and the second year's data for final classification. This norm exists for all the quality traits and does not take the influence of the environment on the genetic expression for each of the quality characteristics into consideration. The evaluation process is very costly and if more localities were being unnecessarily analysed, this would be a waste of research funds. All the different breeding areas in South Africa uses the same evaluation procedure, although the genotype x environment interaction differs significantly for each of these areas.

In the single channel marketing system, wheat cultivars were released for commercial production after meeting the minimum quality requirements (11 primary and 11 secondary parameters) set by the Wheat Technical Committee, functioning under the auspices of the former Wheat Board and comprising representatives from all the sectors of the industry. However, once these cultivars had been released for production purposes, they were deemed to be of equal quality worth and the grain was mixed at the point of receipt (silo's). Buyers were then obliged to receive and accept grain of these mixtures of cultivars for milling and baking purposes, irrespective of the quality (minimum BL2 grade) of the grain. It thus follows that these released wheat cultivars with superior quality characteristics were never scientifically and objectively identified and were thus also never in demand by the processing industry.

The new liberal wheat-marketing environment lends itself to buying on an individual cultivar basis, as is the common practice in many countries, which have deregulated wheat-

marketing systems. However, only limited and unscientific information on the relative milling and baking worth of the different South African wheat cultivars is available to breeders, producers, buyers and processors of grain. Few attempts have been carried out in order to establish the milling and baking quality of South African wheats, but they all failed because the data available for the wheat cultivars were not generated under the same environmental conditions. This made it very difficult to compare milling and baking quality between different cultivars.

Therefore, the goals of this study can be summarized as follows:

- To develop a data set for irrigation wheat cultivars in relation to their milling and baking quality characteristics generated under similar environmental locations and seasons.
- To determine the source, size and magnitude of genotype x environment interaction for spring wheat under irrigation.
- To determine the optimal locality, year, and replication combinations regarding the screening of spring wheat genotypes for milling and baking quality under irrigation. Such information makes the total cost estimation to conduct the trials possible in relation to the efficiency of the statistical analysis process.
- To compare the various available statistical procedures in assessing performance stability regarding milling and baking characteristics in order to identify the most suitable method. With this information on hand scientists and breeders will be able to select the most appropriate procedure in order to determine genotype performance as well as stability regarding the relevant milling and baking characteristics.
- To determine which of the cultivars exhibit the best stability in order to identify the superior wheat genotypes. These genotypes can then be selected for specific or larger regions and a better understanding of the interaction of these genotypes with the environment.

- To evaluate the different existing methods available regarding their suitability for grouping different genotypes into homogeneous groups according to their milling and baking characteristics respectively.
- The effectiveness of above mentioned methods in order to identify superior genotypes according to their milling and baking characteristics will also be determined.
- To illustrate the success with which the abovementioned approaches can be used to evaluate the milling and baking quality characteristics from multilocation field trials for new testing lines to be considered for release.

References

- DRYNAN, R., 2001. Wheat quality in the twenty-first century.
<http://www.wheatworld.org/forum11.ht>.
- VAN LILL, D. & PURCHASE, J.L., 1995. Directions in breeding for winter wheat yield and quality in South Africa from 1930 to 1990. *Euphytica* 82: 79-87.

CHAPTER 2

Literature review

Wheat quality, like grain yield is a complex trait that results from an interaction of various characteristics, which can be divided into two main groups namely those that are being greatly influenced genetically (Baenziger *et al.*, 1985) and those that are on the other hand mostly manipulated by environmentally influences (Benzian and Lane, 1986; Mailhot and Patton, 1988). The interaction between the latter, known as genotype x environment interaction is also very important when ranking cultivars according to their milling and baking performances. The unique inherent genetics of wheat cultivars and the influence of the environment during the growth period have independent and interactive influences on all physical and biochemical quality attributes of wheat (Gaines *et al.*, 1996b). Despite of the fact that genetic improvement is being obtained with the application of modern techniques like molecular markers, environments however, interact with genotypes to prevent them from reaching their genetic potential (Van Deventer, 1986; Peterson *et al.*, 1992; Graybosch *et al.*, 1995).

A study carried out by Baker and Kosmolak, (1977) in Western Canada found that tall statured, hard red spring wheat lines with similar genetic backgrounds produced varying effects on all quality parameters measured, indicating that both cultivar and environment had a large effect on the expression wheat quality traits. Environmental factors include both biotic and abiotic stresses and breeders are being faced with a big challenge in developing genotypes, which could resist these stresses, and at the same time produce good bread making quality (Mamuya, 2000).

The process of cultivar screening by breeders in order to determine their inherent milling and baking qualities as well as their physiological adaptation to environments, may improve and

reduce variability of bread-making quality. Moreover, the use of recommended varieties and proper management by producers will reduce the spectrum of environmental effects to those, which cannot be controlled, like climate (Van Lill, 1992). Different parameters have been developed and are mainly being used by breeders and the processing industry to screen cultivars and evaluate their milling and baking potential (Mamuya, 2000). Some of the basic quality analysis done on wheat grain and flour before cultivars are released in the South African system will be discussed in the following paragraphs.

2.1 Milling characteristics

For good milling quality, the kernels should be plump and uniformly large in size to permit ready separation of foreign material, absorb water readily and uniformly in the tempering process, and produce a high yield of flour of low yellow pigment and ash content with a maximum and clean separation from the bran and germ without undue consumption of power. Milling characteristics can nowadays be determined with some degree of precision on a small scale (Geddes, 1941).

2.1.1 Test weight (hectolitre mass)

Test weight or also known as hectolitre mass is defined as the weight per unit volume of grain and is the function of kernel density and packing efficiency and is widely recognized as an important grading factor in wheat. Packing efficiency is a heritable trait associated with grain shape, whereas kernel density is more related to the environment in which the grain is grown. Kernel shrivelling due to environmental stresses results in decreased test weights. This implies that the evaluation of wheat cultivars for test weight will be affected by genotype x environment interaction. However, test weight fluctuations are much smaller than for yield, which implies that test weight can be tested on single plots instead of replicated, plots. Moreover, yield components are exposed to environmental influences for the entire plant life

cycle, whereas those of test weight are exposed only for a limited period during the ripening phase (Jalaluddin and Harrison, 1989).

Test weight (hectolitre mass) is also an economically important parameter, because it may predict potential flour yield (Finney *et al.*, 1987; Nel *et al.*, 1998a). According to Park *et al.* (1997), relatively higher test weight and thousand kernel weight values resulted in higher total flour yield and good milling attributes, growing location significantly affected these two parameters in both hard white and hard red wheat samples. Higher test weight is indicative of grain plumpness (McDonald, 1994) visible in a growth season with favourable growth conditions during grain filling (Evans *et al.*, 1975). During grain filling, growth conditions, which affect test weight negatively, are moisture stress, high temperature, nitrogen supply shortages and occurrence of diseases. According to Van Deventer (1986) the contribution made by South African winter wheat cultivars to the variation in hectolitre mass was significant at 38.2%. Contrary to this in the study of spring wheats, Nel *et al.* (1998a) found the contribution by cultivars to the total variation was only 0.8% and thus nonsignificant. However, cultivar x environment interaction was responsible for 12.5% of the variation in hectolitre mass, and as a source of variation had a more pronounced effect when compared to that of grain yield or protein content.

In South Africa a test weight of 76 kg hl^{-1} is preferable. Some researchers like Charles *et al.* (1996) have also indicated that higher test weight is an indication of higher protein content, which is one of the quality parameters. For endosperm it is the strength of starch-protein interactions that causes endosperm hardness (Barlow *et al.*, 1973). Van Lill and Smith (1997) reported that grains containing higher protein content were inclined to be harder, which in turn increased flour yield.

2.1.2 Thousand kernel mass

Since flour is derived from wheat endosperm, the size, density and shape of the grain determines flour yield potential (Eggitt and Hartley, 1975). Marshall *et al.* (1986) found that

grain size, measured by either grain weight or volume, was correlated with flour yield when seed was stratified for grain size within hard wheat cultivars but not among cultivars. Baker and Golubic (1970) found seed size to be related to milling yield in hard red spring wheat, but found no relationship for the other wheat classes. Peltonen-Sainio and Peltonen (1993) reported that a high thousand kernel mass, is associated with high hectolitre mass and is a desired combination, resulting in higher flour yield within the milling industry. In an attempt to establish an indirect predictive model to flour yield, Steve *et al.* (1995) found a positive and negative relation to flour yield for kernel width and thousand kernel weight, respectively. Kernel width was also correlated with kernel volume ($r^2 = 0.90$, $p = 0.0001$). However, the model explained only a small part of the total variability in flour yield ($r^2 = 0.22$). Therefore, they concluded that higher test weight should not always be regarded as an indication of higher flour yield. In South Africa thousand kernel mass of more than 37 g is preferred.

It appears that endosperm content (revealed by kernel plumpness), which is favored by high photosynthetic rates and/or long grain filling periods is strongly influenced by environmental conditions (Planchon, 1969; Jenner, 1991). Poor growing conditions (hot and dry) increase the degree and amount of kernel shrivelling and decrease flour yield due to a reduced ratio of endosperm to bran (Pinthus, 1973; Yamazaki, 1976; Pumphrey and Rubenthaler, 1983; Simmonds, 1989).

Millar *et al.* (1997) reported measurements made by Canadian researchers that showed a positive correlation between grain size and water absorption for Canadian cultivars irrespective of protein class. Additionally, the correlation coefficient for this relationship was even higher than that observed between starch damage and water absorption. Thus, larger grains exhibit larger water absorption levels than smaller grains. Millar *et al.* (1997) also reported an existing phenomenon where larger kernels tend to show lower falling numbers.

Thus it can be concluded that thousand kernel weight is a measurement of kernel size and is to a certain extent another indicator of extraction. Although it is not a foolproof measurement, smaller kernels generally yield less flour, because their ratio of endosperm to bran is less than for larger kernels.

2.1.3 Vitreousness

The vitreousness of wheat kernels is often considered in connection with apparent hardness in classification of wheat for grading purposes. Vitreousness is associated with high protein content, but is strictly a subjective factor and can be considered as only a rough index of protein content (Halverson & Zeleny, 1988). Some wheats fill their matrixes very good and the observed strength of the kernels increase because of more surface interaction, Thus even soft wheat when grown under favourable conditions can produce vitreous kernels and still remain quite soft (Hoseney, 1987).

2.1.4 Hardness

Hardness is highly heritable and wheat cultivars are specified either to be hard or soft. When compared to hardness, hectolitre mass and thousand kernel mass are more influenced by environmental conditions and tend to vary from one place to another even within the same cultivar. Variation in hardness of winter wheat grown under widely different environmental conditions was found to be affected mainly by genotype (Pomeranz & Mattern, 1988) and to a small extent by environmental and growth conditions (Pomeranz *et al.*, 1985 ; Fowler & De la Roche, 1975b). It is the strength of the starch and protein interactions, embedded within the endosperm, that influence kernel hardness (Barlow *et al.*, 1973). Van Lill and Smith (1997) reported that grains containing higher protein content were inclined to be harder, which in turn increased flour yield.

Flour extraction yield (%) refers to the process whereby the endosperm is separated from the bran by means of sets of fast moving rollers through which the wheat is fed. Extraction is a function of hardness, and endosperm of hard, firm wheat grains tend to separate more easily from the bran during the milling process. In addition, more starch granules are being damaged when hard wheat is milled, thereby increasing the water absorption levels. Flour

extraction, therefore, provides a useful measure of milling efficiency (Bass, 1988; Gibson *et al.*, 1998).

According to Finney *et al.* (1987) the mean differences in the ranges of kernel texture (breakflour yield) that resulted from environmental influences were 1.5 times greater than genotypical differences. Huebner and Gaines (1992) reported the hardness of individual wheat kernels to be influenced by genotype, harvest date and location of the kernels on the head spike.

According to Yamazaki and Donelson (1983) and Day *et al.* (1985) hardness appears to be controlled by two major and several minor genes and is not significantly influenced by growing conditions. Charles *et al.* (1996) reported that wheat grown in more humid environments were softer, producing more break - and patent flours and probably lower levels of damaged starch than those grown in drier environments.

Gaines (1991) proved that drier climates should favour the production of larger, better filled, and harder kernels that tend to produce superior milling characteristics. More moist environments should produce softer kernels that generally produce less damaged starch during milling and lower water absorption values.

2.1.5 Break flour yield

In the grading system, smaller particles are separated according to size on the sieves. As the wheat is being broken open in the break system with the first set of rollers, a small amount of endosperm is reduced to flour. This flour, called "break flour", is sifted out in the grading system (Bass, 1988). Break flour yield was positively correlated with larger kernel size (Kosmolak & Dyck, 1981). Across environments, flour yield was highly correlated with hardness, sedimentation, percent protein and cookie diameter (Basset *e. al.*, 1989).

Gaines (1991) found that both red and white wheat cultivars that produced higher test weights also produced less break flour due to their harder kernel textures. They also reported that in general except for some white wheat cultivars, cultivars with higher break flour yields (in other words had a little softer kernel texture) also had better baking performance. A negative and significant correlation between break flour yield and protein content had been reported.

2.1.6 *Flour yield*

Flour of a wheat variety is obtained by Buhler-milling of a composite wheat sample (Marais & D'Appolonia, 1981a). Before the milling process can start the wheat seed must be tempered or conditioned by means of adding water, to the optimum moisture content of milling. As temper moisture is increased, flour colour improves but flour yield decreases. Wheat hardness is important in determining temper moisture, the optimum for soft wheat can be up to two percent lower than for hard wheats. Conditioning of wheat before milling is done by adding a specific amount of water (ml/kg) to wheat grains. This is necessary in order to limit bran contamination during flour extraction, as it causes larger bran particles and this simplifies the sieving process. It also helps to soften the endosperm, consequently the milling process is shortened, power consumption is reduced and the reduction rollers take longer to wear out.

Milling breaks open the seed, scrapes off as much of the bran as possible and grinds the endosperm into flour. Grinding is done on break rolls and reduction rolls. Separation is made using machines called purifiers and plantsifters. There are four operationally distinct systems in the milling process namely: break system, grading system, purification system and reduction system. The ground material leaving each break roll passes to the sieving system where sifting machines separate the mixture of particles according to size. The coarse co-product from the break system is called the bran and the finer bran-like material from the purification and reduction system is known as shorts. Wheat germ, because of its elastic-like nature, is flattened as it passes through the roller system. Many mills provide

separate equipment to segregate the germ from the bran and shorts. If there is no special equipment to separate the germ, part of it breaks down and ends up in the flour, the balance remains flat and passes to the by-products.

The experimental milling can be performed with either the Brabender Junior Quadrumat mill for smaller samples from as little as 5g (Finney et al., 1987), to flour extraction with a Buhler mill for samples larger than 500g (Lukow, 1991). The Buhler mill is a simplified representation of commercial mills.

According to Steve et al. (1995) flour yield is a complex trait, the sum of many minor effects. Factors that affect removal of the endosperm (kernel texture, endosperm adherence to the bran) as well as the amount of endosperm present (kernel volume, endosperm/bran ratio) impact on flour yield. In their study variable selection and regression analysis indicated that the best predictive model for flour yield to be:

$$\text{Flour yield (\%)} = 40.27 + (14.75)(\text{kernel width}) - (0.35)(\text{thousand kernel weight}).$$

However, the model, although statistically significant ($p = 0.025$), explains only a small part of the total variability in flour yield ($r^2 = 0.22$) and illustrates the difficulty in predicting flour yield indirectly.

A decrease in grain size causes a decrease in milling quality due to a reduction in the proportion of endosperm that can be extracted as flour and an increase in the difficulty in doing so (Wrigley et al. 1994). The process of milling did not have a significant effect on protein content, therefore it may not be necessary to measure both grain protein and flour protein (Bhatt & Derera, 1975). Marshall et al. (1986) reported the importance of kernel volume in determining flour yield. Ghaderi et al. (1971) reported that kernel width showed a higher correlation with kernel volume than did kernel length. Altaf Ali et al. (1969) found that kernel width was correlated with milling yield for samples of grain not graded by seed size. For winter wheats grown in the Free State Van Lill and Smith (1997) found that both cultivar and environment contributed significantly to the variation in the milling characteristics.

2.1.7 Flour colour (*Kent Jones units*)

Flour colour has been important throughout the history of the milling industry and therefore can be categorized as an important criterion of flour quality, especially in South Africa where more white bread is being consumed than both brown bread and cake products. Nowadays many millers measure flour quality against the grade of the flour colour produced, especially because the flour grade are linked to the level of flour extraction (Shuey, 1975).

Colour measurements may be approached in two ways. The first approach is to measure whiteness, which primarily determines the extent of colour removal by bleaching compounds. The second approach largely ignores the whiteness and concentrates on the influence of the branny material in the flour by measuring reflectance with a light source in the green band of the light spectrum (Mailhot & Patton, 1988).

Significant correlations were found between flour pigment content, starch damage and extensigraph measurement (Baker et al., 1971).

Bhatt & Derera (1975) found colour grade not to be correlated with any other traits and, therefore, should be considered as independent traits as far as selection strategies are concerned.

However, colour change may occur due to genetic, environment or G x E interaction effects, consequently affecting the quality of the final products. Changes in flour colour depend on several factors such as; the carotenoid pigments inherent in the wheat kernel, discoloration caused by microbial infestation, particles of bran, darker mill streams, the percent extraction of the flour etc. (Patton and Dishaw, 1968; Shuey and Skarsaune, 1973). Colour from carotenoid pigments normally does not present a problem to the baker because it is usually bleached away by the miller.

Different equipment has been developed and is used by different laboratories, but they all aim at the same target of determining flour brightness. According to user's experience using

flour colour grader series III (Wheat quality Lab. Small Grain Institute), the flour categories are;

Cake flour = - 2.5 to 1:0

White bread = 1.5 to 4.5

Brown bread = 9 to 14

2.1.8. *Farinograph water absorption*

The farinograph measures and records the resistance of dough to mixing. It is used to evaluate water absorption of flours and to determine stability and other characteristics of doughs during mixing.

The farinograph has two scales namely, horizontal scale for time (measured in minutes) and the vertical scale measured in Brabender units (BU) and it varies from 0 to 1000. Lower and higher BU for given flour implies less or higher water absorption values respectively, with a BU of 500 being the optimum. The final amount of water added is the absorption capacity of the flour. Absorption is defined as the amount of water necessary or required for farinograph curve to reach the 500 on the BU line. For South African wheat flour the ideal water absorption level is 62%, but it can go as high as 64%.

Water absorption is among the indicators of baking quality (Finney et al., 1987; Van Lill et al., 1995a). Water absorption gives an indication of the potential of the protein molecules to absorb moisture. In general higher protein content flour results in higher water absorption (Finney and Shogren, 1972). Van Lill and Smith (1997) who noted that grains containing higher protein were inclined to be harder support this. Ash content is liable to increase when hard wheat is milled, consequently improving the water absorption.

Van Lill (1992) studied the correlation between quality characteristics and the different protein fractions. The albumin content showed weak positive correlations with flour protein

content, dough development time, dough stability and water absorption whereas the globulin content positively correlated with dough development time. In contrast, the gliadin and glutenin content were both highly significantly ($p = 0.001$) correlated with flour protein, farinograph properties (dough development time, stability and water absorption) as well as with loaf volume

2.1.9 Single Kernel Characterization System (SKCS)

The Single Kernel Characterization System (SKCS) was developed by Martin *et al.* (1993) at the USDA, Agricultural Research Service, Grain Marketing and Production Research Centre, Manhattan, Kansas. The SKCS developed for wheat classification purposes has shown a potential for determining wheat quality parameters (Martin *et al.*, 1993; Satumbaga *et al.*, 1995; Gaines *et al.*, 1996b; Osborne *et al.*, 1997). The SKCS can be used to measure the mean values of hardness index (SKCS-HI), moisture content (SKCS-MC), kernel weight (SKCS-G) and kernel diameter (SKCS-DIA) of wheat and to calculate the standard deviation (SD) of each parameter using data obtained from 300 kernels. The SKCS is designed to isolate individual kernels, weigh them, crush them between toothed rotors and progressively narrowing the crescent-shaped gap (Gaines *et al.*, 1996b). The SKCS measures hardness based on the force required for crushing single wheat kernels (Ohm *et al.*, 1998). It then uses the algorithms based on the force-deformation profile data to classify wheat samples into, soft, hard or mixed classes, which are "algorithmically forced" toward a value of 75 and 25 for hard and soft wheat respectively. The scale is similar to that used by a near-infrared reflectance spectroscopy (NIRS) method for assessing the texture of bulk samples of wheat (AACC, 1995), (Gaines *et al.*, 1996a).

The cracking strain of wheat kernels subjected to crushing was shown to decrease when kernel diameter decreased. (Newton *et al.*, 1927). Therefore, the SKCS discards kernels below a certain weight, which normally represents shrivelled kernels, because they would influence the average SKCS-hardness value negatively. Moisture content of wheat kernels

softens them, especially for softer textured wheat samples, therefore samples should be analysed at similar moisture contents (Gaines *et al.*, 1996b).

2.2 Baking characteristics

2.2.1 Protein content

Grain protein content is a major contributor to nutritional quality and plays a major role in the functionality of wheat flour (Koekemoer *et al.*, 1999). Quality parameters such as rheological (mixograph, farinograph/consistograph, alveograph and extensograph), sedimentation and loaf volume are mostly influenced by protein content. However, protein quality is limited to an extent, because the quality will only improve further at higher protein content if the gluten content is higher, especially the HMW-glutenin subunits. A linear correlation between protein content and loaf volume normally exists, which indicates protein content to be a measure of quality of wheat (Finney, 1945). Therefore, in assessing wheat quality, higher protein content is an indication of superiority in quality. In South Africa wheat with protein content of about 12% and above is preferred.

In a study carried out by Khan *et al.* (1989) on hard red spring wheats, they determined correlations between the quantity of protein fractions and bread-making quality parameters. The results showed significant positive correlations between protein content and both loaf volume as well as wet gluten content. Peter *et al.* (1998a) also found a high, positive and statistically significant correlation of total protein content with wet gluten content in the order of 89%. The correlations between the total protein content and the sedimentation value and loaf volume were good and moderately significant ($r = 0.64$ and $r = 0.61$ respectively).

According to Noaman *et al.* (1990), grain protein content is the consequence of a complex physiological process and is controlled by numerous genes. In a study of winter wheat grown in the Free State of South Africa, Van Lill *et al.* (1995a) reported large variability among genotypes for bread-making characteristics such as protein content, mixograph dough development time and baking strength index.

Grana *et al.* (1988) reported that "high protein genes" incorporated from *Triticum dicoccoides*, increased protein content at yield levels of 61% to 72% when compared to the highest yielding check cultivar. Johnson and Mattern (1980) evaluated 20 000 entries over 13 years and calculated that 5% of the variation in protein content was accounted for by genotypes. This study revealed that actual protein content is mainly determined by growing conditions. Research from the cultivar evaluation programme under irrigation supports this results whereby the cultivar contribution to the total variance for protein content was between two and five percent (Ybema *et al.*, 1998). According to Laubscher (1980) the effect of cultivars on protein content and loaf volume was dominated by that of environment for spring wheat cultivars in the Western and Southern Cape in South Africa, this is also supported by Moss (1973) and Manley and Joubert (1989). Robert *et al.* (1996) reported that relative influences of genotype, environment and genotype x environment interaction on flour protein attributes were compared by calculating the ratios of variance components. The results showed that components associated with environmental factors exceeded genotypic variances for flour protein content, sodium dodecyl sulfate sedimentation volume and low molecular weight saline unextractable protein.

The wheat plant requires a basic amount of nitrogen (N) from the soil to accumulate dry mass and N content in the vegetative tissue to reach acceptable yield and protein content (Deckard *et al.*, 1984). McMullen *et al.* (1988) reported that plant N content at anthesis (NRA) is significantly ($r = 0.61$) related to nitrogen harvest index (NHI). Consequently, the amount of N translocated, significantly correlated with plant N content at anthesis ($r = 0.87$). They also reported that grain protein content was significantly correlated with total plant N content ($r = 0.95$). Therefore, selection for cultivars, which show high, biological N, yields at anthesis (BA) and high remobilization values of this vegetative N will improve grain N concentration (Slafer *et al.*, 1990).

Higher temperature during grain filling, has less effect on N translocation and crude protein would subsequently be increased (Evans *et al.*, 1975). Also higher soil temperatures have shown to favour the mineralisation and uptake of nitrogen (Smika and Greb, 1973). Water

can increase nitrogen availability to the crop as it increases root growth; the mass flow of water, and therefore N, towards the plant; mineralisation of N from soil organic matter; and movement of N fertilisers into the root zone (Sander *et al.*, 1987).

According to Pawlson *et al.* (1992), rainfall prior to grain filling may accelerate nitrogen leaching and other forms of nitrogen loss. As a result they found a negative relationship between rainfall in the three weeks after nitrogen application and nitrogen availability to the crop. On the other hand rainfall later in the season may cause nitrogen dilution by extending leaf life and maintaining photosynthesis and therefore, carbohydrate assimilation (Taylor and Gilmour, 1971).

Nel *et al.* (1998a) reported that significant G x E interactions were found for grain protein content and hectolitre mass for spring wheat grown in the Western and Southern Cape from 1992 - 1995. The lowest and highest grain protein contents were derived from high-yielding and low-yielding environments respectively. However, some of the cultivars showed considerable sensitivity to both high and low protein areas, indicating a lack in stability for this parameter. Similarly, cultivars with higher yields tend to have lower protein contents than cultivars with lower yields at a given level of available N (Terman, 1979; Clarke *et al.*, 1990). This confirms the well-known negative relationship between grain yield and protein content (Johnson *et al.*, 1985; Simmonds, 1996; Koekemoer, 1997).

The relationship between yield and protein content is influenced by the genetic potential for protein content (Stoddard and Marshall, 1990). However, environmental factors such as soil fertility and adequate soil moisture have been reported to be important variables in the determination of final crop quality (Smika and Greb, 1973). According to Van Lill (1992) the diverse effect of agronomic practices on the protein content of cultivars, signifies the importance of crop management to achieve both an acceptable yield and protein content.

Johnson *et al.* (1985) reported that although the amount of grain protein tends to be negatively correlated with yield, the correlation coefficients seldom exceed 60%, indicating that much of the variation in protein is independent of yield and that simultaneous breeding

advances in yield and protein are possible. This is supported by a recent study on selection strategy for combining high grain yield and high protein content in South African wheat cultivars Koekemoer *et al.* (1999). They concluded that selection for grain protein yield would give the best solution towards a simultaneous improvement of both grain yield and protein content.

2.2.2 Protein quality

Protein quality relates to the compositional and quantitative aspects of the gluten storage proteins namely gliadins and glutenins (Wall, 1979). The water and salt soluble fractions (albumins and globulins) are not significantly related to loaf volume, but together with endogenous lipids are considered to enhance loaf volume. Therefore, protein composition is primarily responsible for the differences in loaf volume for cultivars (genotypes) with the same protein content (Finney *et al.*, 1987; Panozzo *et al.*, 1990). Glutenins and gliadins together represent roughly 80% of the total protein in typical wheat flour (Hoseney *et al.*, 1969; Bietz and Wall, 1975; Pritchard and Brock, 1994; Tatham and Shewry, 1995).

The protein content can be affected by agronomic measures for example fertilisation, whereas the composition of the gluten proteins is genetically determined (Sabine *et al.*, 1997). According to Fowler and De la Roche (1975a) genotype is instrumental in determining the quality parameters of wheat, and Payne (1986) stated that protein quality is primarily genetically determined in terms of differences in protein molecular properties.

Harris and Sibbitt (1942) reported that when glutens, prepared from different cultivars, were tested in a standardized starch-gluten test system, loaf volumes were dependent on the source of gluten, that is, the properties of the wheat glutens were cultivar-dependent. Gluten proteins are therefore known as one component of the wheat kernel which influences bread-making quality to a large extent and are responsible for inherent differences in quality of different wheat cultivars (Finney, 1943; Sabine *et al.*, 1997). Since gluten content is

associated with protein content, low gluten content was derived from high grain yielding environments and high gluten content from low grain yielding environments (Nel *et al.*, 2000).

Robert *et al.* (1996) concluded that various components of flour protein differed in their response to environmental and genotypic factors. Flour protein concentration and the percentage of protein present as gliadin and non-gluten proteins were found to be most sensitive to environmental fluctuations. The percentage of protein present as glutenin was found to be nearly totally genotype dependent.

The contributions of gliadins and glutenins to dough properties have long been recognised, and it has been suggested that the gliadins generally contribute to dough extensibility and viscosity, whereas the glutenins are responsible for the dough elasticity (Khathar and Schofield, 1997; Sabine *et al.*, 1997). It is the unique combination of dough viscosity and dough elasticity that comprises the functional properties of dough.

In addition to overall protein content (MacRitchie, 1992), other major effects on loaf quality have been demonstrated due to the glutenin-to-gliadin ratio (Doekes and Wennekes., 1982; MacRitchie, 1987; Pechanek *et al.*, 1997). This is supported by Uthayakumaran *et al.* (1999) who concluded that the protein content and glutenin-to-gliadin ratio (a measure of molecular weight distribution or protein size) have different roles in determining the various dough and bread quality parameters.

The variation in quality is also due to the high molecular weight glutenin subunits (HMW-GS) present (Payne and Lawrence, 1983). Payne *et al.* (1979) and Payne *et al.* (1981) firstly demonstrated that the HMW glutenin subunits are affecting bread-making quality. According to Pomeranz (1988) although the HMW-glutenins make up only 10% of the total gluten and only 1% of the whole endosperm, they are nevertheless of fundamental significance in determining the rheological properties of the dough.

Considerable cytogenetic research has shown that genes for both gliadin and glutenin are located on chromosomes 1 A, 1 B, and 1 D and 6A, 6B, and probably others (Heyne, 1987).

According to Payne *et al.* (1987) and Payne *et al.* (1988) 11 complex loci containing the genes coding for the gluten proteins have been identified. These include loci such as Glu-A1, Glu-B1, Glu-D1 etc., on the group-1 chromosomes, which codes for HMW-GS. Allelic variation at all the loci exists and this results in subunits denoted by numbers like, 0 (null), 1 and 2* in Glu-A1; 6+8, 7, 7+8, 7+9, 13+16, 14+15 and 17+18 in Glu-B1; 5+10, 2+12 and 3+12 in Glu-D1.

Variations in the composition of glutenin subunits (especially HMW) express additively (due to subunits from different loci) on quality of wheat doughs. Consequently, the extent to which glutenins are affecting quality however, was found to be different in diverse countries (Payne *et al.*, 1987; Rogers *et al.*, 1989; Cerny *et al.*, 1992). This may also be ascribed to the effect of environment and genotype x environment interaction.

2.2.3 Falling number

In wheat like other cereal grains, carbohydrate compounds in the form of starch are the major storage compounds. It is due to an added advantage of having proteins as the second largest storage compound which makes it unique (in terms of physical and biochemical properties) and have multiple uses, including bread-making. When flour, water and all the other ingredients required for bread-making are being mixed, the storage proteins hydrate and yield a continuous film like matrix in which the starch granules are embedded (Hoseney, 1985). This characteristic together with higher water absorption enhanced by damaged starch granules, such as when hard wheat is milled, causes unsprouted wheat flour to have a higher falling number.

Under rainy conditions prior to harvesting wheat grain may begin to germinate, a phenomenon known as pre-harvest sprouting (Derera *et al.*, 1977). The alpha-amylase in sprouted wheat results in degradation of starch into simple sugars as energy source for the germination process. The resulting sprouted wheat will have a higher sugar content, which is unacceptable in the baking process. Because pre-harvest sprouting had a detrimental effect

on baking quality, loaf volumes decreased progressively with increased germination. Dough became sticky and difficult to handle, and the crust and crumb colour became darker and the crumb grain became coarser (Lukow & Bushuk, 1984).

Falling number is a method based on the unique ability of α -amylase to liquefy a starch gel. The strength of the enzyme is measured by falling number (FN) apparatus, defined as time in seconds (sec) required to stir and allow the stirrer to fall a measured distance through a hot aqueous flour or meal gel undergoing liquefaction.

The alpha-amylase concentration gives an indication of the starch to sugar conversion in the wheat grain (Hagberg, 1960; Lukow and Bushuk, 1984). Higher falling number implies a smaller or zero conversion rate of starch into sugar. Therefore, unsprouted grains will have more starch which will absorb water and thus provide higher FN values, whereas for sprouted grains the starch content is less and more sugar is present and this results in low FN values. In South Africa a FN value of more than 220s is required for sound wheat.

Flemming *et al.* (1960) observed a larger effect of genotype than environment, with a significant genotype x environment interaction, on the alpha-amylase and protease produced among malted hard wheats. Nel *et al.* (2000) in the study of spring wheat reported insignificant differences in falling number among cultivars and the environments. The variation due to environment was slightly higher, but in agreement with Baker and Kosmolak (1977) who found that the variation was due to cultivar x environment interaction.

Fenn *et al.* (1994) also showed significant genotype x environment interaction for falling number in their study with 1 BL/1 RS -translocation wheats. But in contrast to this Nel *et al.* (2000) believed genotype to be more important than environmental influence. This is also supported by the results from studies with winter wheat cultivars under dry land conditions, where genotypic variation appeared to be dominant (Van Lill and Purchase, 1995; Barnard *et al.*, 1997; Van Lill and Smith, 1997).

2.2.4 SDS-sedimentation test

In a breeding programme, a method is needed for quick and positive identification of new wheat cultivars with good bread-baking quality. Axford *et al.* (1978) introduced the sodium dodecyl sulphate sedimentation test (SDSS test) for estimating the bread-baking quality of wheat cultivars. As the SDSS test is a simple and rapid test and needs only a small sample of flour, it can be used by breeders to classify wheat for bread-baking purposes (De Villiers & Laubscher, 1995). According to Janos (1998) the SDSS volumes of different cultivars are considered relatively stable, implying that it is not very sensitive to environmental effects. Their study showed SDSS volume of whole meal or flour made from cultivars with different quality is genetically relatively stable. SDSS values for South African wheat cultivars, range from 20 ml or less for low protein wheat, representing inferior bread-baking strength, to as high as 70 ml or more for high protein wheat of superior bread-baking strength.

Axford *et al.* (1978) found a significant correlation between SDSS values and loaf volumes (the most important criterium of bread baking quality). Previous evidence indicates that SDSS is the test that singularly gives the best prediction of bread baking potential and strength for hard wheats (Greenaway *et al.*, 1966).

A study was undertaken by De Villiers and Laubscher (1995) to determine the relationship between the SDSS volume, protein content and bread volume of wheat cultivars grown at different locations in the Western Cape Province, in an attempt to determine whether the SDSS test could be used to predict the baking quality of new cultivars in breeding programmes. A significant positive correlation was found between SDSS values and protein content, as well as between SDSS values and loaf volume. From this it is evident that cultivars with good baking quality (high protein content and bread volumes) have high SDSS values, whereas cultivars with poor baking quality (low protein content and bread volumes) have poor SDSS values.

Gröger *et al.* (1997) found a significant correlation between sedimentation volumes and protein content ($r = 0.73$), extensograph dough strength ($r = 0.59$), extensibility ($r = 0.6$) and all farinograph parameters, as well as all alveograph parameters.

Genotype means for SDS-sedimentation value, which reflect both protein quality and loaf volume potential were negatively correlated with the genotypic responses (b-values) ($r = -0.57$). This suggested that genotypes with lower loaf volume potential had higher b-values and thus were generally less stable across environments (Peterson *et al.*, 1992). The aggregative behaviour of flour protein content can be assayed through use of SDSS tests (Graybosch *et al.*, 1996). In hard wheats the 1 B/1 R translocation had substantial and consistent deleterious effects on SDSS volume (Dhaliwal *et al.*, 1987).

2.2.5. *Wet gluten content*

Gluten, an insoluble protein in wheat flour is recognised as a basic quality factor of wheat and it forms the cell walls of the crumb and gives the bread its desired texture (Canada – Alberta farm business management initiative, 1999). The amount of gluten in flour is an index of protein content, and the physical properties of the washed-out gluten provide an index of flour strength (Kulkarni *et al.* 1987). A gluten test gives in a few minutes a measurement of protein quantity and an indication of quality, allowing a rapid decision on how to use the wheat. The simplicity of a gluten determination provides important information and is a practical test for wheat and wheat flour classification at all handling and processing points, (silo/elevator, mill and baker). For a plant breeder, to develop wheats with high protein content and protein quality have always been a major goal. Therefore, gluten tests are valuable in screening different cultivars for protein quality and quantity (Mamuya, 2000).

The glutomatic is an automatic apparatus, which develops the gluten from wheat flour. Dough mixing and subsequent separation of starch and other solubles from the dough takes place in the same test chamber under controlled standardized conditions. The gluten ball is

centrifuged to remove excess water and weighed as wet gluten. This can be examined for elasticity as a protein quality factor. To obtain the dry gluten (protein) amount, the gluten is dried between two Teflon coated hotplates. The higher the percentage of gluten content the higher the expected loaf volume will be (Mamuya, 2000).

The protein content can be affected by agronomic factors like fertilization, whereas the composition of the gluten proteins is genetically determined. The gluten consists mainly of aggregating glutenins and monomeric gliadins. The glutenins are responsible for the dough elasticity, while the extensibility and viscosity of the dough is determined by the gliadins (Colt, 1990; Shewry *et al.*, 1995).

A large portion of variation observed in flour quality may be attributed to variation in gluten protein content and composition (Bietz, 1988). Extensive research has been conducted in attempts to explain wheat quality variation as a function of genetic variation in gluten protein subunit composition (Bietz, 1988; MacRitchie *et al.*, 1990). However, such analyses can only hope to explain that portion of wheat quality variation that is genetically determined. Subunit composition is genetically fixed and hence it can't explain that portion of wheat quality variation that is dependent upon environmental factors such as genotype x environment interaction.

In their study, Robert *et al.* (1996) found that gluten protein fractions were positively correlated with quality parameters, whereas non-gluten fractions were negatively associated with quality. Glutenin was mostly highly positively correlated with loaf grain and texture and was independent of flour protein content. They also noted that flour protein concentration and the percentage of protein present as gliadin and non-gluten proteins were most sensitive to environmental fluctuations. The glutenin part was found to be almost totally genotype dependent.

2.2.6 Mixograph

Mixograph measures and records dough development behaviour and its resistance to mixing. The mixing curve (mixogram) indicates optimum development time (point of minimum mobility); tolerance to over-mixing, descending graph width, other dough characteristics (such as being weak or strong) and estimates water absorption. The mixograph has been used to study dough rheology, blending, quality control and for evaluation of hard, soft and durum wheats (Mamuya, 2000).

During dough mixing, the resistance of the system to extension increases progressively until the point of minimum mobility is reached. This is referred to as the dough development time and is considered as the point where dough is optimally mixed (Finney *et al.*, 1987). The mixing time of the mixograph (in minutes) indicates the rate at which the flour and water are blended together into a quasi-homogeneous mixture in order to develop a gluten matrix and to incorporate air (Spies, 1990). This method proved to be a valuable criterion for the selection of wheat cultivars with superior quality (Van Lill and Purchase, 1995). A mixograph consists of a two-part curve, consisting of ascending and descending arms. High protein flours from hard winter and spring wheat produce curves with long mixing times and high peak values. The ascending slope is an indication of the rate of dough development. Descending slopes are associated with the rate of dough breakdown and are relevant to the wheat variety, production environment, and flour protein content. Generally, the angle between the development and weakening slopes denotes a dough's mixing tolerance. Lower protein, soft wheat flours tend to break down rapidly after reaching a peak and is said to lack mixing tolerance (Walker & Hazelton, 1996).

Mixograph mixing time, peak height and bandwidth are dependent on both protein quality and quantity (Khathar *et al.*, 1994). This in turn, is strongly influenced by the amount of nitrogen fertilizer as well as water stress (Neales *et al.*, 1963) and high temperatures (Campbell and Read, 1968) during kernel filling.

In the study of the effects of cropping systems, Van Lill (1992) observed that dough development time was principally genetically determined when compared to the effects of cropping systems or planting date, especially under climatically favourable weather conditions. However, under unfavourable conditions, the dough weakening response induced by stress after flowering differed amongst cultivars. It was shown that this stress related response was influenced by cropping systems, probably through contributions to soil water conservation or improvement of soil fertility.

In the study of the effect of environment Van Lill (1992) noted that mixograph mixing requirement was largely genetically determined. This signifies its importance as a selection criterion in the assessment of bread baking quality in early generation wheat lines. Low flour protein content appeared to increase mixograph mixing requirement, indicating environmental effects associated with low flour protein, which should be avoided in the evaluation of breeding material. Within cultivars, gliadin and glutenin content appeared to play a subordinate role in variation of mixograph mixing requirement, when compared to flour protein content.

2.2.7 *Alveograph*

The alveograph preceded the other instruments and it first appeared in the early 1920s. It is designed to measure the resistance to bi-axial extension of a thin sheet of flour-water-salt dough (generally at a constant hydration level). A sheet of dough of definite thickness prepared under specific conditions is expanded by air pressure into a bubble until it is ruptured, and internal pressure in the bubble is graphically recorded. It is applicable to all wheat flour types, including very strong bread wheats, which are usually run at an adjusted hydration rate to allow for their higher degree of damaged starch (Walker and Hazelton, 1996).

According to Van Lill and Smith (1997) protein content influences alveographic measurements. They also found that for winter wheats in the summer rainfall region in South

Africa, measurements were more sensitive to environmental effects than genotypes (cultivars).

However, as it is for the other rheological characteristics, protein quality (especially certain glutenins) has more influence on alveograph parameters, and this signifies genetic control for this character. Hou et al. (1996) studied the relationships of quality of glutenin subunits of selected U.S. soft wheat flours to rheological and baking properties. They noted that the high molecular weight glutenin subunits (HMW-GS); 1 was correlated positively with alveograph extensibility (L), subunit 2* with pressure inside the bubble (P) and P/L values and subunit pair 5+10 with P and strength (W) values.

These results are consistent with those of Branlard and Dardevet (1985) who found that subunits 2* and 1 were positively correlated with P and L values respectively. Payne *et al.* (1987) assigned the same quality score to subunits 1 and 2*, and the presence of these subunits in a hard wheat usually indicates a strong wheat for good bread making.

The alveograph stability (ASTAB) value is related to the dough's tenacity and elastic resistance and is a predictor of the dough's ability to retain gas. Alveograph distensibility (AD) is related to the dough's extensibility and predicts the handling characteristics of the dough. Alveograph strength (AS) is the amount of work required for the deformation of the dough and is related to the baking strength of the flour. The P/L ratio (curve configuration ratio) also serves as an index of protein quantity and quality. For example a high ASTAB and short AD would denote a "bucky" or very elastic dough. Weak flours result in low ASTAB and AS values, generally with longer AS values. Likewise, higher ASTAB and AS values with short to medium AD values suggests strong flours (Walker and Hazelton, 1996).

2.2.8 Loaf volume

Loaf volume is obtained from a basic baking test for evaluating bread wheat flour quality by a straight dough process that employs long fermentation and in which all ingredients are

incorporated in the initial mixing step. The method is a 180 min sugar based fermented dough system without shortening. It is intended primarily for laboratory assessment of bread wheat flour quality under vigorous fermentation conditions. Effects of ingredients and processing conditions, and particularly oxidation response, can also be assessed (Mamuya, 2000).

Baking is the final test of wheat flour as it indicates what the final product looks like. The desired higher loaf volume and good (fine) texture is a result of high protein content especially gluten in wheat grains. This also shows that there was no sprouting damage, as flour from sprouted wheat grains result in low loaf volumes and poor texture regardless of a cultivar being of good quality.

Bread is the principal food around the world and provides more nutrients to mankind than any other single food source (Pomeranz and Shellenberger, 1971). Bread making is primarily based on protein concentration and quality (Finney *et al.* 1987). A linear correlation between protein content and loaf volume generally exists, indicating protein content to be a measure of wheat quality (Finney, 1945).

Loaf volume and water absorption are among the indicators of baking quality (Finney *et al.* 1987; Van Lill *et al.* 1995a &b). Loaf volume gives an indication of the gas retention capacity of the dough during the fermentation process and indicates the volume of bread determined by rapeseed displacement (Shogren and Finney, 1984). Water absorption gives an indication of the potential of the proteins to absorb moisture. Generally, higher protein content flour results in higher water absorption (Finney and Shogren, 1972). The more water absorbed, the bigger the volume of dough per unit flour that can be produced.

The SDSS volumes (a measure of flour aggregative ability) have been found to be positively correlated with both protein content and bread volume of the cultivars (De Villiers and Laubscher, 1995). It therefore appears that SDSS values are good parameters for estimating (and predicting) the baking quality of wheat cultivars.

According to Lorenzo (1986) high protein content is not necessarily a prerequisite for high loaf volume. Sandstedt and Ofelt (1940) also observed decreases in loaf volume, thus supporting the above-mentioned theory at higher protein contents (above 13%).

Peterson *et al.* (1997) reported that correlations of protein components with baking parameters were generally low suggesting limited predictive value. Hours of high temperature stress (greater than 32°C) during the grain filling were associated with loaf volume and SDS sedimentation volume, although in a curvilinear fashion. Increasing temperatures stress initially had a positive influence on loaf volume and protein quality, however when temperature stress exceed 90 hours there was a strong negative influence on baking quality. There existed also variation among cultivars regarding this aspect. Randall and Moss (1990), also found in greenhouse trials that dough strength increased with daily temperatures up to 30°C and tends to decrease at higher temperatures.

2.3 References

- AACC –ASSOCIATION OF AMERICAN CEREAL CHEMISTS, 1995. Approved Methods of the AACC, 8th ed. Method 39-70A, approved October 1986, reviewed October 1994. The Association: St Paul, MN.
- ALTAF ALI, A., ATKINS, I.M., ROONEY, L.W. & PORTER, K.B., 1969. Kernel dimension, weight, protein content and milling yield of grain from portions of the wheat spike. *Crop Sci.* 9: 329-330.
- AXFORD, D.W.E., McDERMOTT, E.E. & REDMAN, D.G., 1978. Small scale test of bread making quality. *Mill. Feed Fertil.* 161: 18-20.
- BAENZIGER, P.S., CLEMENTS, R.L., McINTOSCH, M.S., YAMAZAKI, W.T., STIRLING, T.M., SAMMONS, D.J., & JOHNSON, J.W., 1985. Effect of cultivar, environment, and their interaction and stability analyses on milling and baking quality of soft red winter wheat. *Crop Sci.* 25: 5-8.
- BAKER, D. & GOLUMBIC, C., 1970. Estimation of flour yield capacity of wheat. *North-western Miller* 277: 8-11.
- BAKER, R.J. & KOSMOLAK, F.G., 1977. Effects of genotype x environment interaction on bread wheat quality in Western Canada. *Can. J. Plant Sci.* 57: 185-189.
- BAKER, R.J., TIPPLES, H.K. & CAMPBELL, A.B., 1971. Heritabilities of and correlations among wheat quality traits. *Can J. Plant Sci.* 51: 441-448.
- BARLOW, K.K., BUTTROSE, M.S., SIMMONDS, D.H. & VESK, M., 1973. The nature of starch-protein interface with wheat endosperm. *Cereal Chem.* 50: 443-451.

- BARNARD, A., PURCHASE, J.L., SMITH, M.F. & VAN LILL, D., 1997. Determination of pre-harvest sprouting resistance of South African winter wheat (*Triticum aestivum* L.) cultivars. *S. Afr. J. Plant Soil* 14: 4-8.
- BASS, E.J., 1988. Wheat flour milling. In: Y. Pomeranz (Ed.). *Wheat chemistry and technology*. 3rd edn. American Association of Cereal Chemists, St. Paul, Minnesota, pp. 1-56.
- BASSET, L.M., ALLAN, R.E. & RUBENTHALER, G.L., 1989. Genotype x environment interaction of soft white winter wheat quality. *Agron J.* 81: 955-960.
- BENZIAN, B. & LANE, P., 1986. Protein concentration of grain in relation to some weather and soil factors during 17 years of English winter wheat experiments. *J. Sci. Food Agric.* 37: 435-444.
- BHATT, G. M. & DERERA, N.F., 1975. Genotype x environment interactions for, heritabilities of, and correlations among quality traits in wheat. *Euphytica* 24: 597-604.
- BIETZ, J.A., 1988. Genetic and biochemical studies of non-enzymatic endosperm proteins. In: E.G.Heyne (Ed.). *Wheat and wheat improvement*. 2nd ed. Agron. Monogr. 13, ASA, CSSA and SSSA, Madison, WI, pp. 215-242.
- BIETZ, J.A. & WALL, J. S., 1975. The effect of various extractants on the subunit composition and associations of wheat glutenin. *Cereal Chem.* 68: 207-209.
- BRANLARD, G. & DARDEVET, M., 1985. Diversity of grain protein and bread wheat quality. II. Correlation between high molecular weight subunits of glutenin and flour quality characteristics. *J. Cereal Sci.* 3: 345-354.
- BRANLARD, G., ROUSSET, M., LOISEL, W. & AUTRAN, J.C., 1991. Comparison of 46 technological parameters used in breeding for bread. *J. of Genetics & Breeding* 45(4): 263-279.
- CAMPBELL, C.A. & READ, D.W.L., 1968. Influence of air temperature, light intensity, and soil moisture on the growth, yield, and some growth analysis characteristics of Chinook wheat grown in the growth chamber. *Can J. Plant Sci.* 48: 299-311.
- CANADA- ALBERTA FARM BUSINESS MANAGEMENT INITIATIVE, 1999. Wheat other than durum. [HTTP:// www.cadvision.com/violetbook/swht2.ht](http://www.cadvision.com/violetbook/swht2.ht)
- CERNY, J., SASEK, A., ZIMMERMAN, G. & SEIBERT, L., 1992. An evaluation Bovarian and Lower Austrian new cultivars of winter wheat by means of genetic protein markers of baking quality. *Sci. Agric. Bohem.* 2: 113-123.
- CHARLES, S.G., PATRICK, L.F., & GORDON, R., 1996. Milling and baking qualities of some wheats developed for Eastern or North-western regions of the United States and grown at both locations. *Cereal Chem.* 73(5): 521-525.
- CLARKE, J.M., CAMPBELL, C.A., CUTFORTH, H.W., DEPAUW, R.M. & WINKELMAN, E., 1990. Nitrogen and phosphorous uptake, translocation, and utilisation efficiency of wheat in relation to environment and cultivar yield and protein levels. *Can. J. Plant Sci.* 70: 965-977.
- COLT, V., 1990. The genes encoding wheat storage proteins: towards a molecular understanding of bread-making quality and its genetic manipulation. In: J.K. Setlow (Ed.). *Genetic engineering: Principles and methods*, vol 12. Plenum Press, New York, pp. 225-304.
- DAY, P.R., BINGHAM, J., PAYNE, P.I. & THOMPSON, R.D., 1985. The way ahead: Wheat breeding for quality improvement. In: J.M.V. Blanshard, P.J. Frazier & G. Galliard

- (Eds.). Chemistry and physics of baking. The Royal Society of Chemistry, Burlington House, London, pp. 251-261.
- DECKARD, E.L., TSAI, C.Y. & TUCKER, T.C., 1984. Effect of nitrogen nutrition on quality of agronomic crops. In: R.D. Hauck (Ed.). Nitrogen in crop production. ASA-CSSA-SSSA Publishers, Madison, WI USA, pp. 601-615.
- DERERA, N.F. BHATT, G.M. & McMASTER, G.J., 1977. On the problem of pre-harvest sprouting of wheat. *Euphytica* 26: 299-308.
- DE VILLIERS, O.T. & LAUBSCHER, E.W., 1995. Use of the SDS test to predict the protein content and bread volume of wheat cultivars. *S. Afr. Tydskr. Plant Grond* 12(4): 140-142.
- DHALIWAL, A.S., MARES, D.J. & MARSHALL, D.R., 1987. Effects of 1B/1R chromosome translocation on milling and baking quality characteristics of bread wheats. *Cereal Chem.* 64: 72-76.
- DOEKES, G. & WENNEKES, L. M. J., 1982. Effect of nitrogen fertilisation on quality and composition of wheat flour protein. *Cereal Chem.* 59: 276-278.
- EGGIT, P.W.R. & HARLEY, A. W., 1975. Extraction rates – milling processing implications. In: Spicer (Ed.). Bread. Social, Nutritional and agricultural aspects of wheaten bread. Applied Science Publishers, London, pp. 219-234.
- EVANS, L.T., WARDLAW, I.F. & FISCHER, R.A., 1975. Wheat. In: L.T. Evans (Ed.). Crop physiology – some case histories. Cambridge University Press, Cambridge pp. 101-149.
- FENN, D., LUKOW, O.M., BUSHUK, W. & DEPAUW, R.M., 1994. Milling and baking quality of 1BL/IRS translocation wheats. I. Effects of genotype and environment. *Cereal Chem.* 71: 189-195.
- FINNEY, K.F., 1943. Fractioning and reconstructing techniques as tools in wheat flour research. *Cereal Chem.* 20: 381-396.
- FINNEY, K.F., 1945. Methods of estimating and the effect of variety and protein level on the baking absorption of flour. *Cereal Chem.* 22: 149-158.
- FINNEY, K.F. & SHOGREN, M.D., 1972. A ten-gram mixograph for determining and predicting functional properties of wheat flours. *Bakers Digest* 46: 32-35.
- FINNEY, K.F., YAMAZAKI, W.T., YOUNGS, V.L. & RUBENTHALER, G.L., 1987. Quality of hard, soft and durum wheats. In E.G.Heyne (Ed.). Wheat and wheat improvement 2nd ed. ASA-CSSA-SSSA Publishers, Madison, WI USA, pp. 677-748.
- FLEMMING, J.R., JOHNSON, J.A., & MILLER, B.S., 1960. Effect of environment, variety and class of wheat on alpha-amylase and protease activities on malted wheat. *Cereal Chem.* 37: 371.
- FOWLER, D.B. & DE LA ROCHE, I.A., 1975a. Wheat quality evaluation. 1. Influence of genotype and environment. *Can. J. Plant Sci.* 55: 263-267.
- FOWLER, D.B. & DE LA ROCHE, I.A., 1975b. Wheat quality evaluation. 2. Relationships among prediction tests. *Can. J. Plant Sci.* 55: 251-262.
- GAINES, C.S., 1991. Associations among quality attributes of red and white soft wheat cultivars across locations and crop years. *Cer. Chem.* 68(1): 56-59.
- GAINES, C.S., FINNEY, P.F., FLEEGER, L., M., & ANDREWS, L.C., 1996a. Predicting a hardness measurement using the Single-Kernel Characterization System. *Cereal Chem.* 73: 278-283.

- GAINES, C.S., FINNEY, P.L., RUBENTHALTER, G., 1996b. Milling and baking qualities of some wheats developed for Eastern or Northern-western regions of the United States and grown at both locations. *Cereal Chemistry* 73(5): 521-525.
- GEDDES, W.F., 1941. Objectives in breeding for improved quality in hard wheat. *Journal of the American Society of Agronomy* :490-503.
- GHADERI, A., EVERSON, E.H. & YAMAZAKI, W.T., 1971. Test weight in relation to the physical and quality characteristics of soft winter wheat. *Crop Sci.* 11: 515-518.
- GIBSON, L.R., MCCLUSKEY, P.J., TILLEY, K.A., & PAULSEN, G.M., 1998. Quality of hard red winter wheat grown under high temperature conditions during maturation and ripening. *Cereal Chem.* 75: 421.
- GRANA, A., GERECHTER-AMITAI, Z.K. & BLUM, A., 1988. Cereal grain protein improvement. Proceedings of the 7th International Wheat Genetics Symposium, Cambridge, pp. 969-974.
- GRAYBOSCH, R.A., PETERSON, C.J., BAENZIGER, P.S., & SHELTON, D.R., 1995. Environmental modification of hard red winter wheat flour protein composition. *J. Cereal Sci.* 22: 45-51.
- GRAYBOSCH, R.A., PETERSON, C.J., SHELTON, D.R., & BAENZIGER, P.S., 1996. Genotype and environmental modification of wheat flour protein composition in relation to End-use quality. *Crop Sci.* 36: 296-300.
- GREENAWAY, W.T., HURST, N.S., NEUSTADT, M.H. & ZELENY, L., 1996. Micro sedimentation test for wheat. *Cereal Sci. Today* 11: 179-199.
- GRÖGER, S., OBERFORSTER, M., WERTENKER, M., GRAUSGRUBER, H. & LELLEY, T., 1997. HMW glutenin subunit composition and bread making quality of Australian grown wheats. *Cereal Res. Comm.* 25(4): 955-962.
- HAGBERG, S., 1960. A rapid method for determining alpha-amylase activity. *Cereal Chem.* 37: 218-222.
- HALVERSON, J. & ZELENY, L., 1988. Criteria of wheat quality. In: Y. Pomeranz (Ed.). *Wheat: Chemistry and Technology*, 1st ed. Minnesota, USA, pp. 15-45.
- HARRIS, R.H. & SIBBITT, L.D., 1942. The comparative baking qualities of hard red spring wheat starches and glens as prepared by the gluten-starch blend baking method. *Cereal Chem* 19: 763-772.
- HEYNE, E.G., 1987. *Wheat and wheat improvement*. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America. Madison, Wis.
- HOSENEY, C.R., 1985. The mixing phenomenon. *Cereal Foods World* 30: 453-457.
- HOSENEY, C.R., 1987. Wheat hardness. *Cereal Foods World* 32(4): 320-322.
- HOSENEY, R.C., FINNEY, K.F., SHOGREN, M.D. & POMERANZ, Y., 1969. Functional (bread-making) and biochemical properties of wheat flour components. II. Characterisation of gluten protein fractions obtained by ultra-centrifugation. *Cereal Chem* 46: 126-135.
- HOU, G., YAMAMOTO, H. & NG, P.K.W., 1996. Relationships of quality of glutenin subunits of selected U.S. soft wheat flours to rheological and baking properties. *Cereal Chem.* 69: 148.
- HUEBNER, F.R., & GAINES, C.S., 1992. Relation between wheat kernel hardness, environment and gliadin composition. *Cereal Chem.* 69: 148.

- JALALUDDIN, M.D. & HARRISON, S.A., 1989. Heritability, genetic correlation and genotype x environment interactions of soft red winter wheat yield and test weight. *Cer. Res. Communications* 17(1): 43-49.
- JANOS, M., 1998. Inheritance of SDS sedimentation volume of flour in crosses in winter wheat (*Triticum aestivum* L.). *Cereal Res. Comm.* 26(2): 203-210.
- JENNER, C.F., 1991. Effects of exposure of wheat ears to high temperature on dry matter accumulation and carbohydrate metabolism in the grain of two cultivars. II. Carry-over effects. *Aust. J. Plant Physiol.* 18: 179-190.
- JOHNSON, V.A. & MATTERN, P.J., 1980. Genetic improvement of productivity and nutritional quality of wheat. Final report, University of Nebraska-Lincoln.
- JOHNSON, V.A., MATTERN, P.J., PETERSON, C.J. & KUHR, S.L., 1985. Improvement of wheat protein by traditional breeding and genetic techniques. *Cereal Chem.* 62: 350-355.
- KHAN, K., TAMMINGA, G. & LUKOW, O., 1989. The effect of wheat flour proteins on mixing and baking – correlations with protein fractions and high molecular weight glutenin subunit composition by gel electrophoresis. *Cereal Chem.* 66: 391.
- KHATHAR, B.S., BELL, A.E. & SCHOFELD, J.D., 1994. The dynamic rheological properties of gluten and gluten sub-fractions from wheat of good and poor bread-making quality. *J. Cereal Sci.* 22: 29-44.
- KHATHAR, B.S. & SCHOFIELD, J.D., 1997. Molecular and physiochemical basis of bread-making properties of wheat gluten proteins: A critical appraisal. *J. Food Sci. Technol.* 34: 85-102.
- KOEKEMOER, F.P., 1997. Inheritance of protein related characteristics in spring wheat. MSc. Thesis, Orange Free State.
- KOEKEMOER, F.P., LABUSHAGNE, M.T. & VAN DEVENTER, C.S., 1999. A selection strategy for combining high grain yield and high protein content in South African wheat cultivars. *Cereal Res. Comm.* 27(1-2): 107-114.
- KOSMOLAK, F.G. & DYCK, P.L., 1981. Milling and baking qualities of ten spring wheat cultivars from the people's Republic of China. *Cereal Chem* 58(3): 246-247.
- KULKARNI, R.G., PONTE, J.G. & KULP, K., 1987. Significance of gluten content as an index of flour quality. *Cereal Chem.* 64(1): 1-3.
- LAUBSCHER, E.W., 1980. The effect of locality on bread volume, protein content and mixogram properties of wheat cultivars. *Crop Prod.* 9: 49-56.
- LORENZO, A., 1986. Feasibility of developing bread wheat cultivars with acceptable protein content for non-traditional areas. Dissertation Abstracts International, Science and Engineering 47(1), 4B-5B (Abstr.).
- LUKOW, O.M., 1991. Screening of bread wheats for milling and baking quality – a Canadian wheat perspective. *Cereal Foods World* 36: 497-501.
- LUKOW, O.M. & BUSHUK, W., 1984. Influence of germination on wheat quality. I. Functional (bread-making) and biochemical properties. *Cereal Chem.* 61: 336-339.
- MacDONALD, A.A., 1994. Classification and grading In: W.Bushuk & V.F. Rasper (Eds.). *Wheat production: Properties and quality.* Chapman & Hill, London, pp 37-46.
- MaCRITCHIE, F., 1987. Evaluation of contributors from wheat protein fractions to dough mixing and bread-making. *J. Cereal Sci.* 6: 259-268.
- MaCRITCHIE, F., 1992. Physiochemical properties of wheat proteins in relation to functionality. *Adv. Food Nutr. Res.* 36: 1-87.

- MaCRITCHIE, F., DuCROS, D.L & WRIGLEY, C.W., 1990. flour polypeptides related to bread wheat quality. In: Y. Pomeranz (Ed.). *Advances in Cereal Science and Technology*, Volume 10. AACC, St. Paul, MN., pp. 79-146.
- MAILHOT, W.C. & PATTON, J.C., 1988. Criteria for flour quality. In: Y. Pomeranz (Ed.). *Wheat chemistry and technology*. 3rd Ed. American Association of Cereal Chemists, St. Paul, Minnesota, pp 69-88.
- MAMUYA, I.N., 2000. Genotype x environment interaction for quality parameters of irrigated spring wheat. MSc. Agric. Thesis, University of the Orange Free State.
- MANLEY, M. & JOUBERT, G.D., 1989. The effect of cultivar, location and sowing date on the protein content of wheat. *Applied Plant Sci.* 3: 15-17.
- MARAI, G.F. & D'APPLONIA, B.L., 1981. Factors contributing to baking quality difference in hard red spring wheat. II. Bases for different loaf volume properties. *Cereal Chem.* 58(5): 444-447.
- MARSHALL, D.R., MARES, D.J. & MOSS, H.J. & ELLISON, F.W., 1986. Effects of grain shape and size on milling yields in wheat. II. Experimental studies. *Aust J. Agric. Res.* 35: 619-630.
- MARTIN, C.R., ROUSSER, R. & BRABEC, D.L., 1993. Development of single-kernel wheat characterization system. *Trans. ASAE* 36: 1399-1404.
- McMULLEN, P.M., McVETTY, P.B.E. & URQUHART, A.A., 1988. Dry matter and nitrogen accumulation and redistribution and their relationship to grain yield and protein content in wheat. *Can J. Plant Sci.* 68: 311-322.
- MILLAR, S.J., WHITWORTH, M.B. & EVERS, A.D., 1997. Image analysis, the prediction and assessment of wheat quality and milling properties. Proceedings of the International Wheat Quality Conference, Manhattan, Kansas, USA, 18-22 May, 141-152.
- MOSS, H.J., 1973. Quality standards of wheat varieties. *Aust. J. Inst. Agric. Sci.* 39: 109-115.
- NEALES, T.F., ANDERSON, M.J. & WARDLAW, I.F., 1963. The role of the leaves in the accumulation of nitrogen by wheat during ear development. *Aust. J. Agric. Res.* 14: 725-736.
- NEL, M.M., AGENBAG, G.A. & PURCHASE, J.L., 1998. Sources of variation for yield, protein content and hectolitre mass of spring wheat (*Triticum aestivum* L.) cultivars of the Western and Southern Cape. *S. Afr. Tydskr. Plant Grond* 15(2): 72-79.
- NEL, M.M., AGENBAG, G.A. & PURCHASE, J.L., 2000. Sources of variation in spring wheat (*Triticum aestivum* L.) cultivars of the Western and Southern Cape. I. Milling and dough development characteristics. *South African Journal Plant and Soil* 17(1): 30-39.
- NEWTON, R., COOK, W.H. & MALLOCH, J.G., 1927. The hardness of the wheat kernel in relation to protein content. *Sci. Agric. (Ottawa)* 8: 205-219.
- NOAMAN, M.N., TAYLOR, G.A. & MARTIN, J.M., 1990. Indirect selection for grain protein and grain yield in winter wheat. *Euphytica* 47: 121-130.
- OHM, J.B., CHUNG, O.K. & DEYOE, C.W., 1998. Single-kernel Characteristics of hard red winter in relation to milling and Baking Quality. *Cereal Chem.* 75(1): 156-160.
- OSBORNE, B.G., KOTWAL, Z., BLAKENEY, A.B., O'BRIEN, L.O., SHAN, S. & FEARN, T., 1997. Application of the Single-Kernel Characterization System to wheat receiving testing and quality prediction. *Cereal Chem.* 74: 467-470.

- PANOZZO, J.F., O'BRIEN, L., MacCRITCHIE, F. & BEKES, F., 1990. Baking quality of Australian wheat cultivars varying in their free lipid composition. *J. Cereal Sci.* 11: 51-57.
- PARK, W.J., SHELTON, D.R., PETERSON, C.J., MARTIN, T.J., KACHMAN, S.D. & WEHLING, R.L., 1997. Variation in polyphenol oxidase activity and quality characteristics among hard white wheat and hard red winter wheat samples. *Cereal Chem.* 74(1): 7-11.
- PATTON, J. & DISHAW, M., 1968. Flour colour evaluation with green agron. *Cereal Science Today* 13(4): 163-168.
- PAWLSON, D.S., HART, P.B.S., PAULTON, P.R., JOHNSTON, A.E., & JENKINSON, D.S., 1992. Influence of soil type, crop management and weather on the recovery of N¹⁵ labelled fertilizer to winter in spring. *J. Agric. Science* 85: 559-563.
- PAYNE, P.I., 1986. Varietal improvement in the bread-making quality of wheat: Contributions from biochemistry and genetics, and future prospects from molecular biology. Biotechnology and crop improvement and protection. *BCPC Mono no.* 34: 69-81.
- PAYNE, P.I., CORFIELD, K.G. & BLACKMAN, J.A., 1979. Identification of high molecular subunits of glutenin whose presence correlates with bread-making quality in wheats of related pedigree. *Theor. Appl. Genet.* 55: 153-159.
- PAYNE, P.I., CORFIELD, K.G., HOLT, L.M. & BLACKMAN, J.A., 1981. Correlation between the inheritance of certain high molecular weight subunits of glutenin and bread-making quality in progenies of six crosses of bread wheat. *J. Sci. Food Agric.* 32: 51-56.
- PAYNE, P.I., HOLT, L.M. & LISTER, P.G., 1988. *Gli-A3* and *Gli-B3*, two newly designated loci coding for omega-type gliadins and D subunits of glutenin. Proceedings 7th International Wheat Genetics Symposium. Cambridge, England (Eds.) T.E. Miller & R.M.D. Koebner, pp. 999-1002.
- PAYNE, P.I. & LAWRENCE, G.J., 1983. Catalogue of alleles for the complex gene loci: Glu-A1, Glu-B1 & Glu-D1, which code for the high-molecular-weight subunits of glutenin in hexaploid wheats. *Cereal Res. Comm.* 11: 29-35.
- PAYNE, P. I., NIGHTINGALE, M.A., KRATTIGER, A.F. & HOLT, L.M., 1987. The relationship between HMW glutenin subunit composition and the bread-making quality of British grown wheat varieties. *J. Sci. Food Agric.* 40: 51-65.
- PECHANEK, U., KARGER, A., GRÖGER, S., CHARVAT, B., SCHÖGGL, G. & LELLEY, T., 1997. Effect nitrogen fertilization on quality of flour protein components, dough properties and bread-making quality of wheat. *Cereal Chem.* 74: 800-805.
- PELTONEN-SAINIO, P. & PELTONEN, J., 1993. Stability of quality traits in spring cereals cultivated under the growing conditions of Southern Finland. *Acta Agric. Scand. Sect. B. Soil and Plant Sci.* 43: 45-52.
- PETER, I., IVAN, T. IVANKA, S. & IRANA, I., 1998a. Storage proteins characterization of a group of Bulgarian high breadmaking quality wheat lines. *Cereal Res. Comm.* 26(4): 447-454.
- PETERSON, C.J., GRAYBOSCH, R.A., BAENZIGER, P.S. & GROMBACHER, A.W., 1992. Genotype and environment effects on quality characteristics of hard red winter wheat. *Crop Sci.* 32: 98-103.
- PINTHUS, M.J., 1973. Lodging in wheat, barley and oats. The phenomenon, its causes and preventative measures. *Adv. Agron.* 25: 209-253.

- PLANCHON, C., 1969. Photosynthetic activity and yield of soft wheat (*Triticum aestivum* L.). *Genet. Agr.* 23: 485-490.
- POMERANZ, Y., 1988. Composition and functionality of wheat flour components. In: Y. Pomeranz (Ed.). *Wheat chemistry and technology*, AACC, St Paul, MI, USA, pp. 219-370.
- POMERANZ, Y. & MATTERN, P.J., 1988. Genotype x environment interaction effects on hardness estimates in winter wheat. *Cereal Foods World* 33(4): 371-374.
- POMERANZ, Y., PETERSON, C.J. & MATTERN, P.J., 1985. Hardness of winter wheats grown under widely different climatic conditions. *Cereal Chem.* 62(6): 463-467.
- POMERANZ, Y. & SHELLENBERGER, J.A., 1971. Introduction. In: Y. Pomeranz & J.A. Shellenberger (Eds.). *Bread science and technology*, AACC, St Paul, MI, USA, pp. 219-370.
- PRITCHARD, P.F. & BROCK, C.J., 1994. The glutenin fraction of wheat protein: The importance of genetic background on its quantity and quality. *J. Sci. Food Agric.* 65: 401-406.
- PUMPHREY, F.V. & RUBENTHALER, G.L., 1983. Lodging effects on yield and quality of soft white wheat. *Cereal Chem.* 60: 268-270.
- RANDALL, P.J. & MOSS, H.J., 1990. Some effects of temperature regime during grain filling on wheat quality. *Aust. J. Agric. Res.* 41: 603-617.
- ROBERT, A.G., PETERSON, C.J., SHELTON, D.R. & BAENZIGER, P.S., 1996. Genotype and environmental modification of wheat flour protein composition in relation to end-use quality. *Crop Sci.* 36: 296-300.
- ROGERS, W.J., PAYNE, P.I. & HARINDER, K., 1989. The HMW glutenin subunit and gliadin compositions of German-grown wheat varieties and their relationship with bread-making quality. *Plant Breeding* 103: 89-100.
- SABINE, G., OBERFORSTER, M., WERTEKER, M., GRAUSGRUBER, H. & LELLY, T., 1997. HMW glutenin subunit composition and bread-making quality of Austrian grown wheats. *Cereal Res. Comm.* 25(4): 955-962.
- SANDER, D.H., ALLAWAY, W.H. & OLSON, R.A., 1987. Modification of nutritional quality by environmental and production practices. In: R.A. Olson & K.J. Frey (Eds.). *Nutritional quality of cereal grains: Genetic and agronomic improvement*. Madison, WI, USA: ASA-CSSA-SSSA Publishers. *Agronomy Monograph* 28: 45-81.
- SANDSTEDT, R.M. & OFELT, C.W., 1940. A varietal study of the relation between protein quality and protein content. *Cereal Chem.* 17: 714-725.
- SATUMBAGA, R., MARTIN, C., EUSTACE, D. & DEYOE, C.W., 1995. Relationship of physical and milling properties of hard red winter wheat using the single kernel wheat characterization system. *Assoc. Oper. Millers Tech. Bull.* January 6487-6496.
- SIMMONDS, D.H., 1989. Wheat proteins: their chemistry and nutritional potential. In: L.T. Evans and W.P. Peacock (Eds.). *Wheat Science – today and tomorrow*, Cambridge University Press, Cambridge, pp 129-148.
- SIMMONDS, N.W., 1996. Yields of cereal grain and protein. *Exp. Agric.* 23: 351-356.
- SHEWRY, P.R., TATHAM, A.S., BARRO, F., BARCELO, P. & LAZZERI, P., 1995. Biotechnology of bread making: Unravelling and manipulating the multi-protein gluten complex. *Bio/Technology* 13: 1185-1190.
- SHOGREN, M.D. & FINNEY, K.F., 1984. Bread-making test for 10 grams of flour. *Cereal Chem.* 61: 418-423.

- SHUEY, W.C., 1975. Flour colour as a measurement of flour quality. *Bakers Digest*: 18-26.
- SHUEY, W.C. & SKARSUANE, S.K., 1973. The relation between flour mineral content and flour colour reflectance values. *Cereal Science Today* 18(8): 229-230.
- SIMMONDS, N.W., 1996. Yields of cereal grain and protein. *Exp. Agric.* 23: 351-356.
- SLAFER, G.A., ANDRADE, F.H. & FEINGOLD, S.E., 1990. Genetic improvement of bread wheat (*Triticum aestivum* L.) in Argentina: relationship between nitrogen and dry matter. *Euphytica* 50: 63-71.
- SMIKA, D.E. & GREB, B.W., 1973. Protein content of winter wheat grain as related to soil and climatic factors in the Semi-arid Central Great Plains. *Agric. J.* 65: 433-436.
- SPIES, R., 1990. Application of rheology in the bread wheat industry. In: H. Faridi & J.M. Faubion (Eds.). Dough rheology and baked product texture. Van Nosstrand Reinhold, New York, pp. 343-361.
- STEVE, F.S., ROBERT, K.B., PATRICK, L.F. & EDWARD, E.G., 1995. Relationship of test weight and kernel properties to milling and baking quality in soft winter wheat. *Crop Sci.* 35: 949-953.
- STODDARD, P.C. & MARSHALL, D.R., 1990. Breeding Australian wheat for improved grain protein concentration. Proceedings of the 6th assembly, Wheat Breeding Society of Australia (Inc.), Tamworth, pp. 227-232.
- TATHAM, A.S. & SHEWRY, P.R., 1995. The s-poor prolamins of wheat, barley and rye. *J. Cereal Sci.* 22: 1-16.
- TAYLOR, A.C. & GILMOUR, A.R., 1971. Wheat protein prediction from climate factors in southern New South-Wales. *Australian J. of Experimental Agriculture* 11: 546-549.
- TERMAN, G.L., 1979. Yields and protein content of wheat grain as effected by cultivar, N, and environmental growth factors. *Agron J.* 71: 437-440.
- UTHAYAKUMARAN, S., GRAS, P.W., STODDARD, F.L. & BEKES, F., 1999. Effect of varying protein content and glutenin-gliadin ratio on the functional properties of wheat dough. *Cereal Chem.* 76(3): 389-394.
- VAN DEVENTER, C.S. 1986. Genotipe x omgewinginteraksie by winterkoring in die Oranje Vrystaat. *S. Afr. J. Plant Soil* 3: 147-148.
- VAN LILL, D., 1992. Environmental effects on yield and bread-making quality of some South African wheat cultivars. PhD Thesis, University of Stellenbosch.
- VAN LILL, D. & PURCHASE, J.L., 1995. Directions in breeding for winter wheat yield and quality from 1930 to 1990. *Euphytica* 82: 79-87.
- VAN LILL, D., PURCHASE, J.L., SMITH, M.F., AGENBAG, G.A. & DE VILLIERS, O.T., 1995a. Multivariate assessment of environmental effects on hard red winter wheat. I. Principal components analysis on yield and bread making characteristics. *S. Afr. J. Plant Soil* 12: 158-163.
- VAN LILL, D., PURCHASE, J.L., SMITH, M.F., AGENBAG, G.A. & DE VILLIERS, O.T., 1995b. Multivariate assessment of environmental effects on hard red winter wheat. I. Canonical correlation and canonical variate analysis on yield and bread-making characteristics. *S. Afr. J. Plant Soil* 12: 164-169.
- VAN LILL & SMITH, M.F., 1997. A quality strategy for wheat (*Triticum aestivum* L.) where growth environments predominates. *S. Afr. J. Plant Soil* 14: 183-191.
- WALKER, C.E. & HAZELTON, J.L., 1996. Dough rheological tests. *Cereal Foods World* 41(1): 23-28.

- WALL, J.S., 1979. The role of wheat proteins in determining baking quality. In: R.G.Wyn Jones (Ed.). Recent advances in the biochemistry of cereals. Academic Press, New York, pp. 275-308.
- WRIGLEY, C. W., BLUMENTHAL, C., GRAS, P.W. & BARLOW, E. W. R., 1994. Temperature variation during grain filling and changes in wheat-grain quality. *Aust. J. Plant Phys.* 21: 875-885.
- YAMAZAKI, W.T., 1976. Soft wheat quality of pre-ripe, harvested wheat. *Crop Sci.* 16: 572-575.
- YAMAZAKI, W.T. & DONELSON, J.T., 1983. Kernel hardness of some U.S. wheats. *Cereal Chem.* 60: 344-350.
- YBEMA, S.G., PURCAHSE, J.L., DU PLESSIS, J.C., NEL, C., VAN DER MERWE, H.S.C.A., VAN RENSBURG, B. & HATTING, H.A., 1998. Report on the National wheat cultivar evaluation programme under irrigation, Small Grain Institute, pp. 24-26

CHAPTER 3

Effect of G x E interaction on milling and baking quality of irrigated spring wheat cultivars in South Africa

3.1 Abstract

Five spring wheat cultivars (*Triticum aestivum* L.) were grown in five environments from 1997 through 1999. The cultivars used in this study displayed a broad range in milling and baking quality. The best and poorest cultivar in overall milling performance was Karioga and SST 822 respectively, while the best and poorest overall baking performance had been displayed by Karioga and SST 876 respectively. The fact that the South African grading system does not accommodate different hardness classes currently cannot be ignored anymore. Wheat hardness classes could improve the genotype's contribution to flour yield, to the advantage of the milling industry. All the characteristics related to gluten strength and the elastic properties namely SDS-sedimentation test, wet gluten content standardized at 12% protein, mixograph mixing time, alveograph strength, alveograph distensibility and alveograph P/L ratio displayed genotypic variance values above 30% and even as high as 57.65% for mixograph mixing time. These traits can be efficiently used in order to improve dough-handling properties in a given progeny. Genotype x location interaction components for most of the milling and baking characteristics was low, thus indicating that the performance among the genotypes stays the same at each locality.

3.2 Introduction

It is a well-known fact that interactions exist between genotypes and their environment factors in annual crops in South Africa (Van Deventer, 1985; Mladenov *et al.*, 2001). Multi-environment trials play an important role in selecting the best cultivars (or agronomic practices) to be used in future years at different locations and in assessing a cultivar's stability across environments before its commercial release. Cultivars grown in

multi-environment trials react differently to environmental changes. This differential response of cultivars from one environment to another is called genotype x environment interaction (GEI), (Crossa *et al.*, 1998; 1999). Fisher and McKenzie (1923) were the first researchers to report genotype by environment interaction, on which a variance analysis was also carried out. They looked at the response of different potato cultivars in different environments and made the conclusion that yields in certain environments are better suited by a product formula than a sum formula.

According to Comstock and Moll (1963) the occurrence of genotype and environment interaction is the result when the phenotypic response of genotypes differs. Therefore, interaction with the environment disturbs the ranking order of genotypes and severe interactions can be expected if environmental conditions vary markedly (Weber and Westermann, 1994). Normally some plant characteristics with low heritabilities such as yield, show high interactions with most environment effects. Under those conditions it is very difficult to discriminate against genotypes according to their average performance. Therefore the average phenotypic value for a given genotype characteristic with a low heritability is not an accurate indication of its genotypic value. Further, it is very likely that the superiority of one genotype above another in the presence of genotype by environment interaction is most likely a product from some sort of existing interaction. This kind of interaction is also responsible for the variation in ranks of genotypes at different environments in South Africa (Van Deventer, 1985). Genotype x environment interaction was insignificant in hectolitre mass and falling number of wheat, while significant genotype x environment interactions were observed for thousand kernel mass and grain protein concentration (Peltonen-Saino and Peltonen, 1993).

According to Freeman (1973) various statistical methods had been proposed by some researchers in order to analyse interactions in general. Firstly, it is necessary to determine if there are interactions present. Only then can the importance and the effect of the interactions be looked at. The underlying cause must be determined, if there is a significant genotype by environment interaction present. Mostly breeders are interested in the effect that genotype by environment interaction has on their breeding programmes.

The research of Abou-El-Fittough *et al.* (1969) showed that genotype by environment interaction can be divided into resultant interaction components, which assist breeders in quantifying the proportional contribution of each interaction effect.

Sprague and Federer (1951) showed how to calculate the various variance components from a variance analysis, by means of eliminating the effects of genotypes, environments and their interactions. Various researchers used this method in order to determine the different interaction effects (Miller, *et al.* 1959; Allard and Bradshaw, 1964; Cooper and De Lacy, 1994). Allard and Bradshaw (1964) also emphasized the importance of genotype by year interactions for breeders.

In wheat (*Triticum aestivum* L.) breeding programmes primary emphasis is usually given to factors that affect yield. Although South Africa is not an exporting country, grain quality is also of major importance. Therefore stringent quality standards have been drawn up, the enforcement of which is accomplished through restricted cultivar release. The acceptability of an entry depends on the South African Wheat Technical Committee's belief whether the quality data lies within the specified margins according to a biological quality standard which is being used as the benchmark.

Defining wheat quality is complex, because it is viewed differently by producers, millers and bakers (Baker *et al.* 1999). Producers are concerned primarily with yield; yield stability and disease resistance (Cox *et al.* 1989). As defined by the miller, wheat quality relates to the sanitary condition of the grain and its physical characteristics such as test weight, kernel weight, kernel size, hardness and flour yield (Posner, 1988; Salem and Piland, 1995; Gwartz *et al.* 1996). Wheat quality from the bakers' prospective is related to flour properties, such as protein content, water absorption, starch damage, mixing time, mixing tolerance, fermentation tolerance and loaf volume (Salem and Piland, 1995). Many of these important flour characteristics depend on protein quantity *and* quality (Finney *et al.* 1987a; Faridi and Finley, 1989; Van Lill *et al.* 1993b). While protein content is governed by environmental factors, protein composition focuses on the relative proportions of specific storage proteins namely gliadins and glutenins (Van Lill *et al.* 1993b). High and low molecular weight glutenin subunit composition contribute to variation in quality (MacRitchie *et al.* 1991). Van Lill *et al.* (1993a) determined that agronomic practices aimed at improvement of growing conditions, enhanced both yield and protein content for South African wheat cultivars under dryland production.

Various researchers proved that certain quality characteristics are not genetically fixed and that the quality of grain shipments reaching the mills is influenced by the genotype

and environmental factors as well as their interaction (Busch *et al.* 1969; McGuire and McNeal, 1974; Peterson *et al.* 1992). Salinger *et al.* (1995) published a paper regarding the influence of climatic factors on the baking quality of bread wheat in New Zealand. They showed that there was a strong influence of temperature (positive) and rainfall (negative) on the quality of spring-sown wheat. In their research it was clear that cultivars' baking scores varied due to the influence of climatic factors. Fowler and de la Roche (1975b) reported that cultivar effects for soft red spring wheat grown in eastern Canada were important for all quality parameters and that large environmental effects were observed for protein and protein-related quality parameters, while relatively small environmental effects were observed for mixograph peak time. Fowler and de la Roche (1975a) found that except for a few instances genotype x year and genotype x location interactions were found to be relatively insignificant. However, evidence from variance components suggested that genotype x location x year interaction could be of greater concern. Baenziger *et al.* (1985) published results that proved cultivar means from an environment were generally highly significant correlated with the regional cultivar means indicating that for preliminary quality evaluations, data from one environment is sufficient for ranking cultivars. Graybosch *et al.* (1996) reported that various components of flour protein differed in their response to environmental and genotypic factors. Flour protein concentration and the percentage of protein present as gliadin and non-gluten proteins were found to be most sensitive to environmental fluctuations. The percentage of protein present as glutenin was found to be nearly totally genotype dependant. They also found that selection based on SDSS volumes, to maintain strong dough and good loaf volumes, coupled with selection for enhanced glutenin content as a means of fixing good loaf volume, could assist breeders in the task of maintaining strong dough and good loaf volumes in the presence of lower protein concentrations. Van Lill and Smith (1997) showed that the incorporation of a range of localities where both protein levels are sufficiently present to be of more importance than the number of harvest seasons over which an entry is evaluated. Gaines *et al.* (1996) proved that cultivar differences due to region of adaptation were generally small but consistent for most milling and baking qualities. Gaines *et al.* (1996) also found that climatic conditions during the growth cycle have a greater influence on most quality traits than genotypes. The environment had a strong influence on grain conditions and consequently grain condition had the largest influence on milling characteristics. Further on it was conclusive from their results that different regions produced flour that varied in relation to their hardness levels and thus influenced starch damage, water absorption and flour yields significantly. In contrast,

Pomeranz *et al.* (1985) as well as Pomeranz and Mattern (1988) observed that genotype had a larger influence on variability of wheat hardness than did location. Starch damage increases with wheat endosperm hardness and is related to rate and level of water absorption and dough development characteristics (Pomeranz and Mattern, 1988). Finney *et al.* (1987a) reported that mean differences in the ranges of kernel texture (break flour yield) that resulted from environmental influences were 1.5 times greater than genotypical differences. Pomeranz and Mattern (1988) proved that for all varieties across locations grain protein content was not correlated with hardness. Some varieties however, showed significant negative or positive relationships between protein content and hardness.

McGuire and McNeal (1975) came to the conclusion that quality characteristics of hard red spring wheat cultivars do not respond similarly when environment favouring these quality characteristics traits improve. Therefore, important quality responses are ignored if only mean quality data are considered or when intracultivar blends across environments are made for quality evaluations. The aim of this study was to determine the source, size and magnitude of genotype x environment interaction for spring wheat under irrigation.

3.3 Materials and methods

Evaluation of wheat quality involves the measurement of a large number of characteristics. Since many of the tests for quality evaluation are time-consuming and expensive, they have been performed traditionally on a limited number of samples. The number of samples to be evaluated may be reduced by combining samples over replicates, locations or years. However, this procedure reduces the precision with which quality characteristics are estimated and may lead to erroneous conclusions if large cultivar by environment interactions do occur (Lukow and McVetty, 1991). Therefore, in order to improve the precision of the analysis the amount of cultivars, localities, replications and years were maintained throughout the study.

3.3.1 Field trials

Five genetically diverse spring wheat cultivars namely, Kariega, Marico, SST825, SST822 and SST876 were the genotypes common in all three years of testing. Small Grain Institute (Agricultural Research Institute) released Kariega and Marico, while Monsanto owns the Plant Breeders Rights on the latter three cultivars. The term "spring wheat" implies that such cultivars do not need a certain degree of vernalization requirements in order to reach full maturity. The genotypes, year of release, status and origin for the genotypes used in this study are indicated in Table 3.1.

Most of the cultivars are semi-dwarf cultivars except for SST822, which is a short growth period double dwarf. Double dwarf wheat cultivars tend to have lower yield potential than semi dwarf wheat cultivars in South Africa. SST876 possesses the solid stem characteristic originating from *Aegilops ventricosa*. The solid stem characteristic improved lodging tolerance dramatically, with resultant higher grain yield. Kariega is the biological quality standard being used by the South African Wheat Technical Committee as a reference cultivar. This implies that all new lines are compared against Kariega for possible release as new cultivars in the irrigation areas. Kariega and Marico are long growth period cultivars while SST 825 and SST 876 are classified as medium growth period cultivars. Seed for the given quality analysis, were obtained from trials conducted in the irrigation areas by the National Cultivar Evaluation Department of Small Grain Institute during 1997,1998 and 1999.

Table 3.1. Genotypes and their pedigrees, year of release, status and origin.

Genotype		Year	Status	Origin
Marico	Broadbill's"	1992	Cultivar	CIMMYT, Mexico
Kariega	SST44//K45400/Sapsucker's"	1993	Cultivar	SGI, RSA
SST822	Not available	1992	Cultivar	Monsanto, RSA
SST825	Tui's"	1992	Cultivar	CIMMYT, Mexico
SST876	SST57/Adam Tas//SST 825	1997	Cultivar	Monsanto, RSA

SGI = Small Grain Institute
 RSA = Republic of South Africa

Wheat production under irrigation in the summer rainfall region entails the production of spring wheat types, which are planted in the fall and winter. There are five main irrigation areas, namely the cooler central irrigation areas (situated next to the Orange, Vaal, Sand and Vet rivers), the warmer northern irrigation areas (along the Eliphants and Crocodile rivers, the Loskop dam irrigation area is also included here), Kwazulu-Natal, Eastern Free State and the Eastern Cape (Cradock). The warmer northern irrigation regions have a lower yield potential compared to that of the cooler central irrigation areas, and this is mainly due to the warmer winter temperatures and therefore a shorter growing season. This leads to a higher growth and development rate, weaker tillering capacity and subsequently lower yields. The irrigation areas represent high yielding environments, which rely heavily on intensive cropping systems.

The region, location, coordinates and number of trials from 1997 until 1999 included for quality analysis can be seen in Table 3.2. Trials were conducted at experimental stations or farms of collaborators where the soil and climate are representative of a specific area.

Table 3.2. Regions with representative localities and the number of trials from 1997 until 1999.

Region	Locality	1997	1998	1999
Warmer areas	Loskop	1	1	1
Cooler areas	Bull Hill	1	1	1
	Prieska	1	1	1
	Hopetown	1	1	1
	Douglas	1	1	1

It is very important to bring cultivar performance in line with the weather conditions that prevailed during the growth cycle. For the 1997 season normal temperatures occurred during the period up to the middle of June in all the regions. Temperatures above average occurred during the second half of winter in all five regions. Above average temperatures were measured during the grain filling period from August through to October. This had a negative influence on the yield and hectolitre mass levels.

During the 1998 season normal to above average temperatures occurred in all the irrigation areas during the second part of the winter months up to the end of August. Below average temperatures were measured during September and October which had a positive influence on grain filling period resulting in higher yields and hectolitre masses. In some of the areas heavy rain showers were observed which lowered the hectolitre masses slightly.

Regarding the 1999 season normal to above normal temperatures occurred during the growth period up to the end of August in all the irrigation areas. Above average temperatures occurred in all five irrigation areas during the second half of the winter. Relatively low temperatures occurred during September and October, which had a positive effect on yield and hectolitre mass.

The cultivars were planted according to a randomised block design with four replicates. Trial plots consisted of eight rows 0.17 m apart and six meter in length, which were then later reduced to five meters length to produce a net plot size value of 6.8m². The seeding rate was standardized for each cultivar according to its 1000 kernel weight. Therefore, the seeding rate for each cultivar differed in order to establish a uniform stand of plants per square meter.

Fertilization was applied according to target yield recommendations for each region. Applications on the trial plots were done according to recommendations based on individual soil analyses obtained from soil samples. Weed and pest control was performed when necessary. At harvesting, the two side rows were cut out in order to reduce the side-row effect, which can influence yield positively, thus the net plot size harvested for the quality analysis was 5.1 m². The plots were harvested with a Wintersteiger plot combine.

The soil profiles in the cooler central irrigation areas are mostly sandy and red in colour. Soils with high clay contents are found in the warmer northern irrigation regions. Maximum temperatures above 30°C during kernel filling period are a common phenomenon that eventually increases the risk for drought stress with consequently low hectolitre masses and high protein contents (Koekemoer, 1997). Mostly the total rainfall figures in all the irrigation areas except Kwazulu-Natal do not exceed 200mm during the growth cycle.

3.3.2. Quality analysis

Test weight or hectolitre mass (HLM, kg/hl) was determined using a Franklin chondrometer. The mass of a thousand kernels counted with a Numigral seed counter (Tripette et Renaud Paris France) was considered as the thousand kernel mass (TKM, g). After 50 grains had been cut with a farinator, vitreous kernels (VK, %) were determined as the total of two points per fully vitreous grain and one point per grain with at least 50% vitreousness. Grain samples of approximately 50 g were milled with a Falling Number KT-120 laboratory mill (1.0mm sieve) after which Hagberg Falling Numbers (FLN, s) were determined (AACC, 1983) from a 6.1 g sample to compensate for altitude ($\pm 1340\text{m}$). The grain protein contents (GPC-Leco, %) and flour protein contents (FPC-Leco, %) were determined with a Leco-FP2000 (AACC, 1995). Flour extraction rate (FLY, %) and break flour yields (BFLY, %) were calculated after experimental milling in a pneumatic Buhler MLU202 mill (Buhler-Miag, Uzwil, Switzerland), (AACC, 1983). A Kent Jones and Martin colour grader was used to measure flour colour standardised at a 76% flour extraction rate (FCL76, kj units). Single kernel characteristics were determined using the SKCS 4100 (Perten Instruments, Springfield, IL), this instrument provides characteristics like kernel diameter (average diameter of 300 kernels), hardness index (the index as percentage of the pressure of two rollers to crush 300 kernels) and kernel weight (the average weight of 300 kernels in mg).

Mixograph dough development time (MDT, min) was determined with a 35g National Mixograph (National Mfg., Lincoln, Nebraska), (AACC, 1983). Other rheological analyses performed according to approved methods (AACC, 1983) included the Brabender Farinograph quality determinant water absorption (FABS, %), the Chopin Alveograph determinants: dough strength (AS, cm^2), Alveograph stability (ASTAB, mm), Alveograph distensibility (AD, mm) and the ratio of stability to distensibility (P/L). In this study, micro loaves were baked from 100g of flour, using an optimized straight dough method (Finney, 1984). Loaf volumes were then determined by rapeseed displacement directly after baking, using a pup loaf volumeter. The SDS-sedimentation (sodium dodecyl sulphate –SDS) test was used to measure the relative gluten strength as it indicates the differences in the quantities of the polymeric glutenins (gel protein), (AACC, 1983). Wet-gluten content was determined with the glutomatic; the glutomatic is an

automatic apparatus, which develops gluten of wheat flour from a 2% NaCl solution. The dough mixing and subsequent separation of starch and other solubles from the dough takes place in the same test chamber under controlled standardized conditions. The ball is then centrifuged to remove excess water and weighed as wet gluten.

In order to simplify the discussion, all the quality characteristics were divided into two groups namely milling and baking characteristics. The milling characteristics are represented by hectolitre mass (HLM), thousand kernel mass (TKM), Vitreous kernel (VK), SKCS weight (SKCS-G), SKCS diameter (SKCS-DIA), SKCS hardness index (SKCS-HI), Farinograph water absorption (FABS), break flour yield (BFLY) and flour yield (FLY). The baking characteristics are represented by falling number (FLN), grain protein content determined by the Leco (GPC-Leco), flour protein content determined by the Leco (FPC-Leco), Wet gluten content standardized at 12% protein content (WGC-12), SDS-sedimentation value (SDSS), mixograph development time (MDT), alveograph strength (AS), alveograph distensibility (AD), alveograph stability (ASTAB), alveograph P/L index (P/L), loaf volume (LFV) and loaf volume standardized at 12% protein content (LFV-12) in order to eliminate the positive effect of protein content on bread loaf volume.

3.3.3. *Statistical analysis*

Bartlett (1947) test was used to determine if the variances of the different milling and baking characteristics showed any homogeneity of residual variances (deviations from the regression line) at the test levels of $\alpha = 0.01$ and $\alpha = 0.001$. Because Bartlett's test is much more sensitive to non-normality than the F-test, a smaller test level than the customary $\alpha = 0.05$ can be used. This ensures that the residual variances are not declared heterogeneous when F-tests for the comparison of the slopes and elevations can tolerate some heterogeneity. A test of $\alpha = 0.001$ may also be suitable and one would really be concerned if heterogeneity was evident at this level (Van Ark, 1995). The results however showed that the α -value for all the milling and baking characteristics separately varied between ($\alpha = 0.01$) and ($\alpha = 0.001$). The original version of the data was thus used in the analysis, because homogeneity of the residual variances confirmed that the comparison of the slopes regarding the regression lines is valid.

The model of Sprague and Federer (1951) used in this study allows one to determine the variance components for each effect separately. The model is as follows:

$$Y_{ijk} = \mu_i + d_i + \epsilon_j + \gamma_{ij} + \epsilon_{ijk}$$

where $\sum_i d_i = \sum_j \epsilon_j = \sum_{ij} \gamma_{ij} = 0$

Where also Y_{ijk} = the k^{th} replication of the i^{th} genotype in the j^{th} environment

μ_i = the average for the i^{th} genotype

d_i = the genotype effect for the i^{th} genotype

ϵ_j = the environment effect for the i^{th} genotype in the j^{th} environment

γ_{ij} = the interaction effect

ϵ_{ijk} = random error

The combined variance analysis was used in order to establish the influence of the genotype by environment interaction in this study. In the combined variance analysis the genotype by environment interaction was separated into their resultant different interaction components namely; genotype by year, genotype by locality and genotype by year by locality interaction. This separation supplies a method of determining the expected variance components for each effect separately and provides the means to compare them mutually (Miller *et al.*, 1959).

The statistical package AgrobasesTM (1999) was used to carry out a factorial analysis that provides the variance analysis which shows the degrees of freedom, mean squares for the above mentioned different variance components. The variance analysis, degrees of freedom, mean squares for the various variance components can be seen in Table 3.3.

For the purpose of this study, all the effects in the variance analysis can be seen as random. Normally three years must be chosen randomly from a period of 12 years or more. There is however, more than enough evidence to prove that the three successive years chosen in this study are representative and include enough variation for optimal and sub-optimal conditions. Unfortunately a factorial analysis could not be carried out on Flour colour adapted to a 76% extraction level (C76) due to the huge variation exhibited by the data, although the original values were quadrated in order to eliminate the



1174 188 11

negative values, the variation still remained too large, therefore the data regarding flour colour will not be discussed in this paper.

Table 3.3. Combined variance analysis regarding years, localities and genotypes.

Source	DF	Mean square	Expected variances
Years	y-1		
Localities	l-1		
Localities x years	(l-1)(y-1)		
Genotypes	(g-1)	M ₅	$\sigma_e^2 + r\sigma_{gly}^2 + ry\sigma_{gl}^2 + rl\sigma_{gy}^2 + rly\sigma_g^2$
Genotypes x years	(g-1)(y-1)	M ₄	$\sigma_e^2 + r\sigma_{gly}^2 + rl\sigma_{gy}^2$
Genotypes x localities	(g-1)(l-1)	M ₃	$\sigma_e^2 + r\sigma_{gly}^2 + ry\sigma_{gl}^2$
Genotypes x localities x years	(g-1)(l-1)(y-1)	M ₂	$\sigma_e^2 + r\sigma_{gly}^2$
Error	(ly(r-1)(g-1))	M ₁	σ_e^2

Where g, r, l, and y represent the genotypes, replications, localities and years respectively

σ_e^2 = Estimated variance of error

σ_{gy}^2 = Estimated variance component due to genotype and year interaction

σ_{gl}^2 = Estimated variance component due to genotype and locality interaction

σ_{gly}^2 = Estimated variance component due to genotype, year and locality interaction

The expected variance components for each of the effects in the variance analyses were determined separately. The average variance components were calculated from the linear function of the mean squares. The procedure followed was similar to that described by Liang *et al.* (1966).

$$\begin{aligned}
 \text{(i) Genotype } (\sigma_g^2) &= \frac{M_5 + M_2 - M_3 - M_4}{rly} \\
 \text{(ii) Genotype x years } (\sigma_{gy}^2) &= \frac{M_4 - M_2}{rl} \\
 \text{(iii) Genotype x localities } (\sigma_{gl}^2) &= \frac{M_3 - M_2}{ry} \\
 \text{(iv) Genotype x localities x years } (\sigma_{gly}^2) &= \frac{M_2 - M_1}{r} \\
 \text{(v) Error} &= M_1
 \end{aligned}$$

3.4 Results and discussion

3.4.1 Cultivar comparisons

The milling and baking characteristics for each of the cultivars are presented in Table 3.4 and Table 3.5 respectively. Wide ranges in each of the quality parameters and significant differences between Kariega and the rest of the cultivars regarding all parameters except vitreous kernels (VK) were observed.

All three parameters namely TKM, SKCS-DIA and SKCS-G are indicators for kernel size. Since flour is derived from wheat endosperm, the size, density and shape of the grain determines the flour yield potential (Eggitt and Hartley, 1975). Marshall *et al.* (1986) found that grain size, measured by either TKM or volume (HLM), was correlated with flour yield when seed was stratified for grain size within hard wheat cultivars but not among cultivars. Shuey and Gilles (1972) also showed that the milling industry prefers that high thousand kernel mass should occur in combination with high hectolitre mass, resulting in a higher flour yields. From Table 3.4 it is evident that the TKM and SKCS-G values for both Marico and SST 876 are significantly lower than that of Kariega, the biological standard. This indicates that Marico and SST 876 have smaller kernels. SST 825 also displayed a significant larger SKCS-DIA value than that of Kariega. Both SST 876 and SST 822 displayed significant higher HLM values than Kariega. Higher hectoliter mass is indicative of grain plumpness (McDonald, 1994) and may predict potential flour yield (Finney *et al.* 1987b; Nel *et al.* 1998). According to the flour extraction (FLY) percentages from SST876 (76.47%) and Marico (76.87%), which do not differ significantly from Kariega (76.83%) shows that cultivars with smaller kernels can produce good flour yields when kernels are plump (Table 3.4). In the South African context Kariega has a reputation for its exceptional flour yield potential. Gaines (1991) proved that hectolitre mass was positively correlated with flour yield, and that cultivars with higher hectolitre mass produced lower break flour yields.

Hardness is one of the most important characteristics of wheat from the standpoint of milling and end-use properties (Pomeranz and Mattern, 1988), because the milling and flour quality is often influenced by kernel hardness (Gaines *et al.* 1996). Indicators of hardness are VK, SKCS-HI, BFLY and FABS. Table 3.4 demonstrates that none of the cultivars differed significantly from Kariega regarding their VK values. SST 825 (68.86)

showed a significantly higher SKCS-HI value when compared to the rest of the cultivars included. Kariega on the other hand had the lowest SKCS-HI value (59.73). Therefore, it can be concluded that SST825 is significantly harder than the rest of the cultivars, while Kariega's kernel texture could almost be classified as medium to soft. Consequently a significant drop in BFLY can be seen for SST825, SST882 as well as SST876. Significant increases for FABS values were observed for both SST 825 and SST 822. Marico's FABS value was significantly lower than the rest of the cultivars included in this study. Lower dough yields can be a result of the lower water absorption levels observed for Marico's flour.

Table 3.4. Means for milling characteristics of spring wheat cultivars under irrigation (1997-1999).

	HLM	TKM	SKCS-G	SKCS-DIA	VK	SKCS-HI	FABS	BFLY	FLY
Cultivar	(Kg/hl)	(g)	(mg)	(mm)	(%)		(%)	(%)	(%)
Marico	77.86	38.27	37.30	2.50	79.22	65.06	59.86	22.30	76.87
Kariega	78.05	41.08	40.02	2.72	76.56	59.73	62.15	22.69	76.83
SST 825	78.50	40.46	39.71	2.81	78.33	68.86	63.91	18.96	75.59
SST 822	78.89	40.30	39.45	2.70	78.27	66.95	62.83	21.38	75.06
SST 876	79.90	39.64	38.31	2.68	73.18	65.32	62.07	19.62	76.47
CV% [@]	1.77	5.44	5.40	4.96	9.34	5.54	1.87	4.38	1.05
Means*	78.64	39.95	38.96	2.68	77.11	65.18	62.16	20.99	76.16
LSD [#]	0.69	1.08	1.05	0.07	3.57	1.79	0.58	0.46	0.40

*Means = Means represents the averages for 3 replicates, 5 environments and 3 years combined

LSD = Least significant difference at p<0.05

@CV% = Coefficient of variance

HLM = hectolitre mass, TKM = thousand kernel mass VK = Vitreous kernel, SKCS-G = SKCS weight, SKCS-DIA = SKCS diameter, SKCS-HI = SKCS hardness index, FABS = Farinograph water absorption, BFLY = break flour yield and FLY = flour yield.

From Table 3.5 it is evident that the condition of the seed was sound because all the cultivars produced FLN values above 220s, the actual limit set by the South African wheat grading system for non-sprouted wheat samples. SST 822 was the only cultivar that had a significantly higher FLN value than Kariega. Significant differences were observed among the tested cultivars for GPC-Leco and FPC-Leco. SST 822 exhibited significant higher GPC-Leco value and SST 876 significant lower GPC-Leco value in comparison to Kariega. Cultivars with higher grain yield potential (like SST 876) tend to have lower protein contents than cultivars with lower grain yield potential (like SST 822) at a given level of available nitrogen (Terman, 1979; Clarke *et al.* 1990; Nel *et al.* 1998). During the milling process a one percent drop in protein content is normally achieved due

to protein content imbedded in the bran and not being incorporated within the end product namely the flour.

The gluten proteins of wheat are mainly responsible for the visco-elastic structure of dough, thus the SDSS measures the relative bread making potential and gluten strength (De Villiers and Laubscher, 1995) of wheat genotypes and it is not very sensitive to environmental effects (János, 1998). All the cultivars produced SDSS values significantly lower than that of Kariega., however only the SDSS value of SST 876 was low enough to be actually reflected in the bread making quality and gluten strength values (Table 3.5). WGC-12 predicts loaf volume and gluten strength, from the results in Table 3.5 it is evident that WGC-12 is not such an accurate predictor for loaf volume (LFV, LFV-12) than the SDSS test. SST 876 showed significant lower MDT while SST 825, SST 822 as well as Marico showed significant higher MDT values than Kariega. Regarding the alveograph test only SST 825 can be labeled as a cultivar with significantly stronger rheological dough characteristics displayed by its higher AS; ASTAB and P/L. The higher P/L ration of SST 825 can also be a secondary result regarding its improper conditioning due to its harder kernel texture (SKCS-HI value) as seen in Table 3.4. Both the LFV and LFV-12 tests give an indication of the gas retention capacity of the dough during the fermentation process (Shogren and Finney, 1984). Only SST 876 produced a significant lower LFV value than Kariega, due to its weaker dough strength. Sometimes dough strength can be too strong and lower extensibility is then normally observed, in such circumstances the dough shears during the baking process. The gas generated at that point then escapes and bread loaf with low volumes are normally the result.

3.4.2 Location comparisons

The milling and baking characteristics for each of the localities are presented in Table 3.6 and Table 3.7 respectively. Wide ranges in each of the quality parameters and significant differences between the localities regarding all parameters can be seen.

Table 3.5. Means for baking characteristics of spring wheat cultivars under irrigation (1997-1999).

	FLN	GPC-Leco	FPC-Leco	WGC-12	SDSS	MDT	AS	AD	ASTAB	P/L	LFV	LFV-12
Cultivar	(s)	(%)	(%)	(g)	(ml)	(min)	(cm ²)	(mm)	(mm)		(cm ³)	(cm ³)
Marico	309.22	12.53	11.60	30.28	77.13	3.52	40.60	131.44	64.87	0.54	937.40	928.69
Kariega	316.80	12.73	11.97	33.71	80.73	2.60	39.27	150.47	63.24	0.46	969.00	957.40
SST 825	325.42	12.72	11.92	33.17	73.71	2.78	44.00	117.02	84.07	0.75	971.36	933.02
SST 822	329.09	13.15	12.10	34.32	75.51	2.76	36.09	138.96	65.73	0.47	972.09	958.58
SST 876	320.87	12.38	11.64	34.53	67.04	1.98	28.36	126.73	62.42	0.54	913.33	924.22
CV% [@]	7.38	4.59	5.80	6.28	5.77	11.01	13.08	11.25	10.05	19.28	7.01	4.01
Means [*]	320.28	12.70	11.83	33.20	74.82	2.73	37.66	132.92	68.07	0.55	952.64	940.38
LSD [#]	11.71	0.29	0.34	1.03	2.14	0.15	2.44	7.42	3.39	0.05	33.10	18.68

*Means = Means represents the averages for 3 replicates, 5 environments and 3 years combined

LSD = Least significant difference at p<0.01

@ CV% = Coefficient of variance

FLN = falling number, GPC-LECO = grain protein content determined by the Leco, FPC-LECO = flour protein content determined by the Leco, WGC-12% = Wet gluten content at 12% protein content, SDSS = SDS-sedimentation value, MDT = mixograph development time, AS = alveograph strength, AD = alveograph distensibility, ASTAB = alveograph stability, P/L = alveograph P/L index LFV = loaf volume and LFV-12% = loaf volume standardized at 12% protein content.

The locality Loskop, representing the warmer areas, produced the lowest hectolitre mass value. This can be mainly credited to maximum daily temperatures above 32°C and shorter growth periods (Table 3.6). It appears that endosperm content (revealed by kernel plumpness), which is favoured by high photosynthetic rates and/or long grain filling periods is strongly influenced by environmental conditions (Jenner, 1991). From Table 3.6 it is clear that Loskop together with Hopetown produced smaller kernel characteristics (lower TKM, SKCS-G and SKCS-DIA values). Some wheat fill their matrix extremely well and therefore the strength of their kernels increases simply because of more surface interaction. Thus, even soft wheat, when grown under the ideal conditions, can produce vitreous kernels while still remaining soft (Hoseney, 1987). Therefore the SKCS-HI is a much more reliable indicator of kernel hardness. This phenomenon is clearly demonstrated by the high average VK values generated for all cultivars at Douglas in comparison to the average hardness values (SKCS-HI value) observed in Table 3.6.

Table 3.6. Environment means for milling characteristics of spring wheat cultivars under irrigation (1997-1999).

	HLM	TKM	SKCS-G	SKCS-DIA	VK	SKCS-HI	FABS	BFLY	FLY
Cultivar	(Kg/hl)	(g)	(mg)	(mm)	(%)		(%)	(%)	(%)
Bull Hill	78.98	42.34	41.11	2.81	74.27	62.85	62.81	20.92	76.53
Prieska	79.56	41.86	40.90	2.78	79.56	68.25	62.05	20.65	76.00
Hopetown	78.05	38.32	37.73	2.61	79.40	63.65	63.47	21.74	75.62
Douglas	79.56	40.08	38.91	2.65	83.09	66.66	63.37	20.08	76.20
Loskop	77.05	37.16	36.63	2.57	69.24	64.51	59.12	21.55	76.48
CV% [@]	1.77	5.44	5.40	4.96	9.34	5.54	1.87	4.38	1.05
Means*	78.64	39.95	39.06	2.68	77.11	65.18	62.16	20.99	76.16
LSD [#]	0.69	1.08	1.05	0.07	3.57	1.79	0.58	0.46	0.40

*Means = Means represents the averages for 3 replicates, 5 environments and 3 years combined

LSD = Least significant difference at $p < 0.05$

@ CV% = Coefficient of variance

HLM = hectolitre mass, TKM = thousand kernel mass VK = Vitreous kernel, SKCS-G = SKCS weight, SKCS-DIA = SKCS diameter, SKCS-HI = SKCS hardness index, FABS = Farinograph water absorption, BFLY = break flour yield and FLY = flour yield.

Peterson *et al.* (1997) reported that hours of high temperature stress (higher than 32°C) during the grain filling were associated with loaf volume and SDS sedimentation volume, although in a curvilinear fashion. Increasing temperature stress initially had a positive influence on loaf volume and protein quality, however when temperature stress exceeded 90 hours there was a strong negative influence on baking quality. Randall and Moss (1990), also found in greenhouse trials that dough strength increased with daily temperatures up to 30°C and tended to decrease at higher temperatures. This phenomenon is being clearly reflected by the higher MDT and SDSS values generated at Loskop (Table 3.7). Significant inferior average values for AS, ASTAB, AD and P/L regarding Bull Hill, Hopetown and Prieska indicate that the dough generated showed lower elastic properties and gluten strength. When protein content was taken into consideration regarding the evaluation of bread volume, Bull Hill, Hopetown and Loskop produced significant lower bread loaf volumes (LFV-12).

Table 3.7. Environment means for baking characteristics of spring wheat cultivars under irrigation (1997-1999).

	FLN	GPC-Leco	FPC-Leco	WGC-12	SDSS	MDT	AS	AD	ASTAB	P/L	LFV	LFV-12
Cultivar	(s)	(%)	(%)	(g)	(ml)	(min)	(cm ²)	(mm)	(mm)		(cm ³)	(cm ³)
Bull Hill	324.51	12.64	11.77	33.20	72.89	2.44	34.60	120.70	64.53	0.52	934.89	925.73
Prieska	311.02	12.76	11.69	33.60	72.56	2.55	33.18	119.20	67.96	0.55	941.44	953.89
Hopetown	325.00	13.06	12.32	34.49	75.19	2.55	30.40	129.93	59.69	0.53	1041.56	962.11
Douglas	321.62	12.72	12.04	33.29	73.69	2.45	47.62	154.67	74.16	0.63	941.18	936.96
Loskop	319.24	12.33	11.41	31.43	79.82	3.64	42.51	140.76	74.00	0.54	904.11	923.22
CV% [@]	7.38	4.59	5.80	6.28	5.77	11.01	13.08	11.25	10.05	19.28	7.01	4.01
Means*	320.28	12.70	11.83	33.20	74.82	2.73	37.66	132.92	68.07	0.55	952.64	940.38
LSD [#]	11.71	0.29	0.34	1.03	2.14	0.15	2.44	7.42	3.39	0.05	33.10	18.68

*Means = Means represents the averages for 3 replicates, 5 environments and 3 years combined

LSD = Least significant difference at $p < 0.01$

@ CV% = Coefficient of variance

FLN = falling number, GPC-LECO = grain protein content determined by the Leco, FPC-LECO = flour protein content determined by the Leco, WGC-12% = Wet gluten content at 12% protein content, SDSS = SDS-sedimentation value, MDT = mixograph development time, AS = alveograph strength, AD = alveograph distensibility, ASTAB = alveograph stability, P/L = alveograph P/L index LFV = loaf volume and LFV-12% = loaf volume standardized at 12% protein content.

3.4.3 Seasonal comparisons

The milling and baking characteristics for each of the years included in this study are presented in Table 3.8 and Table 3.9 respectively. Significant differences can be seen between the years regarding milling and baking characteristics.

The occurrence of heavy showers at a very late stage during the 1998 growth season influenced test weight (HLM) negatively as demonstrated in Table 3.8. The lower yield realized during the 1997 season due to somewhat unfavourable kernel filling conditions increased protein content and wheat hardness. As already mentioned, Manley *et al.* (2001) found that hardness had a positive linear relationship with protein content and a negative linear relationship with moisture content within certain localities and cultivars. A similar trend can thus be observed for the 1997 season regarding its significant higher FPC-Leco value (Table 3.9) and its significant higher SKCS-HI (Table 3.8).

Table 3.8. Year means for milling characteristics of spring wheat cultivars under irrigation (1997-1999).

	HLM	TKM	SKCS-G	SKCS-DIA	VK	SKCS-HI	FABS	BFLY	FLY
Cultivar	(Kg/hl)	(g)	(mg)	(mm)	(%)		(%)	(%)	(%)
1997	78.77	39.75	39.81	2.74	78.51	71.20	62.03	23.18	76.70
1998	78.14	39.61	37.55	2.65	63.64	61.23	61.96	22.48	75.86
1999	79.00	40.50	39.81	2.66	89.19	63.12	62.51	17.31	75.94
CV% [@]	1.77	5.44	5.40	4.96	9.34	5.54	1.87	4.38	1.05
Means*	78.64	39.95	39.06	2.68	77.11	65.18	62.16	20.99	76.16
LSD [#]	0.54	0.84	0.81	0.05	2.76	1.39	0.45	0.35	0.31

*Means = Means represents the averages for 3 replicates, 5 environments and 3 years combined

LSD = Least significant difference at p<0.05

@CV% = Coefficient of variance

HLM = hectolitre mass, TKM = thousand kernel mass VK = Vitreous kernel, SKCS-G = SKCS weight, SKCS-DIA = SKCS diameter, SKCS-HI = SKCS hardness index, FABS = Farinograph water absorption, BFLY = break flour yield and FLY = flour yield.

The late showers during the 1998 season caused a significant drop in falling number (FLN) values (Table 3.9) although not too much problematic.

The expected variance components for the different quality characteristics are shown in Table 3.10 and Table 3.11, while the proportional contribution of each variance component in relation to the rest of the variance components can be seen in Table 3.12 and Table 3.13.

Table 3.9. Year means for baking characteristics of spring wheat cultivars under irrigation (1997-1999).

	FLN	GPC-Leco	FPC-Leco	WGC-12	SDSS	MDT	AS	AD	ASTAB	P/L	LFV	LFV-12
Cultivar	(s)	(%)	(%)	(g)	(ml)	(min)	(cm ²)	(mm)	(mm)		(cm ³)	(cm ³)
1997	290.29	12.93	12.37	33.28	60.20	2.77	40.99	134.33	71.48	0.62	1017.51	952.33
1998	271.27	12.34	11.42	32.61	81.95	2.49	35.84	128.69	68.33	0.46	946.20	964.53
1999	399.28	12.84	11.75	33.72	82.33	2.92	36.16	135.75	64.39	0.58	894.20	904.28
CV% [@]	7.38	4.59	5.80	6.28	5.77	11.01	13.08	11.25	10.05	19.28	7.01	4.01
Means*	320.28	12.70	11.83	33.20	74.82	2.73	37.66	132.92	68.07	0.55	952.64	940.38
LSD [#]	9.07	0.22	0.26	0.80	1.66	0.11	1.89	5.75	2.63	0.04	25.63	14.46

*Means = Means represents the averages for 3 replicates, 5 environments and 3 years combined

LSD = Least significant difference at p<0.01

@CV% = Coefficient of variance

FLN = falling number, GPC-LECO = grain protein content determined by the Leco, FPC-LECO = flour protein content determined by the Leco, WGC-12% = Wet gluten content at 12% protein content, SDSS = SDS-sedimentation value, MDT = mixograph development time, AS = alveograph strength, AD = alveograph distensibility, ASTAB = alveograph stability, P/L = alveograph P/L index LFV = loaf volume and LFV-12% = loaf volume standardized at 12% protein content.

3.4.4 Variance components

3.4.4.1 Genotypic effect (σ^2_g)

The average mean squares for genotypes measure the phenotypic variation between genotypes. The variance components for genotypes measure the portion of phenotypic variation explained by the genetic differences. The latter is also an indication of the repeatability of a characteristic (Falconer, 1964).

The remaining variance components, represent the non-heritable sources of variance like genotype x year, genotype x locality, genotype x locality x year interactions and the environment component.

3.4.4.1.1 Milling characteristics

All the milling characteristics were highly significant regarding their genotypic variance component, which indicates that significant differences exist between genotypes regarding their genetic contribution for each characteristic (Table 3.10). According to the results tabulated in Table 3.10, VK showed a very low genotypic variance component value in comparison with the total variance observed. TKM and the SKSC-G values also showed relative low genotypic variance component values when compared to their total variance values. This implies that only a small portion of the phenotypic differences between genotypes is of genetic origin.

Table 3.12 exhibits the proportional contribution from the genotypic variance component in comparison to the total variance for a specific characteristic. In the case of VK, the genotypic variance component was only 1.07 percent of the total variance, while in the case of TKM and SKSC-G value, their genotypic variance contribution were 8.57 and 6.09 percent respectively. Regarding VK almost 98 percent of the variance between genotypes were explained by non-genetic sources of variation. Thus the genotype x environment interaction component and large environmental variability responsible for the low observed genotypic variance component values regarding VK, SKCS-G and TKM, makes it very difficult to select effectively for these characteristics.

The above-mentioned results indicate that a low repeatability exist for VK, SKCS-G and TKM for spring wheat under irrigation. This effect is more prominent especially when data is being gathered over years and localities. In such circumstances it will be impossible to measure a line's genotypic contribution according to its phenotypic value, due to the fact that its genotypic value cannot be determined accurately enough. Van Deventer (1985) reported genotypic variance values generated under dryland conditions, which is fairly comparable with the values regarding the milling characteristics generated in this study, except for the genotypic variance value of TKM (55.42%), which was much higher than the 8.57% value observed in this study. Lukow and McVetty (1991) also showed genotypic variation values in the order of 52.8% for TKM. However, the FLY value of 85.90% reported by Lukow and McVetty (1991) was much higher than observed by Van Deventer (1985) namely 26.78%, the latter estimation is also comparable to the value of 24.25% observed in this study.

The genetic variance components for HLM, SKCS-DIA, SKCS-HI, FABS, BFLY and FLY explained 16.22%, 30.36%, 24.53%, 43.15%, 54.25% and 24.25% of the total variance (Table 3.12). This implies that the phenotypic value for a line will be an accurate estimator of its genotypic value. Therefore, the phenotypic value of such characteristics can be used in order to select between lines. Lukow and McVetty (1991) showed genotypic variance value for FABS in the order of 90%.

Variation in hardness of wheat lines grown under widely different environmental conditions was found to be affected mainly by genotype (Pomerantz and Mattern, 1988) and to a small extend by environmental and growth conditions (Pomeranz *et al.* 1985; Fowler and De la Roche, 1975b). When taking the large genotypic contribution of all the characteristics involved in hardness (FABS, BFLY, SKCS-HI and FLY) into consideration the above mentioned statement is being clearly verified (Table 3.12).

3.4.4.1.2 *Baking characteristics*

As in the case of the milling characteristics again all the baking characteristics were also highly significant regarding their genotypic variance component (Table 3.11). According to the results tabulated in Table 3.11, FLN, GPC-Leco, FPC-Leco, LFV and LFV-12 showed very low genotypic variance component values in comparison the total variance

observed. All these characteristics also showed small proportional contributions for their genotypic variance components in comparison to the total variance for a specific character (Table 3.13). Again, this implies that only a small portion of the phenotypic differences between genotypes is of genetic origin. In Table 3.13, all the characteristics related to gluten strength and the elastic properties (SDSS, WGC-12, MDT, AS, AD and P/L) of the dough displayed genotypic variance values above 30% and even as high as 57.65% (MDT). These traits can be efficiently used in order to improve dough-handling properties in a given progeny. Van Deventer (1985) reported a genotypic variance value for MDT of 50.83%; he also reported low genotypic variance values for grain protein content namely 2.17%. Pomeranz and Mattern (1988) also reported a low genotypic variance value for grain protein content (0.18%). Lukow and McVetty (1991) reported genetic variance components for grain protein content (87.4%), MDT (76.1%), FLN (73.1%) and SDSS (75.4%). In contrast to the results from Lukow and McVetty (1991), the values for FLN (2.17%) and grain protein content (10.50%) were much lower in our results which indicates that the genotype environment interaction plays a larger role in the expression of these traits under South African conditions. Van Lill *et al.* (1993b) reported genotypic variance values for LFV in the range of 45.54%.

3.4.4.2 *Genotype x location interaction (σ^2_{gl})*

Because a negative expected variance does not have a significant impact, a zero replaced the values of the relevant characteristics in Tables 10 and 11. Non-significant mean sum of square values were observed for TKM, SKCS-G and SKCS-DIA as well as FPC-Leco, WGC-12 and SDSS regarding the milling and baking characteristics respectively (Table 3.10 and Table 3.11). Although the rest of the traits for both milling and baking characteristics showed significant mean sum of square values, the impact of these variance components were minor for spring wheat production under irrigation. Thus, the results in Table 3.12 (for milling characteristics) and Table 3.13 (for baking characteristics) showed that the genotype x location interaction is not the main reason why some of the variance components expressed for genotypes are so low. Only in the case of vitreous kernels (VK), the genotype x location interaction was larger than that of the genotypes (Table 3.12). The magnitude for the observed genotype x location variance for VK is about nine times bigger than the variance component for genotypes. Thus, the magnitude of the genotype x location interaction for VK is partly responsible for

the low genotype variance and it is the only characteristics where multiple environment testing is needed to accurately assess genetic potential of wheat lines. These results confirm those of Peterson *et al.* (1986), who noted that although cultivar by environment interactions were statistically significant, the effects of cultivar flour and dough properties were far greater than the interaction effects. Baenziger *et al.* (1985) reached similar conclusions for soft red winter wheat quality parameters.

3.4.4.3 Genotype x year interaction (σ^2_{gy})

Although the mean sum of square values were significant for all the milling and baking characteristics, except Alveograph distensibility (AD) their magnitude was small, thus it can be concluded that genotype x year interaction was not the main cause for the low genotype variation observed in some instances (Table 3.12 and Table 3.13). However when compared to the genotype x location interaction component the influence of genotype x year interaction component regarding the total variance was, for most of the milling and baking characteristics, larger. Only for two characteristics namely HLM and FABS the genotype x year interaction values were lower than that of the genotype x location values (Table 3.12).

From the above mentioned data it is evident that breeders in South Africa have less control over years than localities in order to make improvements regarding milling and baking characteristics.

The genotype x year interaction component for milling characteristics that normally influence kernel size (namely TKM and SKCS-G) could partly be responsible for the low corresponding genotype variance components seen in Table 3.12. The genotype x year interaction component for VK (10.70%) also showed a higher contribution to the total variance than the genotype variance component (0.74%). Regarding the baking characteristics FN, GPC-Leco, FPC-Leco and LFV expressed genotype x year interaction variance components larger than the genotype variance component (Table 3.13). It is interesting to note that for LFV-12 where the protein content had been standardized at 12% the effect of genotype x year effect had been reduced from 3.08 (LFV) percent to 0.13 percent (Table 3.13).

3.4.4.4 *Genotype x location x year interaction (σ^2_{gly})*

The results in Table 3.12 showed that the genotype x location x year interaction is significant for all the milling characteristics except SKCS-DIA and VK. Significant differences can be seen in Table 3.13 for the genotype x location x year interaction regarding all the baking characteristics, except for GPC-Leco and WGC-12. The values for genotype x location x year interaction regarding the milling characteristics varied between 3.61% for VK and 29.59% for FLY (Table 3.12). The values for genotype x location x year interaction regarding the baking characteristics varied between 4.90% for GPC-Leco and 36.81% for P/L (Table 3.13). If the genotype x location x year interaction is significant, it means that there is an important differential response to environmental variation which is not displayed by the location and year groupings. A large genotype x location x year interaction value means that factors like temperature, moisture and diseases generate unique conditions to which genotypes react differently. A significant genotype x location x year interaction also shows that stratification of the environment into different sub-zones in order to decrease genotype x environment interaction will not be successful in the irrigation areas.

Large genotype x location x year interaction means indicate that the size of the genotype x location vary from year to year. The superiority of one genotype above another is a function of the genotype x environment interaction for that specific year. In the following year the genotype x location x year interaction may favour a different genotype. The size of the genotype x location x year interaction seems to be the main reason why the ranks for genotypes differ from year to year.

3.5 Conclusions

The best and poorest cultivar in overall milling performance was Kariega and SST 822 respectively, while the best and poorest overall baking performance was displayed by Kariega and SST 876 respectively. From the cultivar comparisons regarding the milling quality, it was clear that the cultivars expressed different kernel hardness values. The genotype's contribution to the expression of flour yield is about 85.90% under Canadian conditions, however in this study it is 24.25%. Canada has to export most of its wheat production annually, therefore only cultivars with exceptional milling and baking qualities are being released. Because, they have hardness classes and make an effort to release cultivars with similar kernel characteristics this could be the reason why the observed genotypic variance value for flour yield is about three times bigger than that in South Africa.

From the data in Table 3.4 it is clear that the local cultivars exhibit different hardness values. In Canada there are two hardness classes available for the same existing variation observed in this study. When hard wheat is not properly conditioned, the flour quality such as the Alveograph distensibility and thus P/L value can be influenced negatively. This can generate unnecessary variation, which in turn degrades good milling attributes of cultivars. Even the experimental evaluation procedure for the Buhler mill extraction does not allow proper conditioning for harder wheats and therefore numerous good quality hard red wheats are not being released due to unnecessary poor alveograph results. Therefore, the processing industry is being prevented from using these genotypes in their mills and bakeries. Manley *et al.* (2001) also showed that distinguishable hardness classes existed for spring wheat cultivars produced in the Western Cape region, while a positive linear relationship with protein content and a negative linear relationship with moisture content was observed. Further on Manley (2000), reported results on a research project that wheat hardness is determined by the strength of the protein-starch bond on the endosperm. Both the Canadian and South African bread wheat samples examined revealed a large range of hardness values and therefore a great difference in endosperm structures. Manley (2000) concluded that the milling and baking industry would benefit from recognizing a variety's hardness level within the bread wheat class and adopting a classification system similar to that of the Canadian system. The fact that the South African grading system does not

accommodate different hardness classes currently cannot be ignored anymore. The single kernel characterization system (SKCS) is a valuable, efficient and quick method for estimation of kernel hardness.

Increased dough strength due to increased temperatures up to 30°C were observed and certain environments generated dough with lower elastic properties as well as gluten strength. All the characteristics related to gluten strength and the elastic properties namely SDS-sedimentation test, wet gluten content standardized at 12% protein, mixograph mixing time, alveograph strength, alveograph distensibility and alveograph P/L ratio displayed genotypic variance values above 30% and even as high as 57.65% for mixograph mixing time. These traits can be efficiently used in order to improve dough-handling properties in a given progeny.

Genotype x location interaction components for most of the milling and baking characteristics were low, thus indicating that the performance of the genotypes stayed the same at each locality. It also implies that there will be no advantage in releasing cultivars for specific localities or areas. From the genotype x year interaction versus genotype x location interaction it is evident that breeders in South Africa have less control over years than localities in order to make improvements regarding milling and baking characteristics for wheat production under irrigation. The low interaction values for the σ^2_{gi} component indicate that the performance among the genotypes stays the same at each locality. The number of localities included for testing could also be lowered without jeopardizing the statistical accuracy. It also indicates that there will be no advantage in releasing cultivars for specific localities or areas.

From the genotype x year interaction for both the milling and baking characteristics it is evident that breeders in South Africa have less control over years than localities in order to make improvements regarding milling and baking characteristics.

The significant genotype x location x year interaction for most milling and baking characteristics suggests that there is an important differential response to environmental variation which is not displayed by the location and year groupings. A large genotype x location x year interaction value means that factors like temperature, moisture and diseases generate unique conditions to which genotypes react differently.

3.6 References

- AACC, 1983. Falling number determination method 56-81B; Experimental milling Buhler method 26-21A; Mixograph method 54-40A; Farinograph method 54-2A using 50g of flour; Alveogram method 54-30A; SDS-sedimentation the method used to determine gluten strength, method 56-70. In *Approved methods*; 8th ed. American Association of Cereal Chemists Inc.; St Paul, MN, USA.
- AACC; 1995. Dumas Leco-FP200 method for protein determination, method 46-30. In *Approved methods*; 8th edn. American Association of Cereal Chemists Inc.; St Paul, MN, USA.
- ABOU-EL-FITTOUGH, H.A., RAWLINGS, J.O. & MILLER, P.A., 1969. Genotype by environment interaction in cotton – their nature and related environmental variables. *Crop. Sci.* 9: 377-381.
- AGROBASE™, 1999. Agronomic Software Inc., 71 Waterloo St. Winnipeg, Manitoba, R3N0S4, Canada.
- ALLARD, R.W. & BRADSHAW, A.D., 1964. Implication of genotype-environment interaction in plant breeding. *Crop. Sci.* 4: 503-508.
- BAENZIGER, P.S., CLEMENTS, R.L., McINTOSH, M.L., YAMAZAKI, W.T., STARLING, T.M., SAMMONS, D.J. & JOHNSON, J.W., 1985. Effect of cultivar, environment, and their interaction and stability analyses on milling and baking quality of soft red winter wheat. *Crop. Sci.* 25: 5-8.
- BAKER, S., HERRMAN, J. & LOUGHIN, T., 1999. Segregating hard red winter wheat into dough factor groups using single kernel measurements and whole grain protein analysis. *Cereal Chem.* 76(6): 884-889.
- BARRTLETT, M.S., 1947. The use of transformations. *Biometrics* 2: 39-52.
- BUSCH, R.H., SHUEY, W.C. AND FROHBERG, R.C., 1969. Response of hard red spring wheat (*Triticum aestivum* L.) to environments in relation to six quality characteristics. *Crop. Sci.* 9: 813-817.
- CLARKE, J.M., CAMPBELL, C.A., CUTFORTH, H.W., DEPAUW, R.M. & WINKELMAN, E., 1990. Nitrogen and phosphorous uptake, translocation, and utilization efficiency of wheat in relation to environment and cultivar yield and protein levels. *Can. J. Plant Sci.* 70: 965-977.
- COMSTOCK, R.E. & MOLL, R.H., 1963. Genotype-environment interactions: 164-196. In: *Statistical genetics and plant breeding*. *Nat. Acad. Sci. – Nat. Res. Council*. Publ. Number 982. Washington D.C.
- COOPER, M. & DE LACY, I H., 1994. Relationships among analytical methods used to study genotypic variation and genotype by environment interaction in plant breeding multi-environments experiments. *Theor. Appl. Genet.* 88: 561-572.
- COX, T.S., SHOGREN, M.D., SEARS, R.G. MARTIN, T.J. & BOLTE, L.C., 1989. Genetic improvement in milling and baking quality of red hard winter wheat cultivars, 1919-1988. *Crop. Sci.* 29: 626-631.
- CROSSA, M.V.J., SAYRE, K., REYNOLDS, M. RAMIREZ, M.E. & TALBOT, M., 1998. Interpreting genotype x environment interaction in wheat by Partial Least Square Regression. *Crop. Sci.* 38: 679-689.
- CROSSA, M.V.J., VAN EEUWIJK, F.A., RAMIREZ, M.E. & SAYRE, K., 1999. Using Partial Least Square Regression, Factorial Regression, and AMMI models for interpreting genotype x environment interaction. *Crop. Sci.* 39: 955-967.

- DE VILLIERS, O.T. & LAUBSCHER, E.W., 1995. Use of the SDSS test to predict the protein content and bread volume of wheat cultivars. *S. Afr. Tydskr. Plant Grond* 12(4): 140-142.
- EGGITT, P.W.R. & HARTLEY, A.W., 1975. Extraction rates – milling processing implications. In: Spicer (Ed.) *Bread. Social, Nutritional and agricultural aspects of wheaten bread*. Applied Science Publishers, London, pp. 219-234.
- FALCONER, D.S., 1964. *Introduction to quantitative genetics*. Oliver and Boyd, Edinburgh, England.
- FARIDI, H. & FINLEY, J.W., 1989. Improved wheat for baking. *Crit. Rev. Food Sci. Nutr.* 28: 175-209.
- FINNEY, K.F., 1984. An optimized straight-dough bread making method after 44 years. *Cer. Chem.* 61: 20-27.
- FINNEY, K.F., YAMAZAKI, W.T., YOUNGS, V.L. & RUBENTHALER, G.L., 1987a. Quality of hard, soft and durum wheats. In Heyne EG ed. *Wheat and wheat improvement*, 2nd ed. ASA-CSSA Publishers, Madison, 677-748.
- FINNEY, P.L., GAINES, C.S. & ANDREWS, L.C., 1987b. Wheat quality: A quality assessor's view. *Cereal Foods World* 32: 313.
- FISCHER, R.A. & MACKENZIE, W.A., 1923. Studies in crop variation. *J. Agric. Sci.* 13: 311-320.
- FOWLER, D.B. & DE LA ROCHE, I.A., 1975a. Wheat quality evaluation. 2. Relationships among prediction tests. *Can. J. Plant Sci.* 55: 251-262.
- FOWLER, D.B. & DE LA ROCHE, I.A., 1975b. Wheat quality evaluation. 3. Influence of genotype and environment. *Can. J. Plant Sci.* 55: 263-269.
- FREEMAN, G.H., 1973. Statistical methods for the analysis of genotype-environment interactions. *Heredity* 31: 339-354.
- GAINES, C.S., 1991. Associations among quality attributes of red and white soft wheat cultivars across locations and crop years. *Cereal. Chem.* 68(1): 56-59.
- GAINES, S.G., FINNEY, P.L. & RUBENTHALER, G., 1996. Milling and baking of some wheats developed for Eastern or Northwestern regions of the United States and grown at both locations. *Cereal. Chem.* 73(5): 521-525.
- GRAYBOSCH, R.A., PETERSON, C.J., SHELTON, D.R. & BAENZIGER, P.S., 1996. Genotypic and environmental modification of wheat flour protein composition in relation to end-use quality. *Crop. Sci.* 36: 296-300.
- GWIRTZ, J.A., EUSTACE, W.D. & CURRAN, S. P., 1996. Effect of kernel size and test weight on the Kansas State pilot mill. *Assoc. Oper. Miller Tech. Bull.* June: 6731-6741.
- HOSENEY, C.R., 1987. Wheat hardness. *Cereal Foods World* 32(4): 320-322.
- JENNER, C.F., 1991. Effects of exposure of wheat ears to high temperature on dry matter accumulation and carbohydrate metabolism in the grain of two cultivars. II. Carry-over effects. *Aust J. Plant Physiol.* 18: 179-190.
- JÁNOS, M., 1998. Inheritance of SDS SDS sedimentation volume of flour in crosses of winter wheat (*Triticum aestivum* L.). *Cereal Research Comm.* 26(2): 203-210.
- KOEKEMOER, F.P., 1997. Inheritance of protein related characteristics in spring wheat. MSc. Thesis, University of the Orange Free State.
- LIANG, G.H.L., HEYNE, E.G. & WALTER, T.L., 1966. Estimates of variety x environment interaction in yield test of three small grains and their significance on the breeding programmes. *Crop Sci.* 6: 136-138.
- LUKOW, O.M. & McVETTY, P.B.E., 1991. Effect of cultivar and environment on quality characteristics of spring wheat. *Cereal. Chem.* 68(6): 597-601.
- MacRITCHIE, F. & KASARDA, D.D., 1991. Characterization of wheat protein fractions differing in contributions to bread-making quality. *Cereal Chem.* 68: 122-130.

- MARSHALL, D.R., MARES, D.J., MOSS, H.J. & ELLISON, F.W., 1986. Effects of grain shape and size on milling yields in wheat. II Experimental studies. *Aust J. Agric. Res.* 35: 619-630.
- MANLEY, M., 2000. A comparative scanning electron microscopic study of a number of South African and Canadian wheats of different hardnesses. Report to the Wheat Research Trust, University of Stellenbosch.
- MANLEY, M., VAN ZYL, L. & OSBORNE, B.G., 2001. Deriving grain hardness calibrations for whole ground wheat samples by means of particle size index (PSI) method and fourier transform near infrared (FT-NIR) spectroscopy. *S. Afr. J. Plant Soil* 18(2): 69-74.
- McDONALD, A.A., 1994. Classification and grading. In: BUSHUK, W. & RASPER, V.F. (Eds). *Wheat production: Properties and quality*. Chapman & Hill, London, pp 37-46.
- McGUIRE, C.F. & McNEAL, F.H., 1974. Quality response of 10 hard red spring wheat cultivars to 25 environments. *Crop. Sci.* 14: 175-180.
- MILLER, P.A., WILLIAMS, J.C. & ROBINSON, H.F., 1959. Variety x environment interaction in cotton variety tests and their implications on testing methods. *Agron. J.* 51: 132-134.
- MLADENOV, N., PRZULJI, N., HRISTOV, N., DJURIC, V. & MILOVANOVIC, M., 2001. Cultivar-by-environment interactions for wheat quality traits in semi-arid conditions. *Cereal Chem.* 78(3): 363-367.
- NEL, M.M., AGENBAG, G.A. & PURCHASE, J.L., 1998. Sources of variation for yield, protein content and hectoliter mass of spring wheat (*Triticum aestivum* L.) cultivars of the Western and Southern Cape. *S. Afr. Tydskr. Plant en Grond* 15(2): 72-79.
- PELTONEN-SAINIO, P. & PELTONEN, J., 1993. Stability of quality traits in spring cereals cultivated under the growing conditions of Southern Finland. *Acta. Scand., Sect. B., Soil and Plant Sci.* 43: 45-52.
- PETERSON, C.J., JOHNSON, V.A. & MATTER, P.J., 1986. Influence of cultivar and environment on mineral and protein concentrations of wheat flour, bran and grain. *Cereal Chem.* 63: 183-186.
- PETERSON, C.J., GRAYBOCH, R.A., BAENZIGER, P.S. & GROMBACHER, A.W., 1992. Genotype and environment effects on quality characteristics of hard red winter wheat. *Crop. Sci.* 32: 98-103.
- PETERSON, C.J., GRAYBOCH, R.A., SHELTON, D.R. & BAENZIGER, P.S., 1997. Baking quality of hard winter wheat: response of cultivars to environment in the Great Plains. *Wheat: prospects for global improvement. Proceedings of the 5th International Wheat Conference, Ankara, Turkey, 10-14 June 1996*. Kluwer Academic Publishers, Dordrecht, Netherlands: 223-228
- POMERANZ, Y. & MATTERN, P.J., 1988. Genotype and environment interaction effects on hardness estimates in winter wheat. *Cereal Foods World* 33(4): 371-374.
- POMERANZ, Y., PETERSON, C.J. & MATTERN, P.J., 1985. Hardness of winter wheats grown under widely different climatic conditions. *Cereal Chem.* 62: 463.
- POSNER, E.S., 1988. Back to the issue of wheat grading. *Cereal Foods World* 33: 362-365.
- RANDALL, P.J. & MOSS, H.J., 1990. Some effects of temperature regime during grain filling on wheat quality. *Aust. J. Agric. Res.* 41: 603-617.
- SALEM, A., PILAND, S., 1995. Flour quality as viewed by millers and bakers. *Am. Inst. Baking Tech. Bull.* 17(10): 9-13.
- SALINGER, M.J., JAMIESON, P.D. & JOHNSTONE, J.V., 1995. Climate variability and wheat baking quality. *New Zealand J. of Crp. & Hortillogical Sci.* 23(3): 289-298.
- SHOGREN, M.D. & FINNEY, K.F., 1984. Bread-making test for 10 grams of flour. *Cereal Chem.* 61: 418-423.

- SHUEY, W.C. & GILLES, K.A., 1972. Milling evaluation of hard red spring wheats. Part IV. Relation of calculated milling values to milling result. *Northwest. Miller* 279: 14, 15, 26, 27.
- SPRAGUE, G.F. & FEDERER, W.T., 1951. A comparison of variance components in corn yield trials. *Agron. J.* 3: 35-541.
- TERMAN, G.L., 1979. Yields and protein content of wheat grain as effected by cultivar, N, and environmental growth factors. *Agron. J.* 71: 437-440.
- VAN ARK, H., 1995. Introduction to linear correlation and regression. Agricultural Research Council: Agrimetrics Institute.
- VAN DEVENTER, C.S., 1985. Die bepaling van genotipe x omgewinginteraksie by winterkoring. PhD Thesis, University of the Orange Free State.
- VAN LILL, D., PURCHASE, J.L., DE VILLERS, O.T. & SMITH, M.F., 1993a. Effect of cropping systems on five South African wheat cultivars. I. Yield and protein content. *Die SA Tydskrif vir Voedselwetenskap en Voeding* 5(1): 18-21.
- VAN LILL, D., PURCHASE, J.L., DE VILLERS, O.T. & SMITH, M.F., 1993b. Effect of cropping systems on five South African wheat cultivars. II. Bread-making quality and quantitative protein composition. *Die SA Tydskrif vir Voedselwetenskap en Voeding* 5(1): 22-26.
- VAN LILL, D. & SMITH, M., 1997. A quality assurance strategy for wheat (*Triticum aestivum* L.) where growth environment predominates. *S. J. Plant Soil* 14(4): 183-191.
- WEBER, W.E. & WESTERMANN, T., 1994. Prediction of yield for specific locations in German winter-wheat trials. *Plant Breeding* 113: 99-105.

Table 3.10. Expected variance components for the milling characteristics regarding spring wheat cultivars under irrigation

		HLM	TKM	SKCS-G	SKCS-DIA	VK	SKCS-HI	FABS	BFLY	FLY
Source	DF	MS	MS	MS	MS	MS	MS	MS	MS	MS
Replicate	2	0.80	3.10	2.20	0.02	141.73**	16.57	2.86*	2.66**	0.43
Genotype (σ^2_g)	4	29.38**	51.33**	52.41**	0.57**	259.49**	521.80**	99.13**	121.07**	29.10**
Year	2	14.84**	17.21**	128.19**	0.16**	12346.41**	2100.81**	6.67**	771.58**	16.09**
Locality	4	52.78**	222.66**	171.60**	0.49**	1315.39**	223.04**	144.98**	20.50**	6.28**
Genotype x years (σ^2_{gy})	8	4.76**	24.97**	32.47**	0.07**	169.60**	120.38**	3.36**	5.12**	6.97**
Genotype x localities (σ^2_{gl})	16	4.70**	4.93	7.09	0.02	115.99*	44.32**	5.92**	4.07**	2.22**
Year x locality	8	81.60**	130.31**	121.54**	0.31**	2019.35**	998.37**	10.91**	32.71**	8.93**
Genotype x localities x years (σ^2_{gly})	32	3.79**	8.78*	9.69*	0.03	59.31	31.73**	5.49**	4.81**	2.46**
Error (σ^2_e)	148	1.94	4.73	4.46	0.02	51.86	13.04	1.36	0.85	0.64
Total	224									
CV%		1.77	5.44	5.40	4.96	4.96	5.54	1.87	4.38	1.05
R ²		0.81	0.80	0.81	0.77	0.77	0.90	0.87	0.95	0.81
S.E.D.		0.29	0.46	0.45	0.03	0.03	0.76	0.25	0.19	0.17

* = Smallest significant difference at the p<0.05

** = Smallest significant difference at the p<0.01

MS = Mean squares

CV% = Coefficient of variance

R² = Coefficient of determination

S.E.D. = Standard error of difference

Table 3.11. Expected variance components for the baking characteristics regarding spring wheat cultivars under irrigation

Source	DF	FLN MS	GPC-Leco MS	FPC-Leco MS	WGC-12 MS	SDSS MS	MDT MS	AS MS	AD MS	ASTAB MS	P/L MS	LFV MS	LFV-12 MS
Replicate	2	211.21	0.28	0.44	2.78	12.65	0.03	67.79	95.36	85.96	0.01	3518.14	3813.67**
Genotype (σ^2_g)	4	2686.14**	3.80**	2.08**	132.81**	1152.96**	13.70**	1580.19**	7171.92**	3676.48**	0.60**	31201.34**	12068.24**
Year	2	357844.01**	7.47**	17.25**	23.67**	12036.89**	3.53**	623.59**	1044.46**	947.41**	0.56**	287414.68**	76105.34**
Locality	4	1448.56**	3.15**	5.41**	55.94**	396.97**	11.95**	2305.58**	10087.65**	1743.33**	0.09**	121869.61**	13222.94**
Genotype x years (σ^2_{gy})	8	2227.31**	1.35**	1.69**	12.61**	95.43**	0.61**	132.75**	340.20	251.741**	0.07**	20944.97**	3757.87**
Genotype x localities (σ^2_{gl})	16	1172.68*	0.61*	0.78	5.35	28.17	0.47**	118.59**	477.30*	237.60**	0.06**	17135.55**	5850.71**
Year x locality	8	836.82	3.71**	6.43**	27.44**	216.70**	1.96**	524.81**	9470.87**	783.66**	0.26**	113814.49**	10981.34**
Genotype x localities x years (σ^2_{gly})	32	1397.06**	0.41	0.70*	6.06	45.11**	0.42**	44.84*	541.30**	172.16**	0.05**	9018.62*	3711.69**
Error (σ^2_e)	148	558.02	0.34	0.34	4.35	18.62	0.09	24.26	223.79	46.80	0.01	4457.18	1418.66
Total	224												
CV%		7.38	7.38	5.80	6.28	5.77	11.01	13.08	11.25	10.05	19.28	7.01	4.01
R ²		0.91	0.91	0.70	0.69	0.93	0.92	0.88	0.84	0.86	0.85	0.81	0.74
S.E.D.		4.98	0.13	0.14	0.44	0.91	0.06	1.04	3.15	1.44	0.03	14.07	7.94

* = Smallest significant difference at the $p < 0.05$

** = Smallest significant difference at the $p < 0.01$

MS = Mean squares

CV% = Coefficient of variance

R² = Coefficient of determination

S.E.D. = Standard error of difference

CHAPTER 4

Optimal number of locations, years and replicates needed to screen South African spring wheat cultivars for milling and baking quality characteristics.

4.1 Abstract

Five spring wheat cultivars (*Triticum aestivum* L.) were grown in five environments from 1997 through 1999. The cultivars used in this study displayed a broad range in milling and baking characteristics. From the study it was clear that there is not a large improvement in relative efficiency when a second and third replicate is used in the determination of the optimal amount of localities in order to distinguish between genotypes. A similar pattern is also observed regarding the amount of years needed, almost no differences were observed if either three, four or even five year's quality data were taken into account. It has been proven that for both the milling and baking characteristics five trials are needed over a two-year test period, because first, second and third year advanced lines are planted in the same trial. It will be difficult to vary the amount of localities for the different levels of testing. This will shorten the current testing procedure with one year, in order to release new spring wheat cultivars under irrigation.

4.2 Introduction

Currently no proper statistical technique had been used in South Africa in order to determine the optimal number of locality, year and replicate indicators needed to evaluate advanced breeding material for its milling and baking characteristics. The current guideline set by the Wheat Technical Committee of the South African Wheat Research Trust is a test period of three years and five localities per annum. After two years of testing a line will be provisionally classified and after three years of testing a line will be classified for final release. Thus a total of 15 localities are being evaluated during the test period before a cultivar will be released according to the phenotypic expression of its milling and baking quality. The amount of replicates needed for evaluation is

limited to only one. The cost associated with the evaluation of new releases is directly linked to the amount of replicates, localities and years needed to meet the requirements set by the Wheat Technical Committee. Currently the total cost to do a complete quality analysis for one replicate per given locality is extremely expensive.

Researchers developed various statistical procedures from which the amount of replicates, localities and years of testing could be determined from the variance components (Sprague and Federer, 1951). The variance component method provides plant breeders with the means to calculate the theoretical variance for cultivar averages regarding different combinations for localities and years. The optimal allocation for a specific characteristic can be read directly from the graphical illustration (Figure 4.1). The procedure to determine the theoretical variance components from a cultivar's average was described in Chapter 3, paragraph 3.3.3. Jones *et al.* (1960) used the variance component method to prove that two years at five localities are sufficient to distinguish between tobacco cultivars regarding their yield potential in North Carolina. Their results showed that a test period of two years and five localities is sufficient to distinguish between tobacco genotypes in North Carolina. Miller *et al.* (1959) used a similar method to describe the influence that genotype x environment interaction has on the test procedures being used in cotton breeding.

The main aim of this study is to determine the optimal locality, year, and replication combinations regarding the screening of spring wheat genotypes for milling and baking quality under irrigation. Such information makes the total cost estimation to conduct the trials possible in relation to the efficiency of the statistical analysis process.

4.3 Materials and methods

Evaluation of wheat quality involves the measurement of a large number of characteristics. Since many of the tests for quality evaluation are time-consuming and expensive, they have traditionally been performed on a limited number of samples. The number of samples to be evaluated may be reduced by combining samples over replicates, locations or years. However, this procedure reduces the precision with which quality characteristics are estimated and may lead to erroneous conclusions if large

cultivar by environment interactions does occur (Lukow and McVetty, 1991). Therefore, in order to improve the precision of the analysis the amount of cultivars, localities, replications and years were maintained throughout the study.

4.3.1 Field trials

Five genetically diverse spring wheat cultivars namely, Karioga, Marico, SST825, SST822 and SST876 were the genotypes common in all three years of testing. Small Grain Institute (Agricultural Research Institute) released Karioga and Marico, while Monsanto owns the Plant Breeders Rights on the latter three cultivars. The term "spring wheat" implies that such cultivars do not need a certain degree of vernalization requirements in order to reach full maturity. The genotypes, year of release, status and origin for the genotypes used in this study are indicated in Table 3.1.

Most of the cultivars are semi-dwarf cultivars except for SST822, which is a short growth period double dwarf. Double dwarf wheat cultivars tend to have lower yield potential than semi dwarf wheat cultivars in South Africa. SST876 possesses the solid stem characteristic originating from *Aegilops ventricosa*. The solid stem characteristic improved lodging tolerance dramatically, with resultant higher grain yield. Karioga is the biological quality standard being used by the South African Wheat Technical Committee as a reference cultivar. This implies that all new lines are compared against Karioga for possible release as new cultivars in the irrigation areas. Karioga and Marico are long growth period cultivars while SST 825 and SST 876 are classified as medium growth period cultivars. Seed for the given quality analysis, were obtained from trials conducted in the irrigation areas by the National Cultivar Evaluation Department of Small Grain Institute during 1997,1998 and 1999.

Table 4.1. Genotypes and their pedigrees, year of release, status and origin.

Genotype		Year	Status	Origin
Marico	Broadbill's"	1992	Cultivar	CIMMYT, Mexico
Kariega	SST44//K45400/Sapsucker's"	1993	Cultivar	SGI, RSA
SST822	Not available	1992	Cultivar	Monsanto, RSA
SST825	Tui's"	1992	Cultivar	CIMMYT, Mexico
SST876	SST57/Adam Tas//SST 825	1997	Cultivar	Monsanto, RSA

Wheat production under irrigation in the summer rainfall region entails the production of spring wheat types, which are planted in the fall and winter. There are five main irrigation areas, namely the cooler central irrigation areas (situated next to the Orange, Vaal, Sand and Vet rivers), the warmer northern irrigation areas (along the Eliphants and Crocodile rivers, the Loskop dam irrigation area is also included here), Kwazulu-Natal, Eastern Free State and the Eastern Cape (Cradock). The warmer northern irrigation regions have a lower yield potential compared to that of the cooler central irrigation areas, and this is mainly due to the warmer winter temperatures and therefore a shorter growing season. This leads to a higher growth and development rate, weaker tillering capacity and subsequently lower yields. The irrigation areas represent high yielding environments, which rely heavily on intensive cropping systems.

The region, location, coordinates and number of trials from 1997 until 1999 included for quality analysis can be seen in Table 3.2. Trials were conducted at experimental stations or farms of collaborators where the soil and climate are representative of a specific area.

Table 4.2. Regions with representative localities and the number of trials from 1997 until 1999.

Region	Locality	1997	1998	1999
Warmer areas	Loskop	1	1	1
Cooler areas	Bull Hill	1	1	1
	Prieska	1	1	1
	Hopetown	1	1	1
	Douglas	1	1	1

It is very important to bring cultivar performance in line with the weather conditions that prevailed during the growth cycle. For the 1997 season normal temperatures occurred during the period up to the middle of June in all the regions. Temperatures above average occurred during the second half of winter in all five regions. Above average temperatures were measured during the grain filling period from August through to October. This had a negative influence on the yield and hectolitre mass levels.

During the 1998 season normal to above average temperatures occurred in all the irrigation areas during the second part of the winter months up to the end of August. Below average temperatures were measured during September and October which had a positive influence on grain filling period resulting in higher yields and hectolitre masses. In some of the areas heavy rain showers were observed which lowered the hectolitre masses slightly.

Regarding the 1999 season normal to above normal temperatures occurred during the growth period up to the end of August in all the irrigation areas. Above average temperatures occurred in all five irrigation areas during the second half of the winter. Relatively low temperatures occurred during September and October, which had a positive effect on yield and hectolitre mass.

The cultivars were planted according to a randomised block design with four replicates. Trial plots consisted of eight rows 0.17 m apart and six meter in length, which were then later reduced to five meters length to produce a net plot size value of 6.8m². The seeding rate was standardized for each cultivar according to its 1000 kernel weight. Therefore, the seeding rate for each cultivar differed in order to establish a uniform stand of plants per square meter.

Fertilization was applied according to target yield recommendations for each region. Applications on the trial plots were done according to recommendations based on individual soil analyses obtained from soil samples. Weed and pest control was performed when necessary. At harvesting, the two side rows were cut out in order to reduce the side-row effect, which can influence yield positively, thus the net plot size harvested for the quality analysis was 5.1 m². The plots were harvested with a Wintersteiger plot combine.

The soil profiles in the cooler central irrigation areas are mostly sandy and red in colour. Soils with high clay contents are found in the warmer northern irrigation regions. Maximum temperatures above 30°C during kernel filling period are a common phenomenon that eventually increases the risk for drought stress with consequently low hectolitre masses and high protein contents (Koekemoer, 1997). Mostly the total rainfall figures in all the irrigation areas except Kwazulu-Natal do not exceed 200mm during the growth cycle.

4.3.2. Quality analysis

Test weight or hectolitre mass (HLM, kg/hl) was determined using a Franklin chondrometer. The mass of a thousand kernels counted with a Numigral seed counter (Tripette et Renaud Paris France) was considered as the thousand kernel mass (TKM, g). After 50 grains had been cut with a farinator, vitreous kernels (VK, %) were determined as the total of two points per fully vitreous grain and one point per grain with at least 50% vitreousness. Grain samples of approximately 50 g were milled with a Falling Number KT-120 laboratory mill (1.0mm sieve) after which Hagberg Falling Numbers (FLN, s) were determined (AACC, 1983) from a 6.1 g sample to compensate for altitude (\pm 1340m). The grain protein contents (GPC-Leco, %) and flour protein contents (FPC-Leco, %) were determined with a Leco-FP2000 (AACC, 1995). Flour extraction rate (FLY, %) and break flour yields (BFLY, %) were calculated after experimental milling in a pneumatic Buhler MLU202 mill (Buhler-Miag, Uzwil, Switzerland), (AACC, 1983). A Kent Jones and Martin colour grader was used to measure flour colour standardised at a 76% flour extraction rate (FCL76, kj units). Single kernel characteristics were determined using the SKCS 4100 (Perten Instruments, Springfield, IL), this instrument provides characteristics like kernel diameter (average diameter of 300 kernels), hardness index (the index as percentage of the pressure of two rollers to crush 300 kernels) and kernel weight (the average weight of 300 kernels in mg).

Mixograph dough development time (MDT, min) was determined with a 35g National Mixograph (National Mfg., Lincoln, Nebraska), (AACC, 1983). Other rheological analyses performed according to approved methods (AACC, 1983) included the Brabender Farinograph quality determinant water absorption (FABS, %), the Chopin Alveograph determinants: dough strength (AS, cm²), Alveograph stability (ASTAB, mm),

Alveograph distensibility (AD, mm) and the ratio of stability to distensibility (P/L). In this study, micro loaves were baked from 100g of flour, using an optimized straight dough method (Finney, 1984). Loaf volumes were then determined by rapeseed displacement directly after baking, using a pup loaf volumeter. The SDS-sedimentation (sodium dodecyl sulphate –SDS) test was used to measure the relative gluten strength as it indicates the differences in the quantities of the polymeric glutenins (gel protein), (AACC, 1983). Wet-gluten content was determined with the glutomatic; the glutomatic is an automatic apparatus, which develops gluten of wheat flour from a 2% NaCl solution. The dough mixing and subsequent separation of starch and other solubles from the dough takes place in the same test chamber under controlled standardized conditions. The ball is then centrifuged to remove excess water and weighed as wet gluten.

In order to simplify the discussion, all the quality characteristics were divided into two groups namely milling and baking characteristics. The milling characteristics are represented by hectolitre mass (HLM), thousand kernel mass (TKM), Vitreous kernel (VK), SKCS weight (SKCS-G), SKCS diameter (SKCS-DIA), SKCS hardness index (SKCS-HI), Farinograph water absorption (FABS), break flour yield (BFLY) and flour yield (FLY). The baking characteristics are represented by falling number (FLN), grain protein content determined by the Leco (GPC-Leco), flour protein content determined by the Leco (FPC-Leco), Wet gluten content standardized at 12% protein content (WGC-12), SDS-sedimentation value (SDSS), mixograph development time (MDT), alveograph strength (AS), alveograph distensibility (AD), alveograph stability (ASTAB), alveograph P/L index (P/L), loaf volume (LFV) and loaf volume standardized at 12% protein content (LFV-12) in order to eliminate the positive effect of protein content on bread loaf volume.

4.3.3. Statistical analysis

The model of Sprague and Federer (1951) used in this study allows one to determine the variance components for each effect separately as described in Chapter 3.

The formula for calculating the theoretical variance from a cultivar's average, provides an option to determine the optimal amount of replications, localities and years needed to effectively evaluate the genotypes genetic potential for the effects measured before new

cultivars are released. The theoretical variance for a genotype's average (V_x) in a series of replicated trials over localities can be determined as follows:

$$V_x = \frac{\sigma_g^2 + \sigma_{gy}^2/y + \sigma_{gl}^2/l + \sigma_{gyl}^2/ly + \sigma_e^2/rl}{y}$$

Where y = amount of years

l = amount of localities

r = amount of replicates

The theoretical variances for a genotype's average regarding varying amount of localities, years and replications can be calculated by means of incorporating the different combinations of localities, years and replications into the above mentioned formula. The theoretical variances can also be graphically illustrated through plotting the number of years against the amount of localities for different replications. The optimal number of years and localities can then be directly obtained from the plot (Figure 4.1). The figure illustrates the relative size of the variances, which again is represented by the distance of the base to the area of each point. The slope of the graph visually displays the total change due the change in number of localities and years. Taking in consideration that significant genotype and environment interactions may exist, the number of years was varied from one to five and the amount of localities from one to twelve. The theoretical variance averages were repeated for one up to three replicates. The total change due to the change in years, replicates and localities are illustrated visually through the slope of the graphic illustration. In all the figures the height from the base represents the calculated variance from the cultivar average (V_x).

The relative efficiency can be used as a measurement in order to evaluate different combinations of localities, years and replicates. The relative efficiency for a specific combination of localities, years and replicates, are defined as the proportional difference from the current evaluation procedure namely three years and five localities per annum (Jones *et al.*, 1960).

The relative efficiency is determined as follows (Jones *et al.*, 1960):

$$\text{Relative efficiency} = \frac{(\text{Current } V_x - \text{Optimum } V_x)}{\text{Current } V_x} \times \frac{100}{1}$$

4.4 Results and discussion

The graphic illustrations regarding the various combinations for localities, years and replicates can be seen in Figures 4.1 – 4.8 and 4.9 – 4.20 for the milling and baking characteristics respectively. When the lines representing the different variances in the graphs start to even out, it is an indicator of the optimal amount of localities and years at that point. The actual variances can not be obtained directly from the graphical illustrations and can be seen in Tables 4.5 through to Tables 5.24. From all the figures (Figure 4.1 – 4.20) it is clear that there is not a large improvement when a second and third replicate is used in the determination of the optimal amount of localities and years needed in order to distinguish between genotypes. A similar pattern is also observed for the number of years needed, almost no differences were observed if either three, four or even five year's quality data are taken into account. Therefore a third, fourth or even fifth's year analysis will not provide additional information in order to distinguish between spring wheat genotypes under irrigation regarding their milling and baking characteristics. If the localities are kept constant the relative efficiency will improve with 50% if two year's quality data are evaluated and it will increase with a further 33% if a third year's quality data is added. Thus, a total relative efficiency improvement of 83% is being established for including the additional two years in a testing period. If the localities are kept constant again and a second replicate is added the relative efficiency improvement varied between 11.62% and 33.9% for SKCS-hardness index (SKCS-HI) and alveograph distensibility (AD) respectively. Therefore, it can be concluded that the effect of adding years is increasing the relative efficiency much more than the effect of adding replicates.

The relative importance of the total number of localities, years and replicates for the milling and baking characteristics are summarized in Table 4.3 and Table 4.4 respectively. Most of the characteristics that showed low genotype variance component values in Chapter 3, consequently needed more combinations between either localities, years or replicates. For the milling characteristics it was TKM, SKSC-G and VK (Table 4.3). For the baking characteristics it were FLN, (GPC-Leco) and FPC-Leco (Table 4.4). From Tables 6-24 it is noticeable that how the theoretic variance (V_x) declines with an increase in amount of years and test localities. The optimal number of years and test localities which are needed to evaluate spring type wheat under irrigation is a relative

concept and therefore the validity of a test period represented by three years and five localities in order to compare among new genotypes can be questioned.

Table 4.3. Optimal number of localities, years and replicates for milling characteristics

Number of years	Number of Replicates	Number of localities								
		HLM	TKM	SKCS-G	SKCS-DIA	VK	SKCS-HI	BFLY	FLY	Average
1	1	6	6	6	5	8	6	6	5	6
2	1	3	2	2	2	3	2	3	2	3

HLM = hectoliter mass, TKM = thousand kernel mass VK = Vitreous kernel, SKCS-G = SKCS weight, SKCS-DIA = SKCS diameter, SKCS-HI = SKCS hardness index, FABS = Farinograph water absorption, BFLY = break flour yield and FLY = flour yield.

From Table 4.3 it is clear that in order to accommodate all the milling characteristics for a first year analysis, six localities are needed when vitreous kernel is not taken into consideration, VK can be neglected because it is not such an important characteristic. When a second year analysis is taken into consideration a total number of three localities are needed to distinguish between the milling characteristics of genotypes with one replicate (Table 4.3). Therefore, the total number of localities needed for a two-year analysis period is nine. Van Deventer (1985) reported optimum number of localities for a second year quality analysis for winter cultivars produced under dryland conditions in the order 14, 12, 20 and 14 localities for the following characteristics namely, thousand kernel mass (TKM), hectolitre mass (HLM), protein content (GPC) and flour yield (FLY) respectively. The V_x variance for the first year analysis in the above situation was too high and therefore neglected. The higher values for his study can be ascribed to the higher genotype x environment interactions that occurred under dryland conditions. Under irrigation external factors like water and fertilization is much more manageable.

Table 4.4. Optimal number of localities, years and replicates for baking characteristics

Number of years	Number of replicates	Number of localities												
		FLN	GPC	FPC	WGC	SDSS	ASTAB	MDT	AS	AD	PL	LFV	LFV12	Average
1	1	7	6	7	6	6	7	6	5	6	7	5	6	7
2	1	3	2	3	3	3	3	3	2	3	3	2	3	3

FLN = falling number, GPC-LECO = grain protein content determined by the Leco, FPC-LECO = flour protein content determined by the Leco, WGC-12% = Wet gluten content at 12% protein content, SDSS = SDS-sedimentation value, MDT = mixograph development time, AS = alveograph strength, AD = alveograph distensibility, ASTAB = alveograph stability, P/L = alveograph P/L index LFV = loaf volume and lfV-12% = loaf volume standardized at 12% protein content.

In the case of the baking characteristics the optimum number of localities needed for a first year quality analysis is also seven (Table 4.4). For a second year analysis the optimum number of localities with one replicate will be three (Table 4.4). Therefore, the total number of localities needed for a two-year analysis period is ten. From both Tables 4.3 and 4.4 it is evident that if two replicates are included within the quality analysis to improve the relative efficiency, the additional costs for the extra localities will not be an economical option. Due to the fact that first, second and third year advanced lines are planted in the same trial it will be difficult to vary the number of localities for the different levels of testing. Therefore, the set number needed for both the milling and baking characteristics will be five localities over a two year test period. It must be mentioned that trials may need to be discarded due to unforeseen problems that can occur during the growth season, therefore one to two trials should be planted extra in order to make provision for damaged trials.

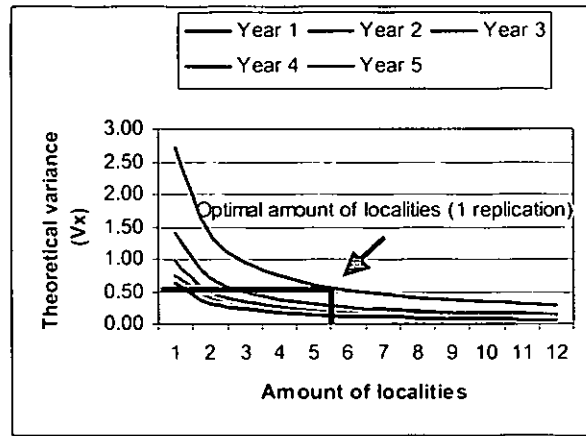
4.5 Conclusions

It was clear that there is not a large improvement in relative efficiency when a second and third replicate is used in the determination of the optimal number of localities and years needed in order to distinguish between genotypes. A similar pattern is also observed for the number of years needed, almost no differences were observed if either three, four or even five year's quality data are taken into account. It can be concluded that the effect of adding years is increasing the relative efficiency much more than the effect of adding replicates. It has been proven that for both the milling and baking characteristics 10 trials are needed over a two-year test period. Due to the fact that first,

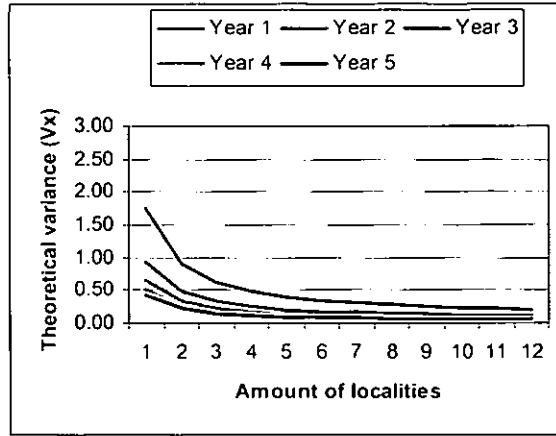
second and third year advanced lines are planted in the same trial it will be difficult to vary the number of localities for the different levels of testing. Therefore, the number set by the Wheat Technical Committee of three years testing at five localities for the spring wheat production under Mediterranean conditions, wheat production under dryland conditions, as well as under irrigation can be questioned. Because the G x E interaction under irrigation is not as severe as in the case of dryland and Mediterranean wheat, the minimum number can be reduced to five localities over a two-year test period. Thus, a decrease in the expenditure per genotype for quality testing is being achieved, as well as a whole year is being gained in relation to the release of new spring wheat cultivars under irrigation.

4.6 References

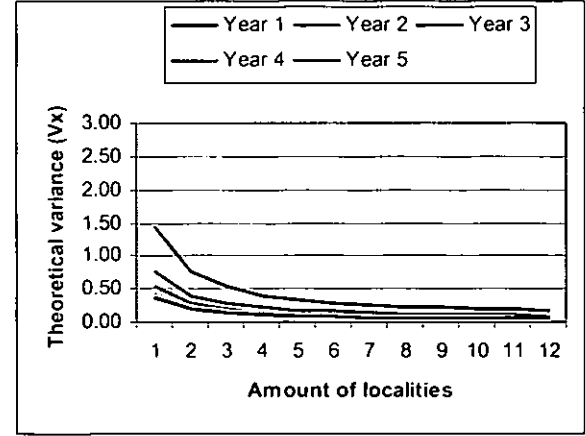
- AACC, 1983. Falling number determination method 56-81B; Experimental milling Buhler method 26-21A; Mixograph method 54-40A; Farinograph method 54-2A using 50g of flour; Alveogram method 54-30A; SDS-sedimentation the method used to determine gluten strength, method 56-70. In *Approved methods*; 8th ed. American Association of Cereal Chemists Inc.; St Paul, MN, USA.
- AACC; 1995. Dumas Leco-FP200 method for protein determination, method 46-30. In *Approved methods*; 8th edn. American Association of Cereal Chemists Inc.; St Paul, MN, USA.
- FINNEY, K.F., 1984. An optimized straight-dough bread making method after 44 years. *Cereal. Chem.* 61: 20-27.
- JONES, G.L., MATZINGER, D.F. & COLLINS, W.K., 1960. A comparison of fluccured tobacco varieties repeated over locations and years with implications on optimum plot allocation. *Agron. J.* 52: 195-199.
- KOEKEMOER, F.P., 1997. Inheritance of protein related characteristics in spring wheat. MSc. Thesis, Orange Free State.
- LUKOW, O.M. & McVETTY, P.B.E., 1991. Effect of cultivar and environment on quality characteristics of spring wheat. *Cereal. Chem.* 68(6): 597-601.
- MILLER, P.A., WILLIAMS, J.C. & ROBINSON, H.F., 1959. Variety x environment interaction in cotton variety tests and their implications on testing methods. *Agron. J.* 51: 132-134.
- SPRAGUE, G.F. & FEDERER, W.T., 1951. A comparison of variance components in corn yield trials. *Agron. J.* 3: 35-541.



1 replicate

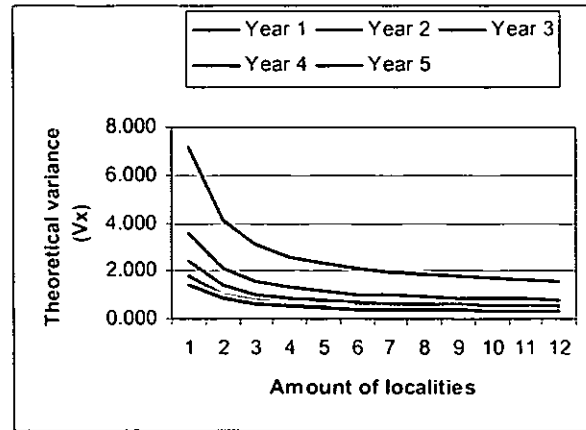


2 replicates

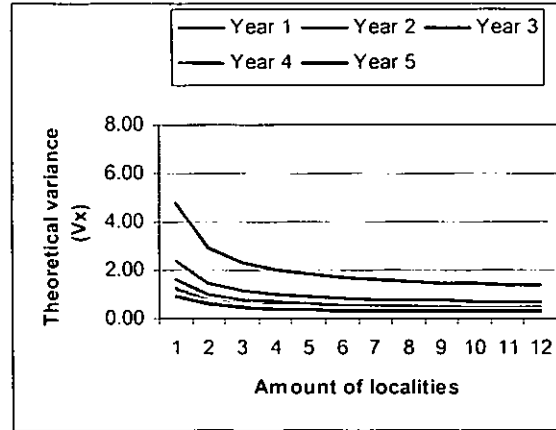


3 replicates

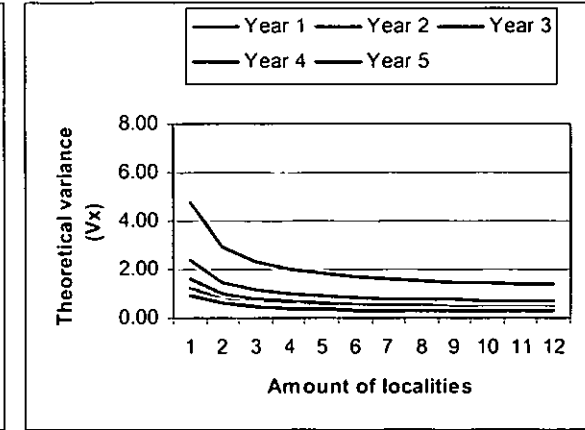
Figure 4.1. Number of localities, years and replicates testing for hectolitre mass (HLM).



1 replicate



2 replicates



3 replicates

Figure 4.2. Number of localities, years and replicates testing for thousand kernel mass (TKM).

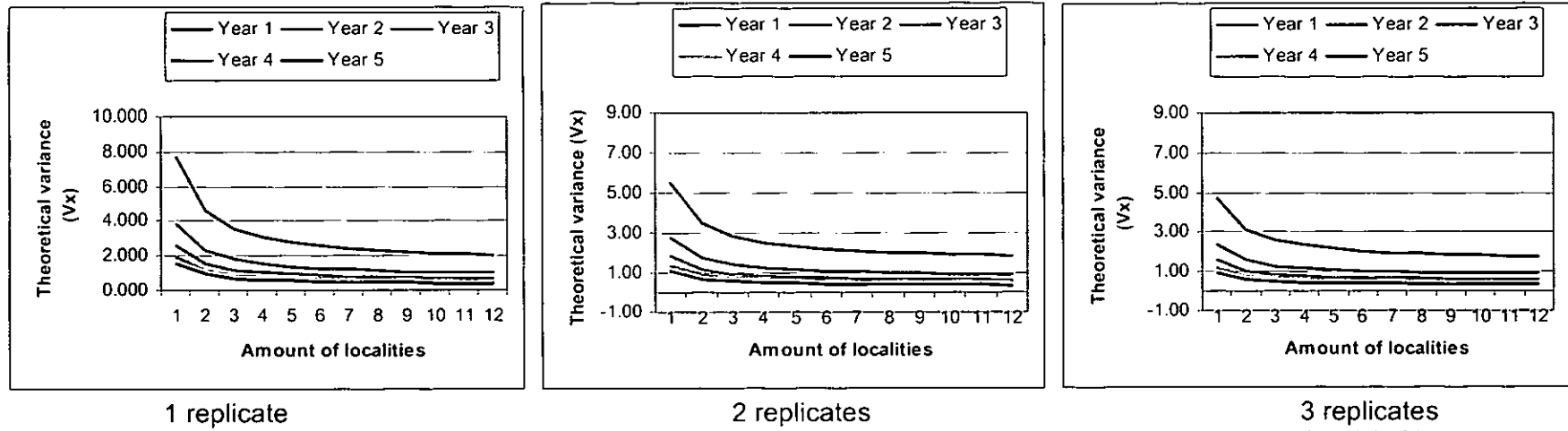


Figure 4.3. Number of localities, years and replicates testing for single kernel characterization kernel weight (SKCS-G).

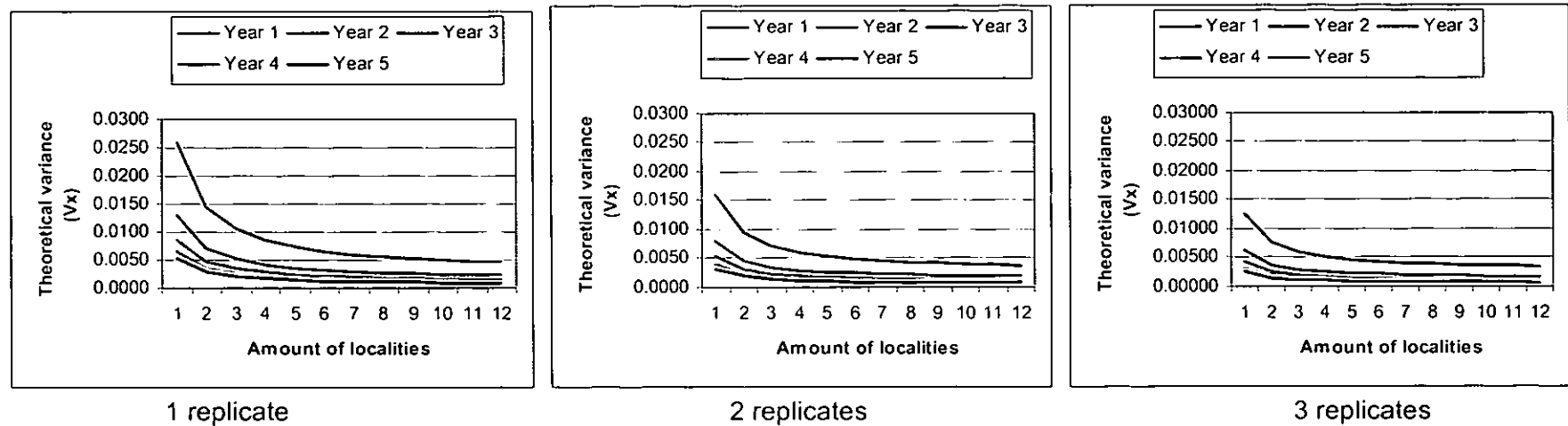
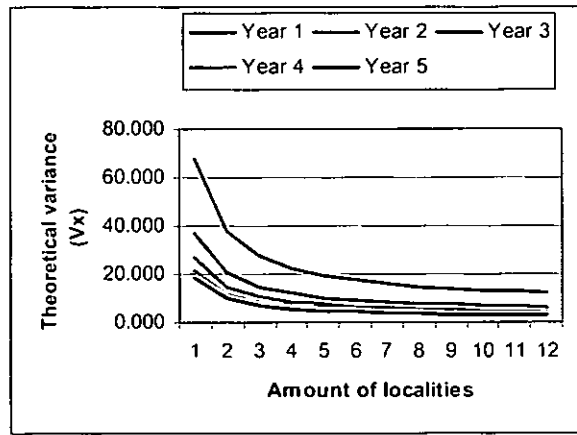
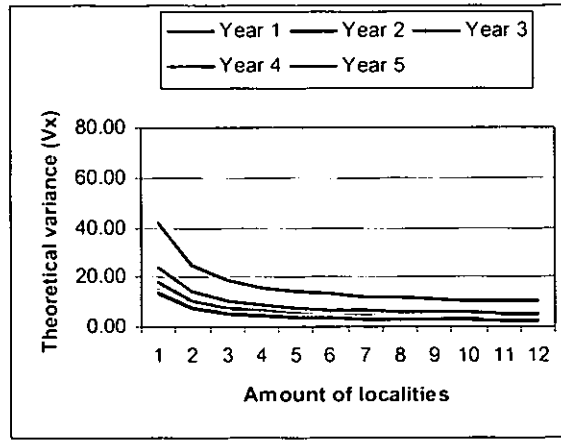


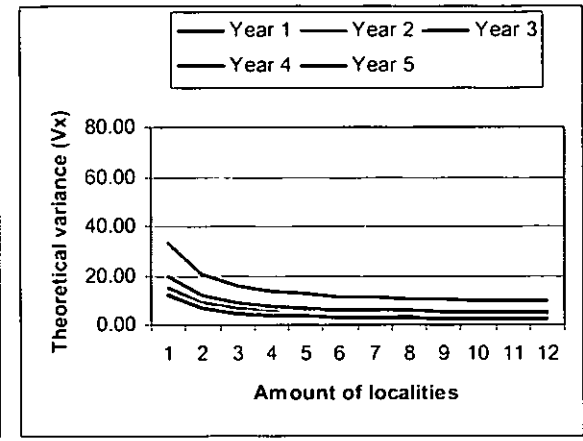
Figure 4.4. Number of localities, years and replicates testing for single kernel characterization kernel diameter (SKCS-DIA).



1 replicate

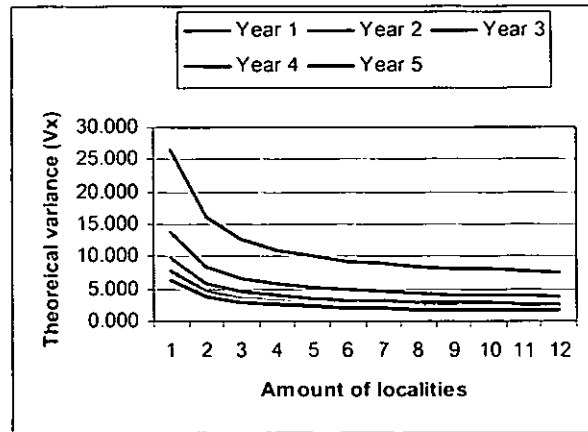


2 replicates

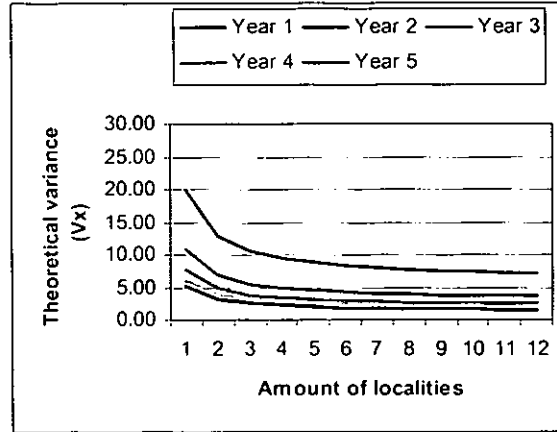


3 replicates

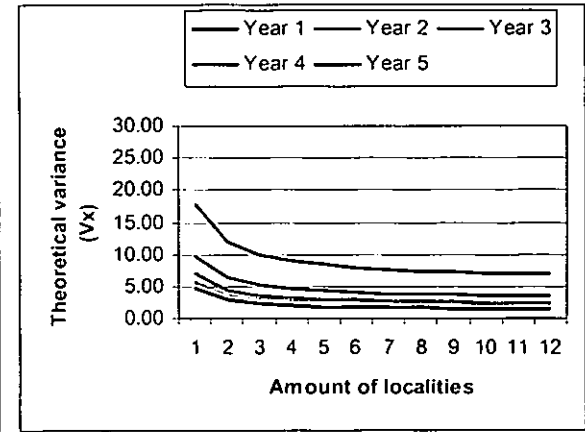
Figure 4.5. Number of localities, years and replicates testing for vitreous kernel (VK).



1 replicate

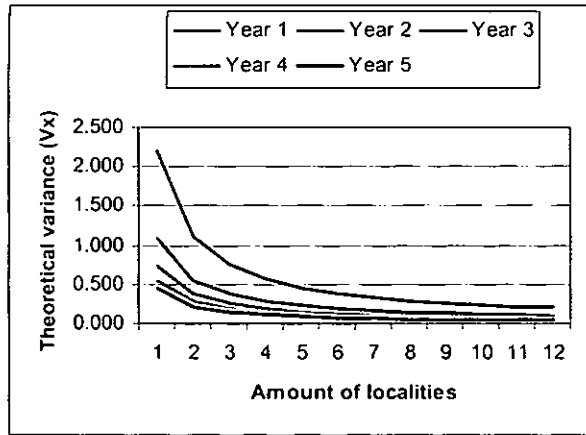


2 replicates

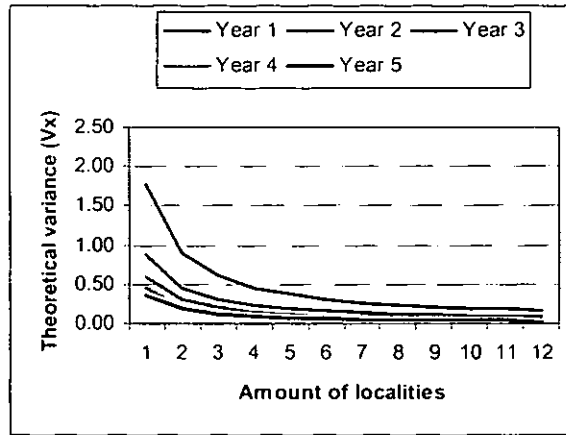


3 replicates

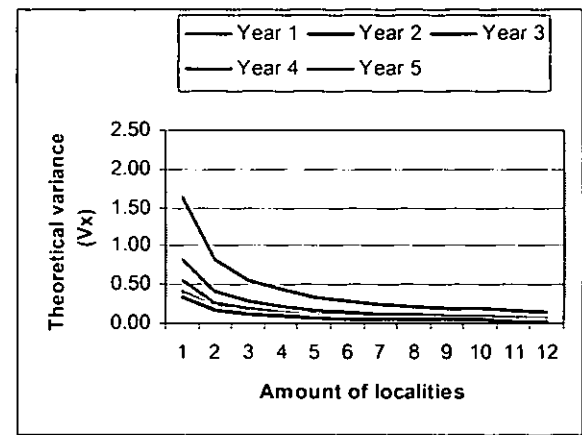
Figure 4.6. Number of localities, years and replicates testing for single kernel characterization kernel hardness (SKCS-HI).



1 replicate

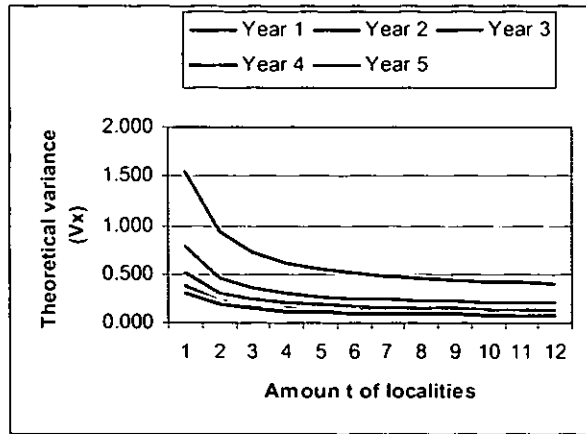


2 replicates

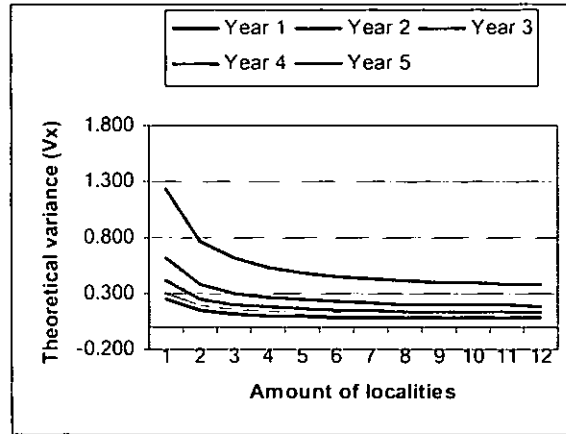


3 replicates

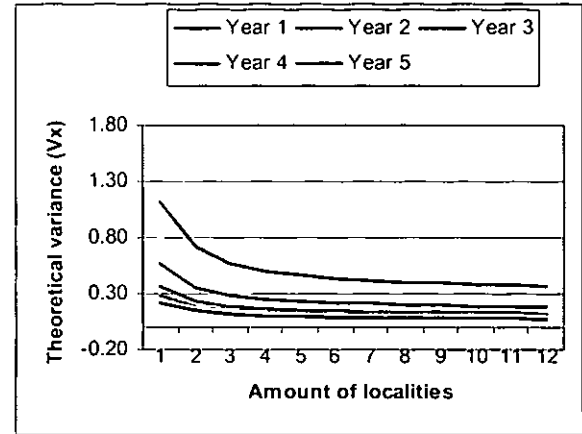
Figure 4.7. Number of localities, years and replicates testing for break flour yield (BFLY).



1 replicate

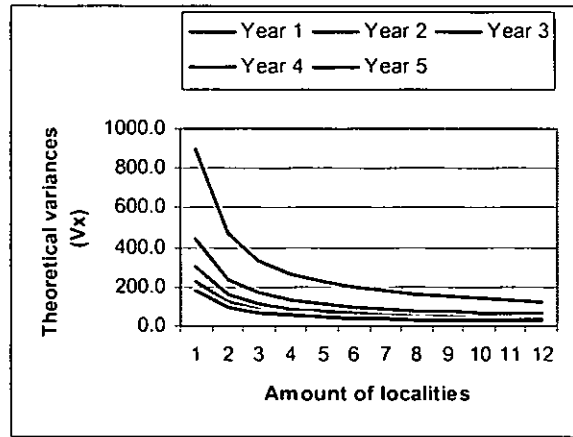


2 replicates

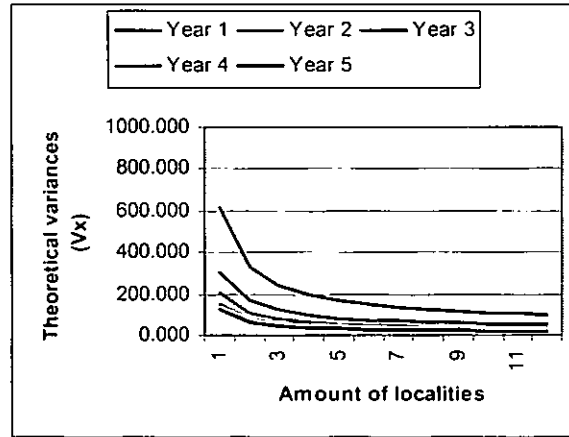


3 replicates

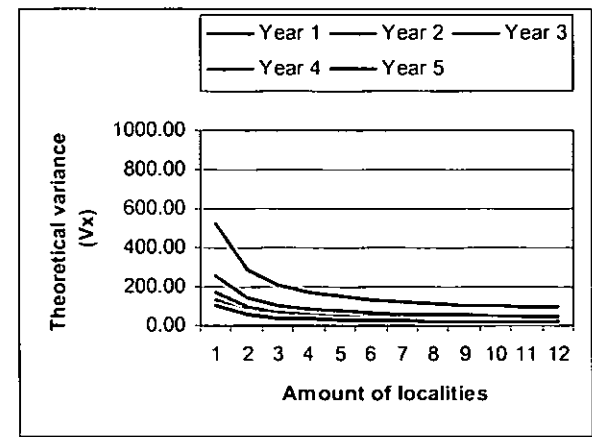
Figure 4.8. Number of localities, years and replicates testing for flour extraction (FLY).



1 replicate

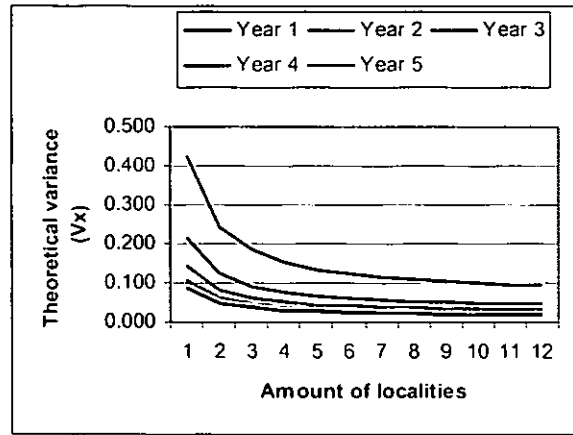


2 replicates

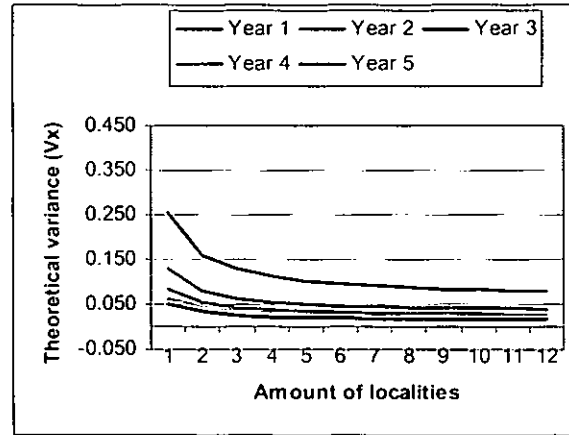


3 replicates

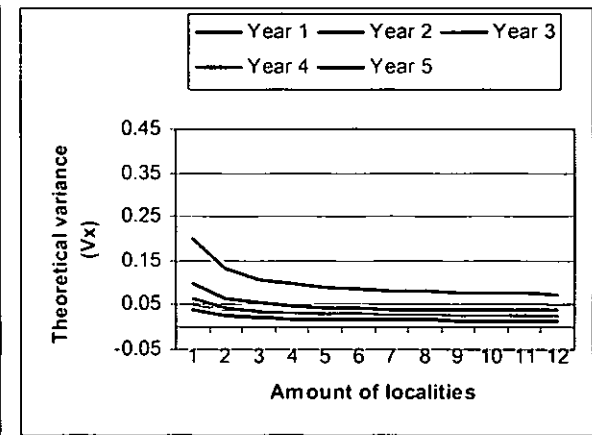
Figure 4.9. Number of localities, years and replicates testing for falling number (FLN).



1 replicate



2 replicates



3 replicates

Figure 4.10. Number of localities, years and replicates testing for grain protein content (GPC-Leco).

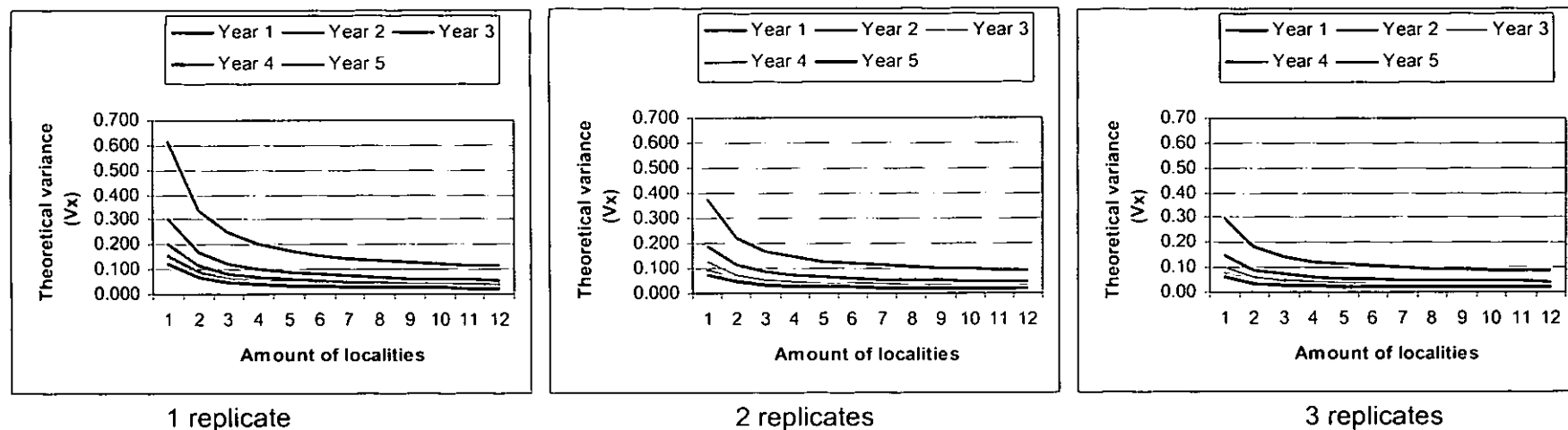


Figure 4.11. Number of localities, years and replicates testing for grain flour protein content (FPC-Leco).

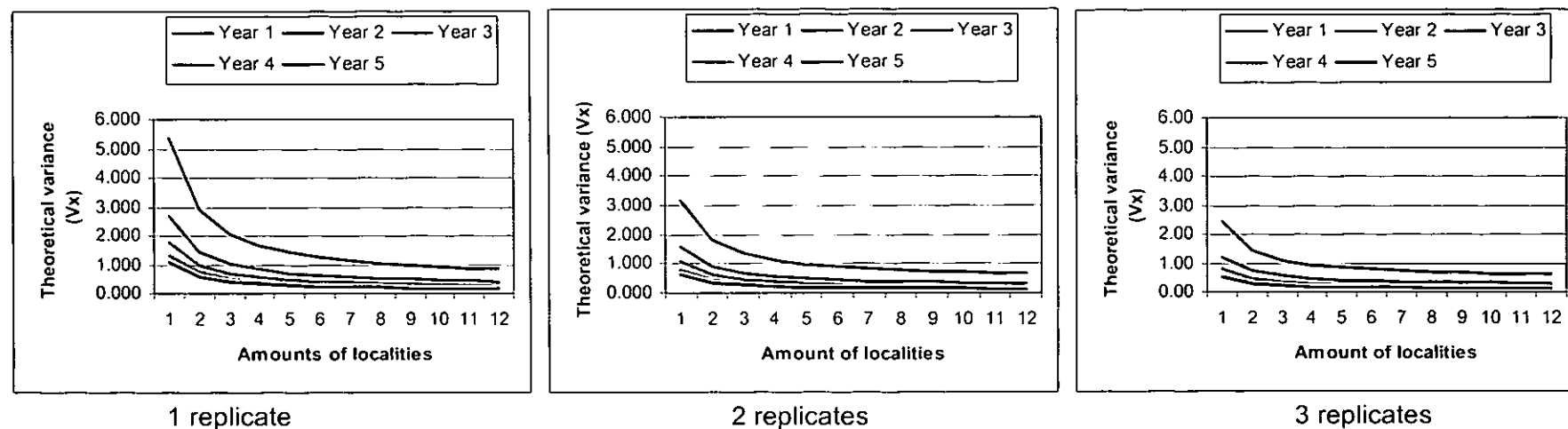
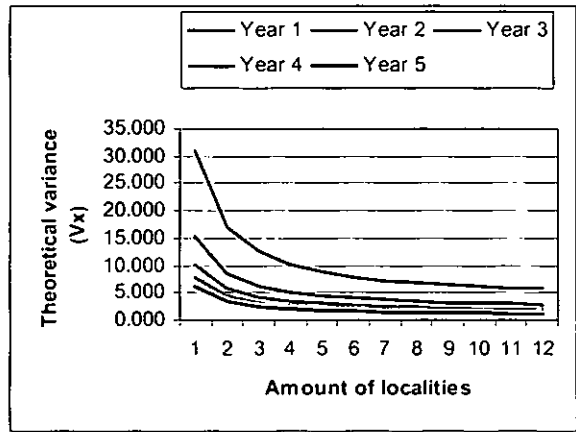
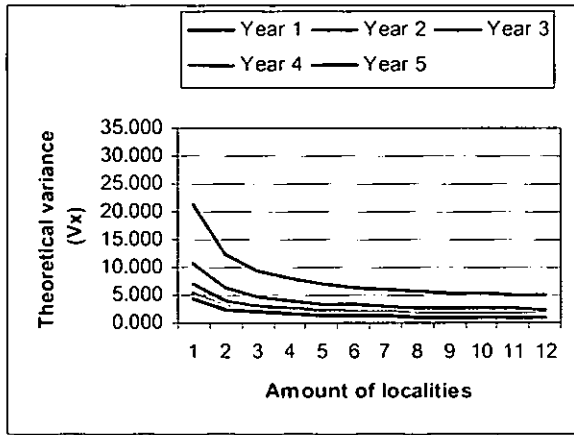


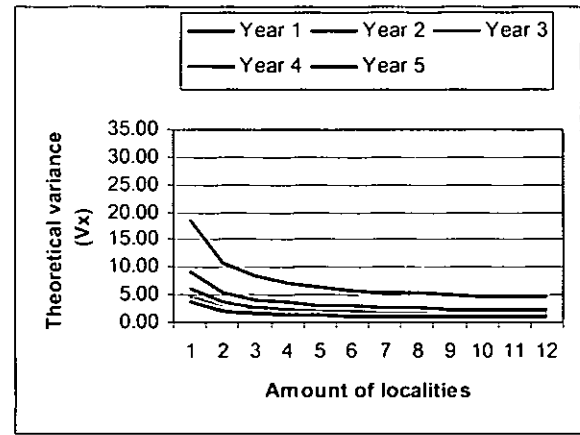
Figure 4.12. Number of localities, years and replicates testing for wet gluten content (WGC-12).



1 replicate

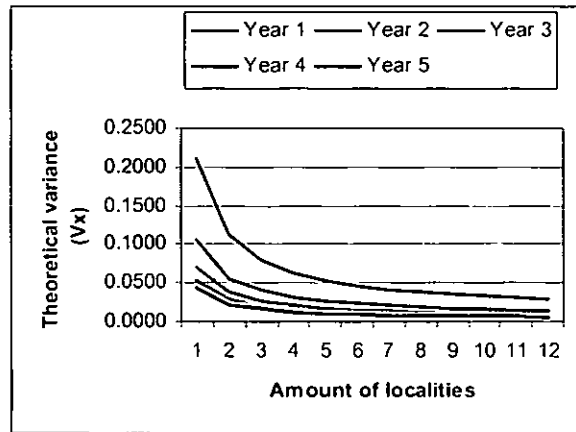


2 replicates

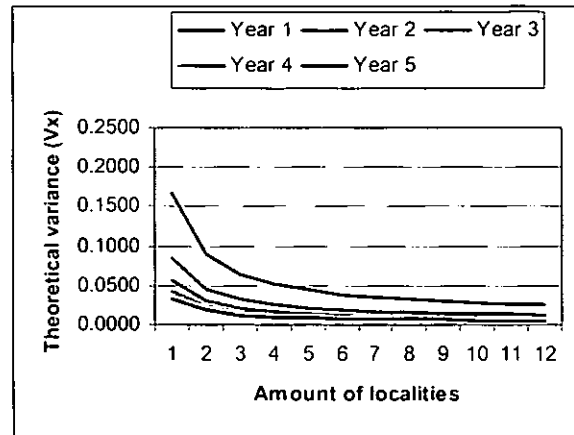


3 replicates

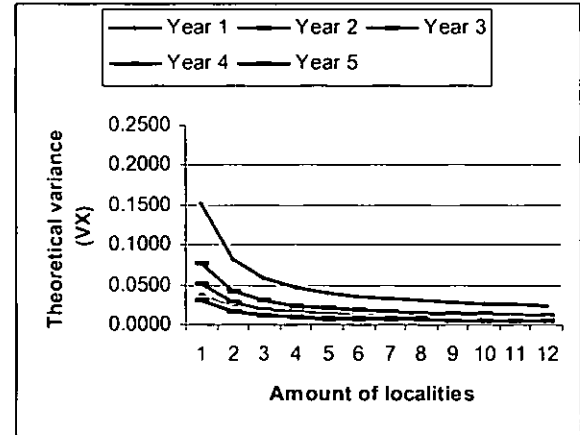
Figure 4.13. Number of localities, years and replicates testing for SDS sedimentation (SDSS).



1 replicate

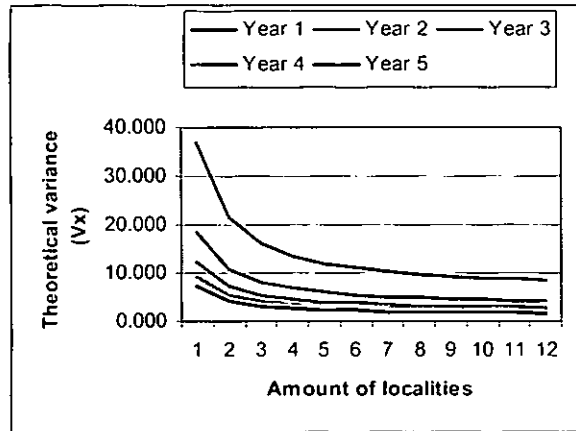


2 replicates

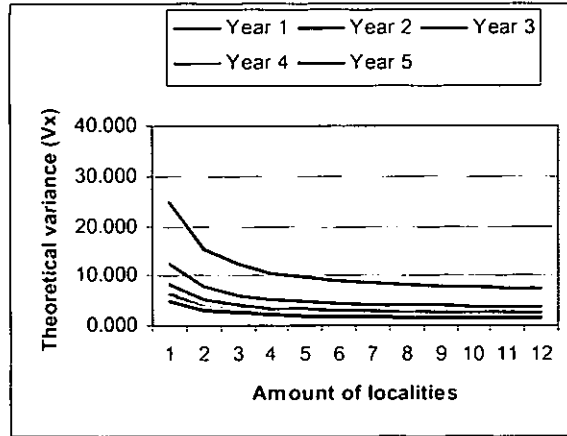


3 replicates

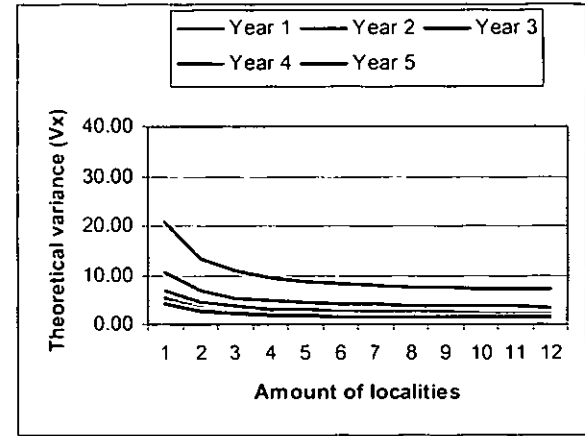
Figure 4.14. Number of localities, years and replicates testing for mixograph developing time (MDT).



1 replicate

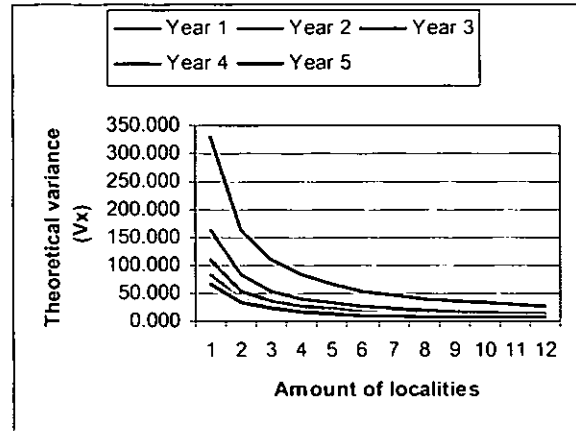


2 replicates

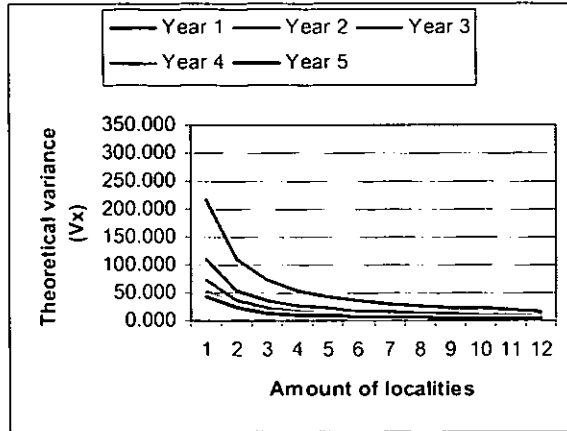


3 replicates

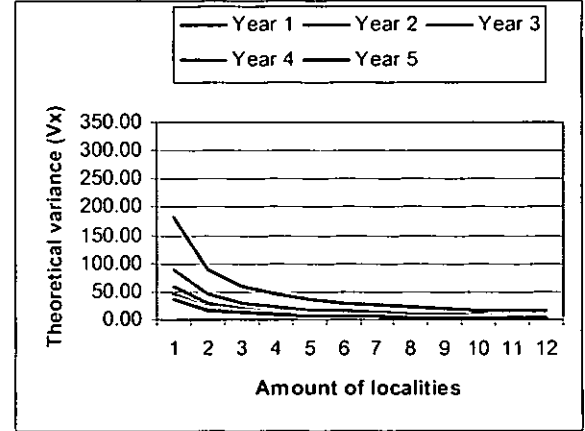
Figure 4.15. Number of localities, years and replicates testing for alveograph strength (AS).



1 replicate



2 replicates



3 replicates

Figure 16. Number of localities, years and replicates testing for alveograph distensibility (AD).

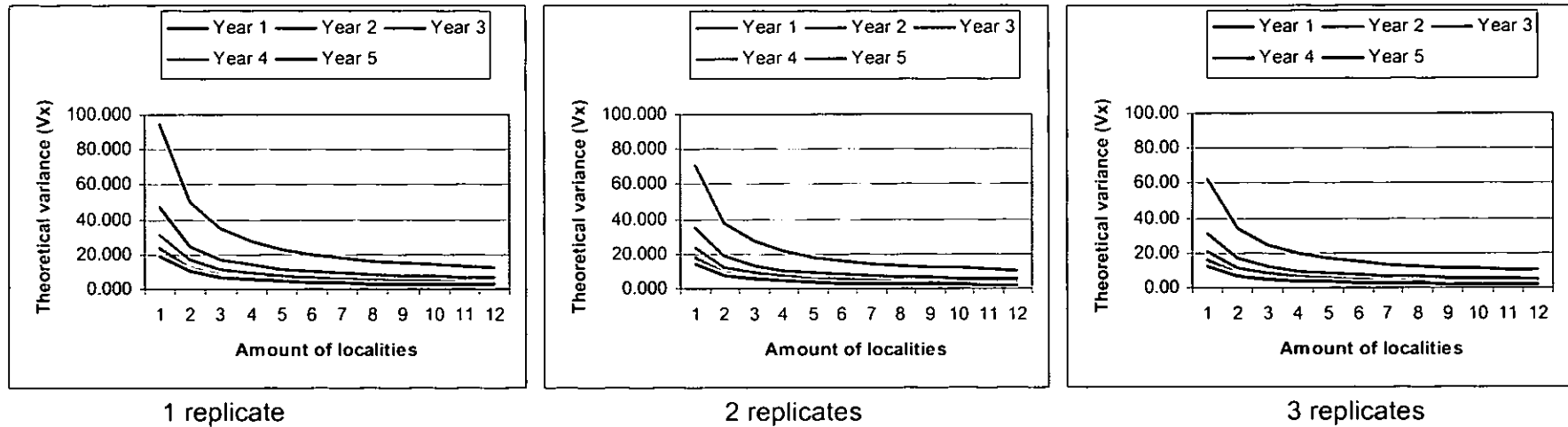


Figure 4.17. Number of localities, years and replicates testing for alveograph stability (ASTAB).

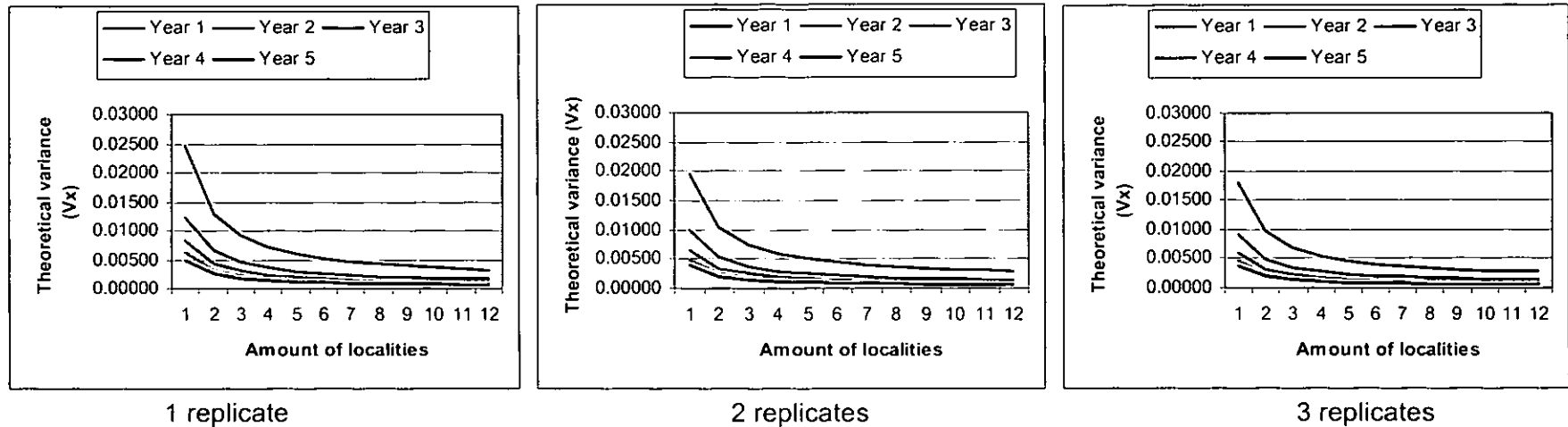


Figure 4.18. Number of localities, years and replicates testing for alveograph P/L value (P/L).

Table 4.5. Theoretic variances (V_x) for hectolitre mass (HLM) for varying localities, years and replicates.

Localities	Years with 1 replication					Years with 2 replications					Years with 3 replications				
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5
1	2.722	1.412	0.975	0.756	0.625	1.752	0.927	0.652	0.514	0.431	1.429	0.765	0.544	0.433	0.367
2	1.394	0.722	0.498	0.386	0.319	0.909	0.480	0.337	0.265	0.222	0.747	0.399	0.283	0.225	0.190
3	0.951	0.492	0.339	0.263	0.217	0.627	0.330	0.232	0.182	0.152	0.519	0.277	0.196	0.155	0.131
4	0.729	0.377	0.260	0.201	0.166	0.487	0.256	0.179	0.141	0.118	0.406	0.216	0.152	0.120	0.101
5	0.596	0.308	0.212	0.164	0.135	0.402	0.211	0.148	0.116	0.097	0.338	0.179	0.126	0.100	0.084
6	0.508	0.262	0.180	0.140	0.115	0.346	0.181	0.127	0.099	0.083	0.292	0.154	0.109	0.087	0.072
7	0.444	0.229	0.158	0.122	0.100	0.306	0.160	0.112	0.087	0.073	0.260	0.137	0.096	0.076	0.063
8	0.397	0.205	0.141	0.109	0.089	0.276	0.144	0.100	0.078	0.065	0.235	0.124	0.087	0.068	0.057
9	0.360	0.186	0.127	0.098	0.081	0.252	0.132	0.092	0.071	0.059	0.216	0.114	0.080	0.062	0.052
10	0.330	0.170	0.117	0.090	0.074	0.233	0.122	0.085	0.066	0.055	0.201	0.106	0.074	0.058	0.048
11	0.306	0.158	0.108	0.083	0.069	0.218	0.114	0.079	0.061	0.051	0.189	0.099	0.069	0.054	0.045
12	0.286	0.147	0.101	0.078	0.064	0.205	0.107	0.074	0.058	0.048	0.178	0.093	0.065	0.051	0.042

Table 4.6. Theoretic variances (V_x) for thousand kernel mass (TKM) for varying localities, years and replicates.

Localities	Years with 1 replication					Years with 2 replications					Years with 3 replications				
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5
1	7.159	3.580	2.386	1.790	1.432	4.794	2.397	1.598	1.199	0.959	4.006	2.003	1.335	1.002	0.801
2	4.119	2.060	1.373	1.030	0.824	2.937	1.468	0.979	0.734	0.587	2.543	1.271	0.848	0.636	0.509
3	3.106	1.553	1.035	0.777	0.621	2.318	1.159	0.773	0.579	0.464	2.055	1.027	0.685	0.514	0.411
4	2.599	1.300	0.866	0.650	0.520	2.008	1.004	0.669	0.502	0.402	1.811	0.906	0.604	0.453	0.362
5	2.295	1.148	0.765	0.574	0.459	1.822	0.911	0.607	0.456	0.364	1.665	0.832	0.555	0.416	0.333
6	2.093	1.046	0.698	0.523	0.419	1.699	0.849	0.566	0.425	0.340	1.567	0.784	0.522	0.396	0.313
7	1.948	0.974	0.649	0.487	0.390	1.610	0.805	0.537	0.403	0.322	1.497	0.749	0.499	0.374	0.299
8	1.839	0.920	0.613	0.460	0.368	1.544	0.772	0.515	0.386	0.309	1.445	0.723	0.482	0.361	0.289
9	1.755	0.877	0.585	0.439	0.351	1.492	0.746	0.497	0.373	0.298	1.405	0.702	0.468	0.351	0.281
10	1.687	0.844	0.562	0.422	0.337	1.451	0.725	0.484	0.363	0.290	1.372	0.686	0.457	0.343	0.274
11	1.632	0.816	0.544	0.408	0.326	1.417	0.709	0.472	0.354	0.283	1.345	0.673	0.448	0.336	0.269
12	1.586	0.793	0.529	0.397	0.317	1.389	0.694	0.463	0.347	0.278	1.323	0.662	0.441	0.331	0.265

Table 4.7. Theoretic variances (V_x) for SKCS kernel weight (SKCS-G) for varying localities, years and replicates.

Localities	Years with 1 replication					Years with 2 replications					Years with 3 replications				
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5
1	7.722	3.861	2.574	1.931	1.544	5.492	2.746	1.831	1.373	1.098	4.749	2.374	1.583	1.187	0.950
2	4.620	2.310	1.540	1.155	0.924	3.505	1.753	1.168	0.876	0.701	3.134	1.567	1.045	0.783	0.627
3	3.586	1.793	1.195	0.897	0.717	2.843	1.422	0.948	0.711	0.569	2.595	1.298	0.865	0.649	0.519
4	3.070	1.535	1.023	0.767	0.614	2.512	1.256	0.837	0.628	0.502	2.326	1.163	0.775	0.582	0.465
5	2.759	1.380	0.920	0.690	0.552	2.313	1.157	0.771	0.578	0.463	2.165	1.082	0.722	0.541	0.433
6	2.553	1.276	0.851	0.638	0.511	2.181	1.090	0.727	0.545	0.436	2.057	1.029	0.686	0.518	0.411
7	2.405	1.202	0.802	0.601	0.481	2.086	1.043	0.695	0.522	0.417	1.980	0.990	0.660	0.495	0.396
8	2.294	1.147	0.765	0.574	0.459	2.015	1.008	0.672	0.504	0.403	1.922	0.961	0.641	0.481	0.384
9	2.208	1.104	0.736	0.552	0.442	1.960	0.980	0.653	0.490	0.392	1.878	0.939	0.626	0.469	0.376
10	2.139	1.070	0.713	0.535	0.428	1.916	0.958	0.639	0.479	0.383	1.842	0.921	0.614	0.460	0.368
11	2.083	1.041	0.694	0.521	0.417	1.880	0.940	0.627	0.470	0.376	1.812	0.906	0.604	0.453	0.362
12	2.036	1.018	0.679	0.509	0.407	1.850	0.925	0.617	0.462	0.370	1.788	0.894	0.596	0.447	0.358

Table 4.8. Theoretic variances (V_x) for SKCS diameter (SKCS-DIA) for varying localities, years and replicates.

Localities	Years with 1 replication					Years with 2 replications					Years with 3 replications				
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5
1	0.02600	0.01300	0.00867	0.00650	0.00520	0.01600	0.00800	0.00533	0.00400	0.00320	0.01267	0.00633	0.00422	0.00317	0.00253
2	0.01433	0.00717	0.00478	0.00358	0.00287	0.00933	0.00467	0.00311	0.00233	0.00187	0.00767	0.00383	0.00256	0.00192	0.00153
3	0.01044	0.00522	0.00348	0.00261	0.00209	0.00711	0.00356	0.00237	0.00178	0.00142	0.00600	0.00300	0.00200	0.00150	0.00120
4	0.00850	0.00425	0.00283	0.00213	0.00170	0.00600	0.00300	0.00200	0.00150	0.00120	0.00517	0.00258	0.00172	0.00129	0.00103
5	0.00733	0.00367	0.00244	0.00183	0.00147	0.00533	0.00267	0.00178	0.00133	0.00107	0.00467	0.00233	0.00156	0.00117	0.00093
6	0.00656	0.00328	0.00219	0.00164	0.00131	0.00489	0.00244	0.00163	0.00122	0.00098	0.00433	0.00217	0.00144	0.00110	0.00087
7	0.00600	0.00300	0.00200	0.00150	0.00120	0.00457	0.00229	0.00152	0.00114	0.00091	0.00410	0.00205	0.00137	0.00102	0.00082
8	0.00558	0.00279	0.00186	0.00140	0.00112	0.00433	0.00217	0.00144	0.00108	0.00087	0.00392	0.00196	0.00131	0.00098	0.00078
9	0.00526	0.00263	0.00175	0.00131	0.00105	0.00415	0.00207	0.00138	0.00104	0.00083	0.00378	0.00189	0.00126	0.00094	0.00076
10	0.00500	0.00250	0.00167	0.00125	0.00100	0.00400	0.00200	0.00133	0.00100	0.00080	0.00367	0.00183	0.00122	0.00092	0.00073
11	0.00479	0.00239	0.00160	0.00120	0.00096	0.00388	0.00194	0.00129	0.00097	0.00078	0.00358	0.00179	0.00119	0.00089	0.00072
12	0.00461	0.00231	0.00154	0.00115	0.00092	0.00378	0.00189	0.00126	0.00094	0.00076	0.00350	0.00175	0.00117	0.00088	0.00070

Table 4.9. Theoretic variances (V_x) for vitreous kernels (VK) for varying localities, years and replicates.

Localities	Years with 1 replication					Years with 2 replications					Years with 3 replications				
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5
1	67.994	37.146	26.863	21.722	18.637	42.064	24.181	18.220	15.239	13.451	33.420	19.859	15.339	13.078	11.722
2	37.673	20.411	14.657	11.780	10.054	24.708	13.929	10.335	8.539	7.461	20.387	11.768	8.895	7.458	6.596
3	27.566	14.833	10.588	8.466	7.193	18.923	10.511	7.707	6.305	5.464	16.042	9.071	6.747	5.585	4.888
4	22.513	12.044	8.554	6.809	5.762	16.030	8.802	6.393	5.188	4.466	13.870	7.722	5.673	4.648	4.033
5	19.481	10.370	7.333	5.815	4.904	14.295	7.777	5.605	4.518	3.867	12.566	6.913	5.028	4.086	3.521
6	17.460	9.255	6.520	5.152	4.332	13.138	7.094	5.079	4.072	3.467	11.697	6.373	4.599	3.754	3.179
7	16.016	8.458	5.938	4.679	3.923	12.311	6.606	4.704	3.753	3.182	11.077	5.988	4.292	3.444	2.935
8	14.933	7.860	5.502	4.324	3.616	11.692	6.239	4.422	3.513	2.968	10.611	5.699	4.062	3.243	2.752
9	14.091	7.395	5.163	4.047	3.378	11.209	5.955	4.203	3.327	2.802	10.249	5.474	3.883	3.087	2.610
10	13.417	7.023	4.892	3.827	3.187	10.824	5.727	4.028	3.178	2.669	9.959	5.295	3.740	2.962	2.496
11	12.865	6.719	4.670	3.646	3.031	10.508	5.540	3.884	3.056	2.560	9.722	5.147	3.623	2.860	2.403
12	12.406	6.465	4.485	3.495	2.901	10.245	5.385	3.765	2.955	2.469	9.525	5.025	3.525	2.775	2.325

Table 4.10. Theoretic variances (V_x) for SKCS hardness index (SKCS-HI) for varying localities, years and replicates.

Localities	Years with 1 replication					Years with 2 replications					Years with 3 replications				
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5
1	26.579	13.989	9.792	7.694	6.435	20.059	10.729	7.619	6.064	5.131	17.886	9.642	6.894	5.521	4.696
2	16.244	8.472	5.881	4.586	3.808	12.984	6.842	4.794	3.771	3.156	11.898	6.299	4.432	3.499	2.939
3	12.800	6.633	4.577	3.550	2.933	10.626	5.546	3.853	3.006	2.498	9.902	5.184	3.611	2.825	2.353
4	11.077	5.713	3.926	3.032	2.495	9.447	4.898	3.382	2.624	2.169	8.904	4.627	3.201	2.488	2.061
5	10.044	5.162	3.534	2.721	2.233	8.740	4.510	3.100	2.395	1.972	8.305	4.292	2.955	2.286	1.885
6	9.355	4.794	3.274	2.514	2.057	8.268	4.251	2.911	2.242	1.840	7.906	4.070	2.791	2.162	1.768
7	8.863	4.531	3.087	2.366	1.932	7.931	4.066	2.777	2.133	1.746	7.621	3.910	2.673	2.055	1.684
8	8.494	4.334	2.948	2.255	1.839	7.679	3.927	2.676	2.051	1.676	7.407	3.791	2.586	1.983	1.621
9	8.207	4.181	2.839	2.168	1.766	7.482	3.819	2.598	1.987	1.621	7.241	3.698	2.517	1.927	1.572
10	7.977	4.058	2.752	2.099	1.707	7.325	3.732	2.535	1.936	1.577	7.108	3.624	2.462	1.882	1.533
11	7.789	3.958	2.681	2.043	1.660	7.196	3.662	2.484	1.894	1.541	6.999	3.563	2.418	1.845	1.501
12	7.632	3.874	2.622	1.996	1.620	7.089	3.603	2.441	1.860	1.511	6.908	3.512	2.380	1.814	1.475

Table 4.11. Theoretic variances (V_x) for break flour yield (BFLY) for varying localities, years and replicates.

Localities	Years with 1 replication					Years with 2 replications					Years with 3 replications				
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5
1	2.191	1.095	0.730	0.548	0.438	1.766	0.883	0.589	0.441	0.353	1.624	0.812	0.541	0.406	0.325
2	1.106	0.553	0.369	0.276	0.221	0.893	0.447	0.298	0.223	0.179	0.822	0.411	0.274	0.206	0.164
3	0.744	0.372	0.248	0.186	0.149	0.602	0.301	0.201	0.151	0.120	0.555	0.278	0.185	0.139	0.111
4	0.563	0.282	0.188	0.141	0.113	0.457	0.228	0.152	0.114	0.091	0.422	0.211	0.141	0.105	0.084
5	0.455	0.227	0.152	0.114	0.091	0.370	0.185	0.123	0.092	0.074	0.341	0.171	0.114	0.085	0.068
6	0.382	0.191	0.127	0.096	0.076	0.312	0.156	0.104	0.078	0.062	0.288	0.144	0.096	0.073	0.058
7	0.331	0.165	0.110	0.083	0.066	0.270	0.135	0.090	0.067	0.054	0.250	0.125	0.083	0.062	0.050
8	0.292	0.146	0.097	0.073	0.058	0.239	0.119	0.080	0.060	0.048	0.221	0.111	0.074	0.055	0.044
9	0.262	0.131	0.087	0.065	0.052	0.215	0.107	0.072	0.054	0.043	0.199	0.099	0.066	0.050	0.040
10	0.238	0.119	0.079	0.059	0.048	0.195	0.098	0.065	0.049	0.039	0.181	0.091	0.060	0.045	0.036
11	0.218	0.109	0.073	0.054	0.044	0.179	0.090	0.060	0.045	0.036	0.166	0.083	0.055	0.042	0.033
12	0.202	0.101	0.067	0.050	0.040	0.166	0.083	0.055	0.042	0.033	0.154	0.077	0.051	0.039	0.031

Table 4.12. Theoretic variances (V_x) for flour yield (FLY) for varying localities, years and replicates.

Localities	Years with 1 replication					Years with 2 replications					Years with 3 replications				
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5
1	1.547	0.774	0.516	0.387	0.309	1.227	0.614	0.409	0.307	0.245	1.121	0.560	0.374	0.280	0.224
2	0.924	0.462	0.308	0.231	0.185	0.764	0.382	0.255	0.191	0.153	0.711	0.355	0.237	0.178	0.142
3	0.716	0.358	0.239	0.179	0.143	0.610	0.305	0.203	0.152	0.122	0.574	0.287	0.191	0.144	0.115
4	0.612	0.306	0.204	0.153	0.122	0.532	0.266	0.177	0.133	0.106	0.506	0.253	0.169	0.126	0.101
5	0.550	0.275	0.183	0.138	0.110	0.486	0.243	0.162	0.122	0.097	0.465	0.232	0.155	0.116	0.093
6	0.508	0.254	0.169	0.127	0.102	0.455	0.228	0.152	0.114	0.091	0.437	0.219	0.146	0.110	0.087
7	0.479	0.239	0.160	0.120	0.096	0.433	0.217	0.144	0.108	0.087	0.418	0.209	0.139	0.104	0.084
8	0.457	0.228	0.152	0.114	0.091	0.417	0.208	0.139	0.104	0.083	0.403	0.202	0.134	0.101	0.081
9	0.439	0.220	0.146	0.110	0.088	0.404	0.202	0.135	0.101	0.081	0.392	0.196	0.131	0.098	0.078
10	0.425	0.213	0.142	0.106	0.085	0.393	0.197	0.131	0.098	0.079	0.383	0.191	0.128	0.096	0.077
11	0.414	0.207	0.138	0.104	0.083	0.385	0.192	0.128	0.096	0.077	0.375	0.188	0.125	0.094	0.075
12	0.405	0.202	0.135	0.101	0.081	0.378	0.189	0.126	0.094	0.076	0.369	0.185	0.123	0.092	0.074

Table 4.13. Theoretic variances (V_x) for falling number (FLN) for varying localities, years and replicates.

Localities	Years with 1 replication					Years with 2 replications					Years with 3 replications				
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5
1	893.05	446.52	297.68	223.26	178.61	614.04	307.02	204.68	153.51	122.81	521.04	260.52	173.68	130.26	104.21
2	474.20	237.10	158.07	118.55	94.84	334.69	167.35	111.56	83.67	66.94	288.19	144.10	96.06	72.05	57.64
3	334.58	167.29	111.53	83.65	66.92	241.58	120.79	80.53	60.39	48.32	210.58	105.29	70.19	52.64	42.12
4	264.77	132.39	88.26	66.19	52.95	195.02	97.51	65.01	48.76	39.00	171.77	85.89	57.26	42.94	34.35
5	222.89	111.44	74.30	55.72	44.58	167.09	83.54	55.70	41.77	33.42	148.49	74.24	49.50	37.12	29.70
6	194.97	97.48	64.99	48.74	38.99	148.47	74.23	49.49	37.12	29.69	132.96	66.48	44.32	33.70	26.59
7	175.02	87.51	58.34	43.76	35.00	135.16	67.58	45.05	33.79	27.03	121.88	60.94	40.63	30.47	24.38
8	160.06	80.03	53.35	40.02	32.01	125.19	62.59	41.73	31.30	25.04	113.56	56.78	37.85	28.39	22.71
9	148.43	74.21	49.48	37.11	29.69	117.43	58.71	39.14	29.36	23.49	107.09	53.55	35.70	26.77	21.42
10	139.12	69.56	46.37	34.78	27.82	111.22	55.61	37.07	27.80	22.24	101.92	50.96	33.97	25.48	20.38
11	131.50	65.75	43.83	32.88	26.30	106.14	53.07	35.38	26.54	21.23	97.69	48.84	32.56	24.42	19.54
12	125.16	62.58	41.72	31.29	25.03	101.91	50.95	33.97	25.48	20.38	94.16	47.08	31.39	23.54	18.83

Table 4.14. Theoretic variances (V_x) for grain protein content (GPC) for varying localities, years and replicates.

Localities	Years with 1 replication					Years with 2 replications					Years with 3 replications				
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5
1	0.426	0.213	0.142	0.107	0.085	0.256	0.128	0.085	0.064	0.051	0.199	0.100	0.066	0.050	0.040
2	0.244	0.122	0.081	0.061	0.049	0.159	0.080	0.053	0.040	0.032	0.131	0.066	0.044	0.033	0.026
3	0.184	0.092	0.061	0.046	0.037	0.127	0.064	0.042	0.032	0.025	0.108	0.054	0.036	0.027	0.022
4	0.154	0.077	0.051	0.038	0.031	0.111	0.056	0.037	0.028	0.022	0.097	0.048	0.032	0.024	0.019
5	0.135	0.068	0.045	0.034	0.027	0.101	0.051	0.034	0.025	0.020	0.090	0.045	0.030	0.023	0.018
6	0.123	0.062	0.041	0.031	0.025	0.095	0.047	0.032	0.024	0.019	0.085	0.043	0.028	0.022	0.017
7	0.115	0.057	0.038	0.029	0.023	0.090	0.045	0.030	0.023	0.018	0.082	0.041	0.027	0.021	0.016
8	0.108	0.054	0.036	0.027	0.022	0.087	0.043	0.029	0.022	0.017	0.080	0.040	0.027	0.020	0.016
9	0.103	0.052	0.034	0.026	0.021	0.084	0.042	0.028	0.021	0.017	0.078	0.039	0.026	0.019	0.016
10	0.099	0.050	0.033	0.025	0.020	0.082	0.041	0.027	0.021	0.016	0.076	0.038	0.025	0.019	0.015
11	0.096	0.048	0.032	0.024	0.019	0.080	0.040	0.027	0.020	0.016	0.075	0.038	0.025	0.019	0.015
12	0.093	0.046	0.031	0.023	0.019	0.079	0.039	0.026	0.020	0.016	0.074	0.037	0.025	0.019	0.015

Table 4.15. Theoretic variances (V_x) for flour protein content (FPC) for varying localities, years and replicates.

Localities	Years with 1 replication					Years with 2 replications					Years with 3 replications				
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5
1	0.610	0.305	0.203	0.153	0.122	0.375	0.188	0.125	0.094	0.075	0.297	0.148	0.099	0.074	0.059
2	0.338	0.169	0.113	0.085	0.068	0.221	0.110	0.074	0.055	0.044	0.182	0.091	0.061	0.045	0.036
3	0.248	0.124	0.083	0.062	0.050	0.169	0.085	0.056	0.042	0.034	0.143	0.072	0.048	0.036	0.029
4	0.203	0.101	0.068	0.051	0.041	0.144	0.072	0.048	0.036	0.029	0.124	0.062	0.041	0.031	0.025
5	0.175	0.088	0.058	0.044	0.035	0.128	0.064	0.043	0.032	0.026	0.113	0.056	0.038	0.028	0.023
6	0.157	0.079	0.052	0.039	0.031	0.118	0.059	0.039	0.030	0.024	0.105	0.053	0.035	0.027	0.021
7	0.144	0.072	0.048	0.036	0.029	0.111	0.055	0.037	0.028	0.022	0.100	0.050	0.033	0.025	0.020
8	0.135	0.067	0.045	0.034	0.027	0.105	0.053	0.035	0.026	0.021	0.095	0.048	0.032	0.024	0.019
9	0.127	0.064	0.042	0.032	0.025	0.101	0.050	0.034	0.025	0.020	0.092	0.046	0.031	0.023	0.018
10	0.121	0.061	0.040	0.030	0.024	0.098	0.049	0.033	0.024	0.020	0.090	0.045	0.030	0.022	0.018
11	0.116	0.058	0.039	0.029	0.023	0.095	0.047	0.032	0.024	0.019	0.088	0.044	0.029	0.022	0.018
12	0.112	0.056	0.037	0.028	0.022	0.092	0.046	0.031	0.023	0.018	0.086	0.043	0.029	0.021	0.017

Table 4.16. Theoretic variances (V_x) for wet gluten content (WGC) for varying localities, years and replicates.

Localities	Years with 1 replication					Years with 2 replications					Years with 3 replications				
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5
1	5.357	2.678	1.786	1.339	1.071	3.182	1.591	1.061	0.795	0.636	2.457	1.228	0.819	0.614	0.491
2	2.897	1.448	0.966	0.724	0.579	1.809	0.905	0.603	0.452	0.362	1.447	0.723	0.482	0.362	0.289
3	2.077	1.038	0.692	0.519	0.415	1.352	0.676	0.451	0.338	0.270	1.110	0.555	0.370	0.278	0.222
4	1.667	0.833	0.556	0.417	0.333	1.123	0.561	0.374	0.281	0.225	0.942	0.471	0.314	0.235	0.188
5	1.421	0.710	0.474	0.355	0.284	0.986	0.493	0.329	0.246	0.197	0.841	0.420	0.280	0.210	0.168
6	1.257	0.628	0.419	0.314	0.251	0.894	0.447	0.298	0.224	0.179	0.773	0.387	0.258	0.197	0.155
7	1.140	0.570	0.380	0.285	0.228	0.829	0.414	0.276	0.207	0.166	0.725	0.363	0.242	0.181	0.145
8	1.052	0.526	0.351	0.263	0.210	0.780	0.390	0.260	0.195	0.156	0.689	0.345	0.230	0.172	0.138
9	0.983	0.492	0.328	0.246	0.197	0.742	0.371	0.247	0.185	0.148	0.661	0.331	0.220	0.165	0.132
10	0.929	0.464	0.310	0.232	0.186	0.711	0.356	0.237	0.178	0.142	0.639	0.319	0.213	0.160	0.128
11	0.884	0.442	0.295	0.221	0.177	0.686	0.343	0.229	0.172	0.137	0.620	0.310	0.207	0.155	0.124
12	0.847	0.423	0.282	0.212	0.169	0.665	0.333	0.222	0.166	0.133	0.605	0.303	0.202	0.151	0.121

Table 4.17. Theoretic variances (V_x) for SDS sedimentation (SDSS) for varying localities, years and replicates.

Localities	Years with 1 replication					Years with 2 replications					Years with 3 replications				
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5
1	30.80	15.40	10.27	7.70	6.16	21.49	10.75	7.16	5.37	4.30	18.39	9.20	6.13	4.60	3.68
2	17.08	8.54	5.69	4.27	3.42	12.42	6.21	4.14	3.11	2.48	10.87	5.44	3.62	2.72	2.17
3	12.50	6.25	4.17	3.13	2.50	9.40	4.70	3.13	2.35	1.88	8.37	4.18	2.79	2.09	1.67
4	10.22	5.11	3.41	2.55	2.04	7.89	3.94	2.63	1.97	1.58	7.11	3.56	2.37	1.78	1.42
5	8.84	4.42	2.95	2.21	1.77	6.98	3.49	2.33	1.75	1.40	6.36	3.18	2.12	1.59	1.27
6	7.93	3.96	2.64	1.98	1.59	6.38	3.19	2.13	1.59	1.28	5.86	2.93	1.95	1.48	1.17
7	7.28	3.64	2.43	1.82	1.46	5.95	2.97	1.98	1.49	1.19	5.50	2.75	1.83	1.38	1.10
8	6.79	3.39	2.26	1.70	1.36	5.62	2.81	1.87	1.41	1.12	5.23	2.62	1.74	1.31	1.05
9	6.40	3.20	2.13	1.60	1.28	5.37	2.69	1.79	1.34	1.07	5.03	2.51	1.68	1.26	1.01
10	6.10	3.05	2.03	1.52	1.22	5.17	2.58	1.72	1.29	1.03	4.86	2.43	1.62	1.21	0.97
11	5.85	2.93	1.95	1.46	1.17	5.00	2.50	1.67	1.25	1.00	4.72	2.36	1.57	1.18	0.94
12	5.64	2.82	1.88	1.41	1.13	4.87	2.43	1.62	1.22	0.97	4.61	2.30	1.54	1.15	0.92

Table 4.18. Theoretic variances (V_x) for alveograph stability (ASTAB) for varying localities, years and replicates.

Localities	Years with 1 replication					Years with 2 replications					Years with 3 replications				
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5
1	93.89	46.95	31.30	23.47	18.78	70.49	35.25	23.50	17.62	14.10	62.69	31.35	20.90	15.67	12.54
2	49.60	24.80	16.53	12.40	9.92	37.90	18.95	12.63	9.47	7.58	34.00	17.00	11.33	8.50	6.80
3	34.83	17.42	11.61	8.71	6.97	27.03	13.52	9.01	6.76	5.41	24.43	12.22	8.14	6.11	4.89
4	27.45	13.73	9.15	6.86	5.49	21.60	10.80	7.20	5.40	4.32	19.65	9.83	6.55	4.91	3.93
5	23.02	11.51	7.67	5.76	4.60	18.34	9.17	6.11	4.59	3.67	16.78	8.39	5.59	4.20	3.36
6	20.07	10.03	6.69	5.02	4.01	16.17	8.08	5.39	4.04	3.23	14.87	7.43	4.96	3.76	2.97
7	17.96	8.98	5.99	4.49	3.59	14.62	7.31	4.87	3.65	2.92	13.50	6.75	4.50	3.38	2.70
8	16.38	8.19	5.46	4.09	3.28	13.45	6.73	4.48	3.36	2.69	12.48	6.24	4.16	3.12	2.50
9	15.15	7.57	5.05	3.79	3.03	12.55	6.27	4.18	3.14	2.51	11.68	5.84	3.89	2.92	2.34
10	14.16	7.08	4.72	3.54	2.83	11.82	5.91	3.94	2.96	2.36	11.04	5.52	3.68	2.76	2.21
11	13.36	6.68	4.45	3.34	2.67	11.23	5.62	3.74	2.81	2.25	10.52	5.26	3.51	2.63	2.10
12	12.69	6.34	4.23	3.17	2.54	10.74	5.37	3.58	2.68	2.15	10.09	5.04	3.36	2.52	2.02

Table 4.19. Theoretic variances (V_x) for mixograph developing time (MDT) for varying localities, years and replicates.

Localities	Years with 1 replication					Years with 2 replications					Years with 3 replications				
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5
1	0.2127	0.1063	0.0709	0.0532	0.0425	0.1677	0.0838	0.0559	0.0419	0.0335	0.1527	0.0763	0.0509	0.0382	0.0305
2	0.1127	0.0563	0.0376	0.0282	0.0225	0.0902	0.0451	0.0301	0.0225	0.0180	0.0827	0.0413	0.0276	0.0207	0.0165
3	0.0793	0.0397	0.0264	0.0198	0.0159	0.0643	0.0322	0.0214	0.0161	0.0129	0.0593	0.0297	0.0198	0.0148	0.0119
4	0.0627	0.0313	0.0209	0.0157	0.0125	0.0514	0.0257	0.0171	0.0129	0.0103	0.0477	0.0238	0.0159	0.0119	0.0095
5	0.0527	0.0263	0.0176	0.0132	0.0105	0.0437	0.0218	0.0146	0.0109	0.0087	0.0407	0.0203	0.0136	0.0102	0.0081
6	0.0460	0.0230	0.0153	0.0115	0.0092	0.0385	0.0193	0.0128	0.0096	0.0077	0.0360	0.0180	0.0120	0.0091	0.0072
7	0.0412	0.0206	0.0137	0.0103	0.0082	0.0348	0.0174	0.0116	0.0087	0.0070	0.0327	0.0163	0.0109	0.0082	0.0065
8	0.0377	0.0188	0.0126	0.0094	0.0075	0.0320	0.0160	0.0107	0.0080	0.0064	0.0302	0.0151	0.0101	0.0075	0.0060
9	0.0349	0.0174	0.0116	0.0087	0.0070	0.0299	0.0149	0.0100	0.0075	0.0060	0.0282	0.0141	0.0094	0.0071	0.0056
10	0.0327	0.0163	0.0109	0.0082	0.0065	0.0282	0.0141	0.0094	0.0070	0.0056	0.0267	0.0133	0.0089	0.0067	0.0053
11	0.0308	0.0154	0.0103	0.0077	0.0062	0.0268	0.0134	0.0089	0.0067	0.0054	0.0254	0.0127	0.0085	0.0063	0.0051
12	0.0293	0.0147	0.0098	0.0073	0.0059	0.0256	0.0128	0.0085	0.0064	0.0051	0.0243	0.0122	0.0081	0.0061	0.0049

Table 4.20. Theoretic variances (V_x) for alveograph strength (AS) for varying localities, years and replicates.

Localities	Years with 1 replication					Years with 2 replications					Years with 3 replications				
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5
1	36.98	18.49	12.33	9.25	7.40	24.85	12.43	8.28	6.21	4.97	20.81	10.40	6.94	5.20	4.16
2	21.42	10.71	7.14	5.36	4.28	15.36	7.68	5.12	3.84	3.07	13.33	6.67	4.44	3.33	2.67
3	16.23	8.12	5.41	4.06	3.25	12.19	6.10	4.06	3.05	2.44	10.84	5.42	3.61	2.71	2.17
4	13.64	6.82	4.55	3.41	2.73	10.61	5.30	3.54	2.65	2.12	9.60	4.80	3.20	2.40	1.92
5	12.08	6.04	4.03	3.02	2.42	9.66	4.83	3.22	2.41	1.93	8.85	4.42	2.95	2.21	1.77
6	11.05	5.52	3.68	2.76	2.21	9.03	4.51	3.01	2.26	1.81	8.35	4.18	2.78	2.11	1.67
7	10.31	5.15	3.44	2.58	2.06	8.57	4.29	2.86	2.14	1.71	8.00	4.00	2.67	2.00	1.60
8	9.75	4.88	3.25	2.44	1.95	8.23	4.12	2.74	2.06	1.65	7.73	3.86	2.58	1.93	1.55
9	9.32	4.66	3.11	2.33	1.86	7.97	3.99	2.66	1.99	1.59	7.52	3.76	2.51	1.88	1.50
10	8.97	4.49	2.99	2.24	1.79	7.76	3.88	2.59	1.94	1.55	7.35	3.68	2.45	1.84	1.47
11	8.69	4.34	2.90	2.17	1.74	7.59	3.79	2.53	1.90	1.52	7.22	3.61	2.41	1.80	1.44
12	8.45	4.23	2.82	2.11	1.69	7.44	3.72	2.48	1.86	1.49	7.11	3.55	2.37	1.78	1.42

Table 4.21. Theoretic variances (V_x) for alveograph distensibility (AD) for varying localities, years and replicates.

Localities	Years with 1 replication					Years with 2 replications					Years with 3 replications				
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5
1	329.63	164.81	109.88	82.41	65.93	217.73	108.87	72.58	54.43	43.55	180.43	90.22	60.14	45.11	36.09
2	164.81	82.41	54.94	41.20	32.96	108.87	54.43	36.29	27.22	21.77	90.22	45.11	30.07	22.55	18.04
3	109.88	54.94	36.63	27.47	21.98	72.58	36.29	24.19	18.14	14.52	60.14	30.07	20.05	15.04	12.03
4	82.41	41.20	27.47	20.60	16.48	54.43	27.22	18.14	13.61	10.89	45.11	22.55	15.04	11.28	9.02
5	65.93	32.96	21.98	16.48	13.19	43.55	21.77	14.52	10.89	8.71	36.09	18.04	12.03	9.02	7.22
6	54.94	27.47	18.31	13.73	10.99	36.29	18.14	12.10	9.07	7.26	30.07	15.04	10.02	7.70	6.01
7	47.09	23.54	15.70	11.77	9.42	31.10	15.55	10.37	7.78	6.22	25.78	12.89	8.59	6.44	5.16
8	41.20	20.60	13.73	10.30	8.24	27.22	13.61	9.07	6.80	5.44	22.55	11.28	7.52	5.64	4.51
9	36.63	18.31	12.21	9.16	7.33	24.19	12.10	8.06	6.05	4.84	20.05	10.02	6.68	5.01	4.01
10	32.96	16.48	10.99	8.24	6.59	21.77	10.89	7.26	5.44	4.35	18.04	9.02	6.01	4.51	3.61
11	29.97	14.98	9.99	7.49	5.99	19.79	9.90	6.60	4.95	3.96	16.40	8.20	5.47	4.10	3.28
12	27.47	13.73	9.16	6.87	5.49	18.14	9.07	6.05	4.54	3.63	15.04	7.52	5.01	3.76	3.01

Table 4.22. Theoretic variances (V_x) for alveograph P/L value (P/L) for varying localities, years and replicates.

Localities	Years with 1 replication					Years with 2 replications					Years with 3 replications				
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5
1	0.02467	0.01233	0.00822	0.00617	0.00493	0.01967	0.00983	0.00656	0.00492	0.00393	0.01800	0.00900	0.00600	0.00450	0.00360
2	0.01300	0.00650	0.00433	0.00325	0.00260	0.01050	0.00525	0.00350	0.00263	0.00210	0.00967	0.00483	0.00322	0.00242	0.00193
3	0.00911	0.00456	0.00304	0.00228	0.00182	0.00744	0.00372	0.00248	0.00186	0.00149	0.00689	0.00344	0.00230	0.00172	0.00138
4	0.00717	0.00358	0.00239	0.00179	0.00143	0.00592	0.00296	0.00197	0.00148	0.00118	0.00550	0.00275	0.00183	0.00138	0.00110
5	0.00600	0.00300	0.00200	0.00150	0.00120	0.00500	0.00250	0.00167	0.00125	0.00100	0.00467	0.00233	0.00156	0.00117	0.00093
6	0.00522	0.00261	0.00174	0.00131	0.00104	0.00439	0.00219	0.00146	0.00110	0.00088	0.00411	0.00206	0.00137	0.00104	0.00082
7	0.00467	0.00233	0.00156	0.00117	0.00093	0.00395	0.00198	0.00132	0.00099	0.00079	0.00371	0.00186	0.00124	0.00093	0.00074
8	0.00425	0.00213	0.00142	0.00106	0.00085	0.00363	0.00181	0.00121	0.00091	0.00073	0.00342	0.00171	0.00114	0.00085	0.00068
9	0.00393	0.00196	0.00131	0.00098	0.00079	0.00337	0.00169	0.00112	0.00084	0.00067	0.00319	0.00159	0.00106	0.00080	0.00064
10	0.00367	0.00183	0.00122	0.00092	0.00073	0.00317	0.00158	0.00106	0.00079	0.00063	0.00300	0.00150	0.00100	0.00075	0.00060
11	0.00345	0.00173	0.00115	0.00086	0.00069	0.00300	0.00150	0.00100	0.00075	0.00060	0.00285	0.00142	0.00095	0.00071	0.00057
12	0.00328	0.00164	0.00109	0.00082	0.00066	0.00286	0.00143	0.00095	0.00072	0.00057	0.00272	0.00136	0.00091	0.00068	0.00054

Table 4.23. Theoretic variances (V_x) for bread loaf volume (LFV) for varying localities, years and replicates.

Localities	Years with 1 replication					Years with 2 replications					Years with 3 replications				
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5
1	6772.8	3386.4	2257.6	1693.2	1354.6	4544.2	2272.1	1514.7	1136.0	908.8	3801.3	1900.6	1267.1	950.3	760.3
2	3783.9	1892.0	1261.3	946.0	756.8	2669.6	1334.8	889.9	667.4	533.9	2298.2	1149.1	766.1	574.5	459.6
3	2787.6	1393.8	929.2	696.9	557.5	2044.8	1022.4	681.6	511.2	409.0	1797.2	898.6	599.1	449.3	359.4
4	2289.5	1144.8	763.2	572.4	457.9	1732.4	866.2	577.5	433.1	346.5	1546.6	773.3	515.5	386.7	309.3
5	1990.6	995.3	663.5	497.7	398.1	1544.9	772.5	515.0	386.2	309.0	1396.3	698.2	465.4	349.1	279.3
6	1791.4	895.7	597.1	447.8	358.3	1419.9	710.0	473.3	355.0	284.0	1296.1	648.1	432.0	327.7	259.2
7	1649.0	824.5	549.7	412.3	329.8	1330.7	665.3	443.6	332.7	266.1	1224.5	612.3	408.2	306.1	244.9
8	1542.3	771.1	514.1	385.6	308.5	1263.7	631.9	421.2	315.9	252.7	1170.9	585.4	390.3	292.7	234.2
9	1459.3	729.6	486.4	364.8	291.9	1211.7	605.8	403.9	302.9	242.3	1129.1	564.6	376.4	282.3	225.8
10	1392.9	696.4	464.3	348.2	278.6	1170.0	585.0	390.0	292.5	234.0	1095.7	547.9	365.2	273.9	219.1
11	1338.5	669.3	446.2	334.6	267.7	1135.9	568.0	378.6	284.0	227.2	1068.4	534.2	356.1	267.1	213.7
12	1293.2	646.6	431.1	323.3	258.6	1107.5	553.8	369.2	276.9	221.5	1045.6	522.8	348.5	261.4	209.1

Table 4.24. Theoretic variances (V_x) for bread loaf volume standardized at 12% protein (LFV-12) for varying localities, years and replicates.

Localities	Years with 1 replication					Years with 2 replications					Years with 3 replications				
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5	Year 1	Year 2	Year 3	Year 4	Year 5
1	2186.1	1093.0	728.7	546.5	437.2	1476.8	738.4	492.3	369.2	295.4	1240.3	620.2	413.4	310.1	248.1
2	1094.6	547.3	364.9	273.6	218.9	739.9	370.0	246.6	185.0	148.0	621.7	310.8	207.2	155.4	124.3
3	730.7	365.4	243.6	182.7	146.1	494.3	247.2	164.8	123.6	98.9	415.5	207.7	138.5	103.9	83.1
4	548.8	274.4	182.9	137.2	109.8	371.5	185.7	123.8	92.9	74.3	312.4	156.2	104.1	78.1	62.5
5	439.7	219.8	146.6	109.9	87.9	297.8	148.9	99.3	74.5	59.6	250.5	125.3	83.5	62.6	50.1
6	366.9	183.5	122.3	91.7	73.4	248.7	124.3	82.9	62.2	49.7	209.3	104.6	69.8	53.5	41.9
7	314.9	157.5	105.0	78.7	63.0	213.6	106.8	71.2	53.4	42.7	179.8	89.9	59.9	45.0	36.0
8	276.0	138.0	92.0	69.0	55.2	187.3	93.6	62.4	46.8	37.5	157.7	78.9	52.6	39.4	31.5
9	245.6	122.8	81.9	61.4	49.1	166.8	83.4	55.6	41.7	33.4	140.5	70.3	46.8	35.1	28.1
10	221.4	110.7	73.8	55.3	44.3	150.4	75.2	50.1	37.6	30.1	126.8	63.4	42.3	31.7	25.4
11	201.5	100.8	67.2	50.4	40.3	137.0	68.5	45.7	34.3	27.4	115.6	57.8	38.5	28.9	23.1
12	185.0	92.5	61.7	46.2	37.0	125.9	62.9	42.0	31.5	25.2	106.2	53.1	35.4	26.5	21.2

CHAPTER 5

Stability analysis of South African spring wheat cultivars under irrigation for milling and baking characteristics.

5.1 Abstract

Five spring wheat cultivars (*Triticum aestivum* L.) were grown in five environments from 1997 through to 1999. The cultivars used in this study displayed a broad range in milling and baking quality. The following statistical analysis was conducted and procedures followed in order to determine stability for the milling and baking characteristics: (i) Wricke's - W_i (1962) ecovalence, (ii) Eberhart and Russell's - S^2d_i (1966) deviation parameter, (iii) Shukla's - σ^2_i (1972) stability variance, (iv) Linn and Binn's - P_i (1988a) cultivar superiority performance and (v) AMMI stability value - ASV (Purchase, 1997). Total correspondence for significance of Spearman's rank correlation coefficients for the different analysis procedures was noted for all the milling and baking characteristics. Lower significant rank correlation coefficients were found in the pairwise comparisons of both Eberhart and Russell's as well as that of Lin and Binn, but in the latter to a lesser extent. This indicates that these stability parameters differ from the other procedures in stability determination and definition, and due to noted deficiencies are consequently not recommended for use. From this study, it would appear that all three the following appropriate methods namely Wricke's ecovalence, Shukla's stability variance as well as the AMMI Stability Value can be used to describe the stability of a genotype.

5.2 Introduction

Genotype x environment interaction (G x E) is an important issue with which plant breeders and agronomists are being confronted world-wide, while in South Africa with its characteristically variable climate the situation is not different. Breeders constantly strive to develop improved varieties 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 therefore generally accept the need for high performance and stable varieties, however there is not consensus about the appropriate definition of stability and on the methods to measure and improve performance stability (Purchase, 1997). The basic cause of differences in yield stability between genotypes is due to 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, nitrogen, temperature, diseases and many other factors (Becker and Léon, 1988).

Although the two main elements that influence genotypic performance such as nutrition and rainfall are being controlled for spring wheat production under irrigation in South Africa, it is still being subjected to considerable variation in soil and climate conditions. This results in significant variation in yield and bread making quality of wheat cultivars cultivated in this region. Most of the genotype and environment interaction research projects that have been carried out until now were on winter wheat production under dryland conditions as well as spring wheat production in the Mediterranean rainfall area down in the Cape Province (Van Lill, *et al.*, 1993; Purchase, 1997; Purchase *et al.*, 2000a; Nel, *et al.* 2000a; Nel, *et al.* 2000b).

Genotype x environment interaction is normally associated with the differential performance of genotypes, tested at various sites and years. Its influence on the selection and recommendation of cultivars has been acknowledged and documented by various researchers (Van Deventer, 1985; Lin *et al.* 1986; Van Lill *et al.* 1993; Purchase, 1997; Purchase *et al.* 2000a; Nel *et al.* 2000a; 2000b; Kasa, 2002). Selection of genotypes is based on the assessment of their phenotypic value in varying environments (Kasa, 2002). According to Crossa (1990) the evaluation of genotype performance at a number of locations provides useful information to determine their adaptation and stability performance. According to Romagosa and Fox (1993) and Yue *et al.* (1997) the measurement of genotype x environment interaction provides insight in determining an optimum breeding strategy of either breeding for specific or wide adaptation, which again depends on the expression of stability under a limited or wide range of environments.

According to Allard and Bradshaw (1964) stability specifically refers to non-erratic performance with respect to agronomic traits and stable cultivars, which shows minimal or low interactions with environments. Stability also represents consistency in ranks of a

cultivar relative to other cultivars in a given set of environments (Yue *et al.*, 1997). Becker and Léon, (1988), stated that varieties, which exhibit high and stable performances, are mostly in demand. Instability is caused by the differential expression of traits across environments or genotype x environment interaction, which decreases progress in selection due to the reduction in the association between genotypic and phenotypic values. Therefore, it complicates the selection process for widely adapted and stable cultivars which can overcome the existing problem of genotype x environment interaction (Romagosa and Fox, 1993).

Lin *et al.* (1986) introduced three concepts of stability namely: Type I, defined as that a genotype is being considered stable if its variance over a range of environments is small. Type II, defined as that a genotype is being considered 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 coefficients in joint linear regression). Type III, stability is being defined as a genotype being considered stable if the residual mean squares from the regression model on the environment index is small, this concept however was firstly introduced by Eberhart and Russell (1966).

Becker and Léon (1988) also made a distinction between two different concepts of stability, namely static and dynamic stability respectively. When a genotype possesses a stable unchanged performance regardless of the variation of the environments and thus implying that its variance over environments is zero, it is being referred to as static stability, which is similar to the Type I stability of Lin *et al.* (1986). Becker (1981) suggested the term dynamic stability to distinguish it from the static concept. Therefore, dynamic stability is being referred to as a genotype having a predictable response to environments and thus having no deviation from this particular response to environments. Becker and Léon (1988) acknowledged that all stability procedures based on quantifying genotype x environment interaction effects actually belong to the dynamic stability concept. Procedures that partition the observed genotype x environment interaction effects, is therefore included within the dynamic concept. Procedures such as Wricke's ecovalance (Wricke, 1962) and Shukla's stability variance (Shukla, 1972), procedures using the regression approach such as proposed by Finlay and Wilkenson (1963), Eberhart and Russell (1966) and Perkins and Jinks (1968), as well as non-parametric stability statistics (Nassar and Hühn, 1987) can be considered as dynamic stability concepts.

Non-parametric statistics for G x E interactions based on ranks provide a useful alternative to parametric approaches being 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 description of the analysed value and (iii) homogeneity of variances and rank-orders are often easy to use and to interpret (Purchase, 1997).

Lin and Binns (1988a, b) proposed a stability concept uniquely different from the above-mentioned concepts. This concept is known as the cultivar performance measurement (P_i) and is defined as the P_i of genotype i as the mean square of distance between genotype i and the genotype with the maximum response. The smaller the value of P_i , the less its distance to the genotype with the maximum yield and thus the better the genotype.

Multivariate techniques are also being applied extensively in stability analysis procedures in order to provide further information on the real multivariate response of genotypes to environments. Data collected from G x E trials are intrinsically complex and have three fundamental aspects: (i) structural patterns, (ii) non-structural noise, and (iii) 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. If there was no interaction, a single variety of wheat would, for example, yield the most world wide, and furthermore the variety trial need only to 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 (Purchase, 1997). The function of experimental design and statistical analyses of multi-location trials is thus to eliminate and discard as much of this unexplained noise as possible (Cossa, 1990). The three main purposes of multivariate analysis are: (i) to eliminate noise from the data pattern, (ii) to summarize the data, and (iii) to reveal a structure to the data (Purchase *et al.*, 2000b). The different multivariate analysis procedures enable researchers to cluster genotypes with similar responses; construct hypotheses, which can also be validated and the data can be analysed and summarized more easily (Gauch, 1982; Cossa, 1990; Hohls, 1995). According to Becker and Léon (1988) the main aim of the various existing multivariate classification systems are to group genotypes together into quantitatively

distinctly homogeneous stability subsets. Within the subsets, no significant G x E interactions will 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 (Purchase, 1997). Another drawback is that a non-existent structure could be forced onto the data, which can complicate the interpretation of the results drastically (Hohls, 1995). However, if well known cultivars or genotypes are being included in the analysis they can serve as paradigms for other genotypes in the same subset (Lin *et al.*, 1986). Techniques that fall into this category are the principal component analysis (PCA), principle coordinates analysis, factor analysis, cluster analysis and the additive main effects and multiplicative interaction method, widely known as the AMMI model (Purchase *et al.*, 2000). The AMMI model's main aim is to combine the analysis of variance for genotype and environment main effects together with the principle component analysis of the G x E interaction into a unified approach (Gauch, 1988; Zobel, Wright and Gauch, 1988).

The main aim of this study was to compare the various available statistical procedures in assessing performance stability regarding milling and baking characteristics in order to identify the most suitable method. With this information on hand scientists and breeders will be able to select the most appropriate procedure in order to determine genotype performance as well as stability regarding the relevant milling and baking characteristics. Secondly, the purpose of this study was to determine which of the cultivars exhibit the best stability in order to identify the superior wheat genotypes. These genotypes can then be selected for specific or larger regions with a better understanding of the interaction of these genotypes with the environment. In assessing the performance of wheat cultivars in the irrigation areas, the determined stability values of cultivars for bread making quality provides essential information on the consistency of spring wheat cultivars with regard to their milling and baking characteristics. This will improve the reliability of recommendations to be made for the processing industry as well as producers.

5.3 Materials and methods

Evaluation of wheat quality involves the measurement of a large number of characteristics. Since many of the tests for quality evaluation are time-consuming and expensive, they have been performed traditionally on a limited number of samples. The number of samples to be evaluated may be reduced by combining samples over replicates, locations or years. However, this procedure reduces the precision with which quality characteristics are estimated and may lead to erroneous conclusions if large cultivar by environment interactions do occur (Lukow and McVetty, 1991). Therefore, in order to improve the precision of the analysis the number of cultivars, localities, replications and years were maintained throughout the study.

5.3.1 Field trials

Five genetically diverse spring wheat cultivars namely, Kariega, Marico, SST825, SST822 and SST876 were the genotypes common in all three years of testing. Small Grain Institute (Agricultural Research Institute) released Kariega and Marico, while Monsanto owns the Plant Breeders Rights on the latter three cultivars. The term "spring wheat" implies that such cultivars do not need a certain degree of vernalization requirements in order to reach full maturity. The genotypes, year of release, status and origin for the genotypes used in this study are indicated in Table 3.1.

Most of the cultivars are semi-dwarf cultivars except for SST822, which is a short growth period double dwarf. Double dwarf wheat cultivars tend to have lower yield potential than semi dwarf wheat cultivars in South Africa. SST876 possesses the solid stem characteristic originating from *Aegilops ventricosa*. The solid stem characteristic improved lodging tolerance dramatically, with resultant higher grain yield. Kariega is the biological quality standard being used by the South African Wheat Technical Committee as a reference cultivar. This implies that all new lines are compared against Kariega for possible release as new cultivars in the irrigation areas. Kariega and Marico are long growth period cultivars while SST 825 and SST 876 are classified as medium growth period cultivars. Seed for the given quality analysis, were obtained from trials conducted

in the irrigation areas by the National Cultivar Evaluation Department of Small Grain Institute during 1997,1998 and 1999.

Table 5.1. Genotypes and their pedigrees, year of release, status and origin.

Genotype		Year	Status	Origin
Marico	Broadbill"s"	1992	Cultivar	CIMMYT, Mexico
Kariega	SST44//K45400/Sapsucker"s"	1993	Cultivar	SGI, RSA
SST822	Not available	1992	Cultivar	Monsanto, RSA
SST825	Tui"s"	1992	Cultivar	CIMMYT, Mexico
SST876	SST57/Adam Tas//SST 825	1997	Cultivar	Monsanto, RSA

SGI = Small Grain Institute

RSA = Republic of South Africa

Wheat production under irrigation in the summer rainfall region entails the production of spring wheat types, which are planted in the fall and winter. There are five main irrigation areas, namely the cooler central irrigation areas (situated next to the Orange, Vaal, Sand and Vet rivers), the warmer northern irrigation areas (along the Eliphants and Crocodile rivers, the Loskop dam irrigation area is also included here), Kwazulu-Natal, Eastern Free State and the Eastern Cape (Cradock). The warmer northern irrigation regions have a lower yield potential compared to that of the cooler central irrigation areas, and this is mainly due to the warmer winter temperatures and therefore a shorter growing season. This leads to a higher growth and development rate, weaker tillering capacity and subsequently lower yields. The irrigation areas represent high yielding environments, which rely heavily on intensive cropping systems.

The region, location, coordinates and number of trials from 1997 until 1999 included for quality analysis can be seen in Table 3.2. Trials were conducted at experimental stations or farms of collaborators where the soil and climate are representative of a specific area.

Table 5.2. Regions with representative localities and the number of trials from 1997 until 1999.

Region	Locality	1997	1998	1999
Warmer areas	Loskop	1	1	1
Cooler areas	Bull Hill	1	1	1
	Prieska	1	1	1
	Hopetown	1	1	1
	Douglas	1	1	1

It is very important to bring cultivar performance in line with the weather conditions that prevailed during the growth cycle. For the 1997 season normal temperatures occurred during the period up to the middle of June in all the regions. Temperatures above average occurred during the second half of winter in all five regions. Above average temperatures were measured during the grain filling period from August through to October. This had a negative influence on the yield and hectolitre mass levels.

During the 1998 season normal to above average temperatures occurred in all the irrigation areas during the second part of the winter months up to the end of August. Below average temperatures were measured during September and October which had a positive influence on grain filling period resulting in higher yields and hectolitre masses. In some of the areas heavy rain showers were observed which lowered the hectolitre masses slightly.

Regarding the 1999 season normal to above normal temperatures occurred during the growth period up to the end of August in all the irrigation areas. Above average temperatures occurred in all five irrigation areas during the second half of the winter. Relatively low temperatures occurred during September and October, which had a positive effect on yield and hectolitre mass.

The cultivars were planted according to a randomised block design with four replicates. Trial plots consisted of eight rows 0.17 m apart and six meter in length, which were then later reduced to five meters length to produce a net plot size value of 6.8m². The seeding rate was standardized for each cultivar according to its 1000 kernel weight.

Therefore, the seeding rate for each cultivar differed in order to establish a uniform stand of plants per square meter.

Fertilization was applied according to target yield recommendations for each region. Applications on the trial plots were done according to recommendations based on individual soil analyses obtained from soil samples. Weed and pest control was performed when necessary. At harvesting, the two side rows were cut out in order to reduce the side-row effect, which can influence yield positively, thus the net plot size harvested for the quality analysis was 5.1 m². The plots were harvested with a Wintersteiger plot combine.

The soil profiles in the cooler central irrigation areas are mostly sandy and red in colour. Soils with high clay contents are found in the warmer northern irrigation regions. Maximum temperatures above 30°C during kernel filling period are a common phenomenon that eventually increases the risk for drought stress with consequently low hectolitre masses and high protein contents (Koekemoer, 1997). Mostly the total rainfall figures in all the irrigation areas except Kwazulu-Natal do not exceed 200mm during the growth cycle.

5.3.2. *Quality analysis*

Test weight or hectolitre mass (HLM, kg/hl) was determined using a Franklin chondrometer. The mass of a thousand kernels counted with a Numigral seed counter (Tripette et Renaud Paris France) was considered as the thousand kernel mass (TKM, g). After 50 grains had been cut with a farinator, vitreous kernels (VK, %) were determined as the total of two points per fully vitreous grain and one point per grain with at least 50% vitreousness. Grain samples of approximately 50 g were milled with a Falling Number KT-120 laboratory mill (1.0mm sieve) after which Hagberg Falling Numbers (FLN, s) were determined (AACC, 1983) from a 6.1 g sample to compensate for altitude (\pm 1340m). The grain protein contents (GPC-Leco, %) and flour protein contents (FPC-Leco, %) were determined with a Leco-FP2000 (AACC, 1995). Flour extraction rate (FLY, %) and break flour yields (BFLY, %) were calculated after experimental milling in a pneumatic Buhler MLU202 mill (Buhler-Miag, Uzwil, Switzerland), (AACC, 1983). A Kent Jones and Martin colour grader was used to

measure flour colour standardised at a 76% flour extraction rate (FCL76, kj units). Single kernel characteristics were determined using the SKCS 4100 (Perten Instruments, Springfield, IL), this instrument provides characteristics like kernel diameter (average diameter of 300 kernels), hardness index (the index as percentage of the pressure of two rollers to crush 300 kernels) and kernel weight (the average weight of 300 kernels in mg).

Mixograph dough development time (MDT, min) was determined with a 35g National Mixograph (National Mfg., Lincoln, Nebraska), (AACC, 1983). Other rheological analyses performed according to approved methods (AACC, 1983) included the Brabender Farinograph quality determinant water absorption (FABS, %), the Chopin Alveograph determinants: dough strength (AS, cm²), Alveograph stability (ASTAB, mm), Alveograph distensibility (AD, mm) and the ratio of stability to distensibility (P/L). In this study, micro loaves were baked from 100g of flour, using an optimized straight dough method (Finney, 1984). Loaf volumes were then determined by rapeseed displacement directly after baking, using a pup loaf volumeter. The SDS-sedimentation (sodium dodecyl sulphate –SDS) test was used to measure the relative gluten strength as it indicates the differences in the quantities of the polymeric glutenins (gel protein), (AACC, 1983). Wet-gluten content was determined with the glutomatic; the glutomatic is an automatic apparatus, which develops gluten of wheat flour from a 2% NaCl solution. The dough mixing and subsequent separation of starch and other solubles from the dough takes place in the same test chamber under controlled standardized conditions. The ball is then centrifuged to remove excess water and weighed as wet gluten.

In order to simplify the discussion, all the quality characteristics were divided into two groups namely milling and baking characteristics. The milling characteristics are represented by hectolitre mass (HLM), thousand kernel mass (TKM), Vitreous kernel (VK), SKCS weight (SKCS-G), SKCS diameter (SKCS-DIA), SKCS hardness index (SKCS-HI), Farinograph water absorption (FABS), break flour yield (BFLY) and flour yield (FLY). The baking characteristics are represented by falling number (FLN), grain protein content determined by the Leco (GPC-Leco), flour protein content determined by the Leco (FPC-Leco), Wet gluten content standardized at 12% protein content (WGC-12), SDS-sedimentation value (SDSS), mixograph development time (MDT), alveograph strength (AS), alveograph distensibility (AD), alveograph stability (ASTAB), alveograph P/L index (P/L), loaf volume (LFV) and loaf volume standardized at 12% protein content (LFV-12) in order to eliminate the positive effect of protein content on bread loaf volume.

5.3.3 Statistical analysis

5.3.3.1. Analysis of variance

An analysis of variance (ANOVA) was performed on all the milling and baking data of each of the individual trials, using the statistical software package AgrobasesTM. Thereafter a combined analysis of variance was performed on the pooled set of data of all the trials over a three-year period also using AgrobasesTM.

5.3.3.2 Homogeneity of variances

Bartlett (1947) test was used to determine if the variances of the different milling and baking characteristics showed any homogeneity of residual variances (deviations from the regression line) at the test levels of $\alpha = 0.05$ and $\alpha = 0.01$. Because Bartlett's test is much more sensitive to non-normality than the F-test, a smaller test level than the customary $\alpha = 0.05$ can be used. This ensures that the residual variances are not declared heterogeneous when F-tests for the comparison of the slopes and elevations can tolerate some heterogeneity. A test of $\alpha = 0.001$ may also be suitable and one would really be concerned if heterogeneity was evident at this level (Van Ark, 1995). The results however showed that the α -value for all the milling and baking characteristics separately varied between ($\alpha = 0.01$) and ($\alpha = 0.01$). The original version of the data was thus used in the analysis, because homogeneity of the residual variances confirmed that the comparison of the slopes regarding the regression lines is valid.

5.3.3.3 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 resulting values as determined with the statistical software package AgrobasesTM (1999) are estimates of the G x E interaction effects for each entry, squared and summed across all environments, as a measure of stability. The ecovalence (W_i) or stability of the i^{th} genotype is an estimation of its interaction with the environments, squared and summed across environments as a measurement of stability and is expressed as:

$$W_i = \sum_j (Y_{ij} - \bar{Y}_j - \bar{Y}_{.j} + \bar{Y}_{..})^2$$

Where Y_{ij} is the mean performance of genotype i in the j^{th} environment and \bar{Y}_j and $\bar{Y}_{.j}$ are the genotype and environment mean deviations respectively, and $\bar{Y}_{..}$ is the overall mean. Accordingly, genotypes with low ecovalance have smaller fluctuations from the mean across different environments and are therefore more stable.

5.3.3.4 Eberhart and Russell's joint regression analysis

Eberhart and Russell's joint regression analysis was carried out with the statistical software package AgrobasesTM (1999). Eberhart and Russell (1966) proposed a joint linear regression model where the sum of squares for environments and G x E interactions are being pooled and then being subdivided into linear effect between environments (with 1 df), a linear effects for G x E (with G-1 df), and a deviation from regression for each genotype (with E-2 df). In effect, the residual mean square from the regression model across environments is used as an index of stability and a stable genotype is one in which the deviation from regression mean square (s^2d_i) is small:

$$s^2d_i = \frac{1}{E-2} [E_j (X_{ij} - \bar{X}_i - \bar{X}_{.j} + \bar{X}_{..})^2 - (b_i - 1)^2 E_j (\bar{X}_{.j} - \bar{X}_{..})^2]$$

5.3.3.5 Shukla's procedure of stability variance (σ^2_i)

Shukla's stability variance for each genotype across environments was determined with the AgrobasesTM statistical programme. Shukla (1972) defined the concept of stability variance as an unbiased estimate of the variance of genotype i as its variance across environments after the main effects of environmental means have 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:

$$\sigma^2_i = \frac{1}{(G-1)(G-2)(E-1)} [G(G-1)\sum_j (Y_{ij} - \bar{Y}_i - \bar{Y}_{.j} + \bar{Y}_{..})^2 - \sum_i \sum_j (Y_{ij} - \bar{Y}_i - \bar{Y}_{.j} + \bar{Y}_{..})^2]$$

Where Y_{ij} is the mean yield of the i^{th} genotype in the j^{th} environment, \bar{Y}_i is the mean of genotype i in all the environments, $\bar{Y}_{.j}$ is the mean of all the genotypes in j^{th} environments and $\bar{Y}_{..}$ is the mean of all genotypes and all environments. The ratio of σ^2_i to the pooled error mean square (σ^2_e) is used to approximate the F-test.

A genotype is called stable if its stability variance (σ^2_i) is equal to the environmental variance (σ^2_e) which means that $\sigma^2_i = 0$. A relatively large value of σ^2_i will thus indicate greater instability of genotype i . As the stability variance is the difference between the two sums of squares, it can be negative, but negative estimates of variance can be observed in variance components problems. Negative estimates of σ^2_i may be taken as equal to zero as usual (Purchase, 1997).

5.3.3.6 Lin & Binns' cultivar performance measurement (P_i)

The data set was analysed according to the procedure recommended by Lin & Binns (1988b) 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 AgrobasesTM statistical programme.

Lin and Binns (1988a, 1988b) proposed the use of cultivar performance measurements (P_i) and defined P_i of genotype i as the mean squares of distance between genotype i and the genotype with the 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 the genotype i in environment j , Y_i is the mean deviation of the 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 is the distance to the genotype with maximum yield and thus the better the genotype (Purchase, 1997).

5.3.3.7 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. 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 (Purchase, 1997):

$$\text{AMMI Stability Value (ASV)} = \sqrt{\frac{\text{IPCA1 Sum of squares}}{\text{IPCA2 Sum of squares}} (\text{IPCA1 score})^2 + [\text{IPCA2 score}]^2}$$

In effect the AMMI Stability Value (ASV) is the distance from zero in a two dimensional scattergram of IPCA1 scores against IPCA2 scores. 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 (Purchase, 1997)

5.3.3.8 Combined comparison of stability analysis procedures

To statistically compare the six stability analysis procedures used in this study, Spearman's coefficient of rank correlation was used (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 $d_i = X_i - Y_i$ ($i = 1, 2, \dots, n$) 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

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

with $n-2$ degrees of freedom

If $t = t_{(0.01; N-2)}$, the null hypothesis is discarded and r_s is described as highly significant.

5.4 Results and discussion

5.4.1 Stability analysis of the cultivars

5.4.1.1 Analysis of variance

In Tables 5.3 and 5.4 the analyses of variance results for the milling and baking results are being indicated respectively. Both the ANOVA's indicated highly significant differences for genotypes, environments and most importantly genotype x environment interaction. As indicated in Chapter 3 the percentage contribution for each variance component in relation to the total variance for milling and baking characteristics

respectively for genotypes varied between 1.07% (Vitreous kernels) and 57.65% (mixograph development time) (Tables 3.12 and 3.13). The difference is explained by the second (environment, genotype x locality interaction and genotype x year interaction) and third order interactions (genotype x year x locality interaction). The extent of the second and third order interaction indicates an overwhelming influence of the environment on both milling and baking performance of wheat cultivars in the respective irrigation wheat producing areas.

In Table 5.5 and 5.7 the mean values regarding the milling and baking characteristics are indicated respectively, the least significant difference value between genotypes as the main effect, using Tukey's pairwise comparison is also shown. Ranking orders for each cultivar regarding their mean milling as well as baking values are being tabulated in Tables 5.6 and 5.8.

All three parameters namely thousand kernel mass (TKM), single kernel diameter (SKCS-DIA) and single kernel weight (SKCS-G) are indicators for kernel size. From Table 5.5 it is evident that the TKM and SKCS-G values for both Marico and SST 876 are significantly lower than that of Kariega, the biological standard. This indicates that Marico and SST 876 have smaller kernels than the rest of the cultivars. Although kernel size is an indication of flour yield (Eggitt and Hartley, 1975), the observed smaller kernel sizes of Marico (76.87%) and SST 876 (76.47%) did have an effect on their flour yield when compared to Kariega (76.83%) (Table 5.5). Both SST 876 and SST 822 displayed significantly higher hectoliter mass (HLM) values than Kariega. Higher hectolitre mass is also indicative of grain plumpness (McDonald, 1994) and may predict potential flour yield (Finney *et al.* 1987; Nel *et al.* 1998). In the case of SST 876 and Marico their high hectolitre mass values (as an indicator of grain plumpness) had a larger positive influence on the expression of their flour yield potential than their kernel size.

Hardness is one of the most important characteristics of wheat from the standpoint of milling and end-use properties (Pomeranz and Mattern, 1988), because the milling and flour quality is often influenced by kernel hardness (Gaines *et al.*, 1996). Indicators of hardness is VK, SKCS-HI, BFLY and FABS. Table 5.5 demonstrates that none of the cultivars differed significantly from Kariega regarding their VK values. SST 825 (68.86) showed a significant higher SKCS-HI value when compared to the rest of the cultivars included. Kariega on the other hand had the lowest SKCS-HI value (59.73). Therefore,

it can be concluded that SST825 is significantly harder than the rest of the cultivars, while Kariega's kernel texture could almost be classified as medium to soft. Consequently a significant drop in BFLY can be seen for SST825, SST882 as well as SST876. Significant increases for FABS values were observed for both SST 825 and SST 822, due to higher starch damage levels. Marico's FABS value was significantly lower than the rest of the cultivars included in this study. Lower dough yields can be a result from the lower water absorption levels observed for Marico's flour.

Table 5.5. Means for milling characteristics of spring wheat cultivars under irrigation.

Cultivar	HLM (Kg/hl)	TKM (g)	SKCS-G (mg)	SKCS-DIA (mm)	VK (%)	SKCS-HI	FABS (%)	BFLY (%)	FLY (%)
Marico	77.86	38.27	37.30	2.50	79.22	65.06	59.86	22.30	76.87
Kariega	78.05	41.08	40.02	2.72	76.56	59.73	62.15	22.69	76.83
SST 825	78.50	40.46	39.71	2.81	78.33	68.86	63.91	18.96	75.59
SST 822	78.89	40.30	39.45	2.70	78.27	66.95	62.83	21.38	75.06
SST 876	79.90	39.64	38.31	2.68	73.18	65.32	62.07	19.62	76.47
CV% [@]	1.85	5.33	5.18	5.27	9.07	5.77	1.84	4.55	1.04
Means [*]	78.64	39.95	38.96	2.68	77.11	65.18	62.16	20.99	76.16
LSD [#]	0.61	0.88	0.85	0.06	2.92	1.57	0.48	0.40	0.33

*Means = Means represents the averages for 3 replicates, 5 environments and 3 years combined

LSD = Least significant difference at the $p < 0.05$

@ CV% = Coefficient of variance

HLM = hectolitre mass, TKM = thousand kernel mass VK = Vitreous kernel, SKCS-G = SKCS weight, SKCS-DIA = SKCS diameter, SKCS-HI = SKCS hardness index, FABS = Farinograph water absorption, BFLY = break flour yield and FLY = flour yield.

From Table 5.6 it is clear that Kariega mostly ranked first or second regarding its milling characteristics except for HLM, VK and SKCS-HI, due to the softer nature of its kernel texture. This again underlines why Kariega has such a reputation for its exceptional flour yield potential within the South African context. SST 825 also consistently ranked second or third regarding its milling characteristics except for its BFLY. This can be ascribed to its harder observed kernel texture, which normally produces lower break flour yields. SST 876 and Marico mostly ranked 4th and 5th regarding their milling characteristics (Table 5.6).

Table 5.6. Ranks for milling characteristics of spring wheat cultivars under irrigation.

Cultivar	HLM (Kg/hl)	TKM (g)	SKCS-G (mg)	SKCS-DIA (mm)	VK (%)	SKCS-HI	FABS (%)	BFLY (%)	FLY (%)
Marico	5	5	5	5	1	4	5	2	1
Kariega	4	1	1	2	4	5	3	1	2
SST 825	3	2	2	1	2	1	1	5	3
SST 822	2	3	3	3	3	2	2	3	5
SST 876	1	4	4	4	5	3	4	4	3

HLM = hectolitre mass, TKM = thousand kernel mass VK = Vitreous kernel, SKCS-G = SKCS weight, SKCS-DIA = SKCS diameter, SKCS-HI = SKCS hardness index, FABS = Farinograph water absorption, BFLY = break flour yield and FLY = flour yield.

From Table 5.7 it is evident that the condition of the seed was sound because all the cultivars produced falling number (FLN) values above 220s, the actual limit set by the South African wheat grading system for non-sprouted wheat samples. SST 822 was the only cultivar that had a significantly higher FLN value than Kariega. Significant differences were observed among the tested cultivars for GPC-Leco and FPC-Leco. SST 822 exhibited significant higher GPC-Leco value and SST 876 significant lower GPC-Leco value in comparison to Kariega. Cultivars with higher grain yields (like SST 876) tend to have lower protein contents than cultivars with lower grain yields (like SST 822) at a given level of available nitrogen (Terman, 1979; Clarke *et al.*, 1990; Nel *et al.*, 1998).

The gluten proteins of wheat are mainly responsible for the visco-elastic structure of dough, thus the SDS sedimentation test (SDSS) measures the relative bread making ability and gluten strength (De Villiers and Laubscher, 1995) of wheat genotypes, which is not very sensitive to environmental effects (János, 1998). All the cultivars produced SDSS values significantly lower than that of Kariega, however only the SDSS value of SST 876 was low enough to be actually reflected in the bread making ability and gluten strength values (Table 5.7). The mixograph mixing time (MDT) of SST 876 was significant lower than that of Kariega, while SST 825, SST 822 as well as Marico showed significantly higher MDT values than Kariega. Regarding the alveograph test, only SST 825 can be labelled as a cultivar with significantly stronger rheological dough characteristics displayed by its higher AS; ASTAB and P/L (Table 5.7). The higher P/L ratio of SST 825 can also be a secondary result regarding its improper conditioning due to its harder kernel texture (SKCS-HI value) as seen in Table 5.7. Both the LFV and LFV-12 tests give an indication of the gas retention capacity of the dough during the

fermentation process (Shogren and Finney, 1984). Only SST 876 produced a significant lower LFV value than Karioga, due to its weaker dough strength.

Table 5.7. Means for baking characteristics OF spring wheat cultivars under irrigation.

	FLN	GPC-Leco	FPC-Leco	WGC-12	SDSS	MDT	AS	AD	ASTAB	P/L	LFV	LFV-12
Cultivar	(s)	(%)	(%)	(g)	(ml)	(min)	(cm ²)	(mm)	(mm)		(cm ³)	(cm ³)
Marico	309.22	12.53	11.60	30.28	77.13	3.52	40.60	131.44	64.87	0.54	937.40	928.69
Karioga	316.80	12.73	11.97	33.71	80.73	2.60	39.27	150.47	63.24	0.46	969.00	957.40
SST 825	325.42	12.72	11.92	33.17	73.71	2.78	44.00	117.02	84.07	0.75	971.36	933.02
SST 822	329.09	13.15	12.10	34.32	75.51	2.76	36.09	138.96	65.73	0.47	972.09	958.58
SST 876	320.87	12.38	11.64	34.53	67.04	1.98	28.36	126.73	62.42	0.54	913.33	924.22
CV% [@]	8.01	4.39	5.58	6.07	5.87	11.44	11.91	11.34	9.35	21.40	6.73	4.12
Means [*]	320.28	12.70	11.83	33.20	74.82	2.73	37.66	132.92	68.07	0.55	952.64	940.38
LSD [#]	9.48	0.23	0.28	0.84	1.83	0.13	1.87	6.29	2.73	0.05	26.74	16.18

*Means = Means represents the averages for 3 replicates, 5 environments and 3 years combined

LSD = Least significant difference at P<0.01

@CV% = Coefficient of variance

FLN = falling number, GPC-LECO = grain protein content determined by the Leco, FPC-LECO = flour protein content determined by the Leco, WGC-12% = Wet gluten content at 12% protein content, SDSS = SDS-sedimentation value, MDT = mixograph development time, AS = alveograph strength, AD = alveograph distensibility, ASTAB = alveograph stability, P/L = alveograph P/L index LFV = loaf volume and LFV-12% = loaf volume standardized at 12% protein content.

Similar distinguishable patterns are not as easily visible when comparing the rankings of the baking versus milling characteristics in Tables 5.8 and 5.6 respectively. However when separating the characteristics that influence the rheological properties of the dough (MDT, AS, AD, ASTAB and P/L) it is clear that SST 876 ranked mostly last, while SST 825 ranked mostly first with Karioga in between (Table 5.8).

Table 5.8. Ranks for baking characteristics of spring wheat cultivars under irrigation.

	FLN	GPC-Leco	FPC-Leco	WGC-12	SDSS	MDT	AS	AD	ASTAB	P/L	LFV	LFV-12
Cultivar	(s)	(%)	(%)	(g)	(ml)	(min)	(cm ²)	(mm)	(mm)		(cm ³)	(cm ³)
Marico	5	4	5	5	2	1	2	3	3	3	4	4
Kariega	4	2	2	3	1	4	3	1	4	5	3	2
SST 825	2	3	3	4	4	2	1	5	1	1	2	3
SST 822	1	1	1	2	3	3	4	2	2	4	1	1
SST 876	3	5	4	1	5	5	5	4	5	2	5	5

FLN = falling number, GPC-LECO = grain protein content determined by the Leco, FPC-LECO = flour protein content determined by the Leco, WGC-12% = Wet gluten content at 12% protein content, SDSS = SDS-sedimentation value, MDT = mixograph development time, AS = alveograph strength, AD = alveograph distensibility, ASTAB = alveograph stability, P/L = alveograph P/L index LFV = loaf volume and LFV-12% = loaf volume standardized at 12% protein content.

5.4.2 Stability methods

5.4.2.1 Wricke's ecovalence concept (W_i)

Wricke (1962) defined the concept of ecovalence as the contribution of each genotype to the genotype x environment interaction sum of squares. The ecovalence W_i or the stability of the i^{th} genotype is its interaction with environments, squared and summed across environments. Genotypes with low ecovalence have smaller fluctuations from the mean across different environments and are therefore stable. Wricke's ecovalence concept values for the milling as well as the baking characteristics can be seen in Tables 5.9 and 5.10.

According to Wricke's ecovalence analysis the cultivar Marico was very stable for the following milling characteristics namely; SKCS-DIA, VK, SKSCS-HI and BFLY. Marico had intermediate stable values for SKCS-G, TKM and FABS, but was unstable for HLM and FLY (Table 5.9). Kariega showed stable values for HLM and FABS, but exhibited intermediate stable W_i values for VK and FLY. Kariega's W_i values were unstable for TKM, SKSC-G, SKCS-DIA, SKSC-HI and BFLY. SST 825 however displayed stable W_i values for SKCS-G and VK, while it had intermediate stable W_i values for TKM, FABS and FLY. SST 825 was unstable for HLM, SKCS-DIA, SKCS-HI and BFLY. SST 822's W_i values were stable for SKCS-DIA, BFLY and FLY. It also had intermediate stable W_i values for HLM, TKM, SKCS-G and SKCS-HI, while it was unstable for VK and FABS. SST876 showed stable W_i values for its milling traits

involved in kernel size (HLM, TKM, SKCS-G and SKCS-DIA) and had intermediate stable values for SKCS-HI, FABS and BFLY, while it was unstable for VK and FLY (Table 5.9).

Table 5.9. Wricke's ecovalence values of milling characteristics for spring wheat cultivars under irrigation.

Cultivar	HLM	R	TKM	R	SKCS-G	R	SKCS-DIA	R	VK	R	SKCS-HI	R	FABS	R	BFLY	R	FLY	R
Marico	24.52	5	42.13	4	49.45	4	0.10	3	247.20	2	72.19	1	18.14	2	5.31	2	14.14	5
Kariega	9.30	1	46.40	5	73.77	5	0.16	5	298.42	3	278.86	4	13.17	1	30.51	4	10.17	2
SST825	19.50	4	40.10	3	43.28	2	0.15	4	228.27	1	296.48	5	21.65	4	32.55	5	12.33	3
SST822	14.05	3	35.79	2	46.85	3	0.08	2	530.01	5	139.98	3	24.60	5	4.62	1	6.83	1
SST876	10.88	2	22.19	1	36.73	1	0.07	1	399.71	4	108.67	2	21.47	3	13.75	3	13.17	4

HLM = hectolitre mass, TKM = thousand kernel mass VK = Vitreous kernel, SKCS-G = SKCS weight, SKCS-DIA = SKCS diameter, SKCS-HI = SKCS hardness index, FABS = Farinograph water absorption, BFLY = break flour yield and FLY = flour yield.
R = ranking order

Wricke's ecovalence analysis for the baking characteristics showed that the cultivar Marico was very stable for the following traits namely; SDSS and ASTAB, it also showed intermediate stable values for GPC-Leco, AS, AD, P/L and LFV-12, while it was unstable for FLN, FPC-Leco, WGC-12, MDT and LFV (Table 5.10). Kariega showed stable W_i values for WGC, MDT, ASTAB, P/L, LFV and LFV-12, it had intermediate stable W_i values for FLN, GPC-Leco, FPC-Leco, SDSS, AS and AD. SST 825 exhibited stable baking values for AS and AD, as well as intermediate stable W_i values for FLN, WGC-12, MDT, ASTAB and LFV-12. SST 825 also had unstable W_i values for GPC-Leco, FPC-Leco, SDSS, P/L and LFV. SST 822 was stable for GPC-Leco, FPC-Leco, WGC, SDSS, MDT, AS, P/L, LFV and LFV-12, it displayed intermediate stable W_i values for AD and ASTAB, only milling characteristic namely FLN was unstable. SST876 showed stable W_i values for FLN, GPC-Leco and FPC-Leco, with unstable baking traits such as SDSS, MDT, AS, AD, ASTAB, P/L and LFV-12 (Table 5.10).

Table 5.10. Wricke's ecovalence values of baking characteristics for spring wheat cultivars under irrigation.

Cultivar	FLN	R	GPC-leco	R	FPC-leco	R	WGC-12	R	SDSS	R	MDT	R	AS	R	AD	R	ASTA B	R	P/L		LFV	R	LFV-12	R
	X 1000						x 100						x 100		x 1000		x 100				x 1000		x 1000	
Marico	10.39	5	2.49	4	4.10	4	4.10	5	129.47	2	4.16	5	2.02	3	1.92	4	1.91	1	0.15	3	74.82	4	18.24	4
Kariega	3.64	2	2.02	3	2.80	3	1.64	1	157.55	3	0.61	2	2.42	4	1.67	2	2.04	2	0.13	2	14.26	1	3.31	1
SST825	3.96	3	3.21	5	4.43	5	2.87	4	309.80	5	0.64	3	1.88	2	1.11	1	8.44	4	0.39	5	66.53	5	14.41	3
SST822	7.50	4	1.61	1	2.28	1	1.71	2	103.10	1	0.19	1	1.50	1	1.90	3	5.91	3	0.04	1	36.97	2	7.95	2
SST876	1.74	1	1.88	2	2.56	2	2.34	3	205.15	4	1.76	4	6.81	5	2.63	5	18.92	5	0.38	4	50.86	3	25.27	5

FLN = falling number, GPC-leco = grain protein content determined by the Leco, FPC-leco = flour protein content determined by the Leco, WGC-12 = Wet gluten content at 12% protein content, SDSS = SDS-sedimentation value, MDT = mixograph development time, AS = alveograph strength, AD = alveograph distensibility, ASTAB = alveograph stability, P/L = alveograph P/L index LFV = loaf volume and LFV-12% = loaf volume standardized at 12% protein content.

R = Ranking order

5.4.2.2 Eberhart and Russel's procedure (S^2d_i)

The deviation sums of squares are the sums of variance due deviation from regression divided by (s-2), and subtracting pooled error mean square, where s equals the number of locations for each variety. Varieties with a probability of F at or near zero deviate significantly from linearity and thus for the given set of environments, have a less predictable response. Calculated values according to the Eberhart and Russel's procedure for both the milling and baking characteristics can be seen in Table 5.11 and 5.12 respectively.

Eberhart and Russel's procedure shows that the cultivar Marico was very stable for the following milling characteristics namely; SKCS-DIA, VK, SKSCS-HI and BFLY. Marico had intermediate stable values for SKCS-G, TKM, FLY and FABS, but was unstable for HLM (Table 5.11). Kariega showed stable values for HLM and FABS, but exhibited intermediate stable S^2d_i values for VK and FLY. Kariega's S^2d_i values were unstable for TKM, SKSC-G, SKCS-DIA, SKSC-HI and BFLY. SST 825 however displayed stable S^2d_i values for VK, while it had intermediate stable S^2d_i values for HLM, TKM, SKCS-G and FABS. SST 825 was unstable for SKCS-DIA, SKCS-HI, BFLY and FLY. SST 822's S^2d_i values were stable for HLM, SKCS-DIA, BFLY and FLY. It also had intermediate stable S^2d_i values for TKM, SKCS-G and SKCS-HI, while it was unstable for VK and FABS. SST876 showed stable S^2d_i values for its milling traits namely HLM, TKM, SKCS-G and

SKCS-DIA, while it showed intermediate stable values for SKCS-HI, FABS and BFLY. SST 876 displayed unstable S^2d_i values for VK and FLY (Table 5.11).

Table 5.11. Eberhart and Russel's procedure values regarding milling characteristics for spring wheat cultivars under irrigation.

Cultivar	HLM	R	TKM	R	SKCS-G	R	SKCS-DIA	R	VK	R	SKCS-HI	R	FABS	R	BFLY	R	FLY	R
Marico	1.23	5	1.31	4	2.09	3	-0.0005	2	-7.37	1	1.18	1	0.94	2	0.12	2	0.54	2
Kariega	-0.13	1	1.91	5	4.04	5	0.0060	5	5.27	3	16.82	5	0.40	1	2.03	4	0.56	3
SST825	0.86	4	1.23	3	1.90	2	0.0051	4	-2.80	2	12.46	4	1.17	4	2.06	5	0.67	5
SST822	0.29	3	1.18	2	2.12	4	0.0000	3	11.69	5	4.44	3	1.39	5	0.04	1	0.23	1
SST876	0.17	2	0.11	1	1.37	1	-0.0018	1	11.62	4	3.62	2	1.07	3	0.63	3	0.61	4

HLM = hectolitre mass, TKM = thousand kernel mass VK = Vitreous kernel, SKCS-G = SKCS weight, SKCS-DIA = SKCS diameter, SKCS-HI = SKCS hardness index, FABS = Farinograph water absorption, BFLY = break flour yield and FLY = flour yield.
R = ranking order

Eberhart and Russel's procedure for the baking characteristics showed that the cultivar Marico was very stable for the following traits namely; SDSS and ASTAB, it also showed intermediate stable values for GPC-Leco, AS, AD, P/L and LFV-12, while it was unstable for FLN, FPC-Leco, WGC-12, MDT and LFV (Table 5.12). Kariega showed stable S^2d_i values for GPC-Leco, WGC-12, AS, ASTAB, LFV and LFV-12, it had intermediate stable S^2d_i values for FPC-Leco, SDSS, MDT, AD and P/L. Kariega was unstable for only one baking trait namely FLN. SST 825 exhibited stable baking values for just AD, as well as intermediate stable S^2d_i values for FLN, GPC-Leco, WGC-12, MDT, AS, ASTAB and LFV-12. SST 825 also had unstable S^2d_i values for FPC-Leco, SDSS, P/L and LFV. SST 822 was stable for FPC-Leco, WGC-12, SDSS, MDT, AS, P/L and LFV and LFV-12, it displayed intermediate stable S^2d_i values for FLN and ASTAB, only the following milling characteristic namely GPC-Leco and AD was unstable. SST876 showed stable S^2d_i values for FLN, FPC-Leco, WGC-12, MDT and LFV, intermediate stable baking traits such as GPC-Leco and SDSS. SST 876 had unstable S^2d_i values such as AS, AD, ASTAB, P/L and LFV-12 (Table 5.12).

Table 5.12. Eberhart and Russel's procedure values regarding baking characteristics for spring wheat cultivars under irrigation.

Cultivar	FLN	R	GPC-leco	R	FPC-leco	R	WGC-12	R	SDS S	R	MDT	R	AS	R	AD	R	ASTA B	R	P/L		LFV	R	LFV-12	R
	x 100																				x 1000		x 1000	
Marico	5.73	3	0.94	2	0.16	5	1.70	5	0.75	2	0.163	5	6.42	4	31.52	2	-0.55	1	0.0057	3	1.25	4	0.98	4
Kariega	8.27	5	0.40	1	0.06	3	-0.19	1	6.09	4	0.043	4	0.88	1	53.31	3	-0.51	2	0.0046	2	-0.49	1	-0.34	1
SST825	1.16	2	1.17	4	0.11	4	0.74	4	13.09	5	0.042	3	4.60	3	6.16	1	44.40	4	0.0181	4	2.29	5	0.64	3
SST822	3.92	4	1.39	5	0.01	1	-0.13	2	-1.65	1	-0.010	1	2.22	2	70.55	4	29.88	3	-0.0019	1	0.26	3	0.07	2
SST876	-5.17	1	1.07	3	0.02	2	0.35	3	5.69	3	0.024	2	25.82	5	84.91	5	125.92	5	0.0205	5	0.12	2	1.59	5

FLN = falling number, GPC-leco = grain protein content determined by the Leco, FPC-leco = flour protein content determined by the Leco, WGC-12 = Wet gluten content at 12% protein content, SDSS = SDS-sedimentation value, MDT = mixograph development time, AS = alveograph strength, AD = alveograph distensibility, ASTAB = alveograph stability, P/L = alveograph P/L index LFV = loaf volume and LFV-12% = loaf volume standardized at 12% protein content.

R = Ranking order

5.4.2.3 Shukla's procedure of stability variance (σ^2_i)

The values are estimates from an entry's variance components across environments. This option does not use a covariate and stable varieties have smaller estimates. Shukla's procedure of stability variances for the milling as well as the baking characteristics can be seen in Tables 5.13 and 5.14.

According to Shukla's stability variance procedure the cultivar Marico was very stable for the following milling characteristics namely; SKCS-DIA, VK, SKSCS-HI and BFLY. Marico had intermediate stable values for SKCS-G, TKM and FABS, but was unstable for HLM and FLY (Table 5.13). Kariega showed stable values for HLM, VK and FABS, but exhibited intermediate stable σ^2_i values only for FLY. Kariega's σ^2_i values were unstable for TKM, SKSC-G, SKCS-DIA, SKSC-HI and BFLY. SST 825 however displayed stable σ^2_i values for SKCS-G and VK, while it had intermediate stable σ^2_i values for HLM, TKM and FABS. SST 825 was unstable for SKCS-DIA, SKCS-HI, BFLY and FLY. SST 822's σ^2_i values were stable for SKCS-DIA, BFLY and FLY. It also had intermediate stable σ^2_i values for HLM, TKM, SKCS-G and SKCS-HI, while it was unstable for VK and FABS. SST876 showed stable σ^2_i values for its milling traits involved in kernel size (HLM, TKM, SKCS-G and SKCS-DIA) and had intermediate stable values for VK, SKCS-HI, FABS and BFLY, while it was unstable only for VK (Table 5.13).

Table 5.13. Shukla's procedure of stability variance values of milling characteristics for spring wheat cultivars under irrigation.

Cultivar	HLM	R	TKM	R	SKCS-G	R	SKCS-DIA	R	VK	R	SKCS-HI	R	FABS	R	BFLY	R	FLY	R
Marico	7.36	5	11.71	4	13.20	4	0.025	3	57.87	2	9.78	1	4.71	2	0.35	2	4.04	5
Kariega	1.93	1	13.24	5	21.88	5	0.048	5	76.16	3	83.59	4	2.93	1	9.35	4	2.62	2
SST825	5.57	4	10.99	3	10.99	2	0.044	4	51.10	1	89.88	5	5.96	4	10.08	5	3.39	3
SST822	3.62	3	9.45	2	12.27	3	0.020	2	158.87	5	33.99	3	7.02	5	0.10	1	1.43	1
SST876	2.49	2	4.59	1	8.65	1	0.016	1	112.33	4	22.81	2	5.90	3	3.36	3	3.69	4

HLM = hectolitre mass, TKM = thousand kernel mass VK = Vitreous kernel, SKCS-G = SKCS weight, SKCS-DIA = SKCS diameter, SKCS-HI = SKCS hardness index, FABS = Farinograph water absorption, BFLY = break flour yield and FLY = flour yield.
R = ranking order

Shukla's stability variance procedure analysis for the baking characteristics showed that the cultivar Marico was very stable for SDSS and ASTAB, it also showed intermediate stable values for GPC-Leco, AS, AD and P/L, while it was unstable for FLN, FPC-Leco, WGC-12, MDT, P/L and LFV and LFV-12 (Table 5.14). Kariega showed stable σ^2_i values for WGC-12, MDT, ASTAB, LFV and LFV-12, it had intermediate stable σ^2_i values for FLN, GPC-Leco, FPC-Leco, SDSS, AS, AD and P/L. SST 825 exhibited stable baking values for MDT and AD, as well as intermediate stable σ^2_i values for FLN, WGC-12, AD, ASTAB and LFV-12. SST 825 also had unstable σ^2_i values for GPC-Leco, FPC-Leco, SDSS, P/L and LFV. SST 822 was stable for GPC-Leco, FPC-Leco, WGC-12, SDSS, MDT, AS and P/L, it displayed intermediate stable σ^2_i values for AD, ASTAB, LFV and LFV-12, the only unstable milling characteristic for SST 822 was FLN. SST876 showed stable σ^2_i values for FLN, GPC-Leco and FPC-Leco, with intermediate stable traits like WGC-12, MDT and LFV. SST 876 showed unstable baking traits such as SDSS, AS, AD, ASTAB, P/L and LFV-12 (Table 5.14).

Table 5.14. Shukla's procedure of stability variance values of baking characteristics for spring wheat cultivars under irrigation.

Cultivar	FLN	R	GPC	R	FPC	R	WGC	R	SDSS	R	MDT	R	AS	R	AD	R	ASTA	R	P/L		LFV	R	LFV-12	R
	X 1000												x 10		x 100		X 100				x 1000		x 1000	
Marico	3.23	5	0.69	4	1.18	4	12.42	5	30.08	2	1.46	5	4.61	3	5.20	4	0.02	1	0.032	3	22.37	5	5.69	4
Kariega	0.81	2	0.52	3	0.71	3	3.60	1	40.11	3	0.09	2	6.05	4	4.32	2	0.06	2	0.027	2	0.74	1	-0.06	1
SST825	0.93	3	0.95	5	1.29	5	7.97	4	94.48	5	0.10	3	4.12	2	2.32	1	2.35	4	0.119	5	19.41	4	4.21	3
SST822	2.19	4	0.37	1	0.52	1	3.85	2	20.66	1	-0.07	1	2.74	1	5.12	3	1.45	3	-0.005	1	8.86	2	1.73	2
SST876	0.14	1	0.47	2	0.63	2	6.10	3	57.11	4	0.53	4	21.71	5	7.75	5	6.09	5	0.118	4	13.82	3	8.39	5

FLN = falling number, GPC = grain protein content determined by the Leco, FPC = flour protein content determined by the Leco, WGC = Wet gluten content at 12% protein content, SDS = SDS-sedimentation value, MDT = mixograph development time, AS = alveograph strength, AD = alveograph distensibility, AST = alveograph stability, P/L = alveograph P/L index LFV = loaf volume and LFV-12% = loaf volume standardized at 12% protein content.

R = Ranking order

5.4.2.4 Lin & Binns' cultivar performance measurement (P_i)

The values estimated are the squares of the differences between an entry mean and the maximum mean at a location, summarized and divided by twice the number of locations. Checks need not to be common at all locations. Genotypes with the smallest values tend to have larger yields and be more stable. Calculated values according to Linn and Binn's cultivar performance measurements for both the milling and baking characteristics can be seen in Table 5.15 and 5.16 respectively.

Linn and Binn's cultivar performance measurement values for the cultivar Marico showed that it was very stable for the following milling characteristics namely; FLY and BFLY. Marico had intermediate stable values only for SKCS-HI, but was unstable for HLM, TKM, SKCS-G, SKCS-DIA and FABS (Table 5.15). Kariega showed stable P_i values for TKM, BFLY and FLY, but exhibited intermediate stable P_i values for HLM, SKCS-G, SKCS-DIA, VK and FABS. Kariega's P_i values were unstable only for SKCS-HI. SST 825 however displayed stable P_i values for TKM, SKCS-G, SKCS-DIA, VK, SKCS-HI and FABS, while it had intermediate stable P_i values for HLM. SST 825 was unstable for BFLY and FLY. SST 822's P_i values were stable only for SKCS-HI. It also had intermediate stable P_i values for HLM, TKM, SKCS-G, SKCS-DIA, VK, FABS and BFLY, while it was unstable only for FLY. SST876 showed stable P_i values for its milling traits namely HLM and FLY, while it showed intermediate stable values for TKM, SKCS-G,

SKCS-DIA, SKCS-HI and FABS. SST 876 displayed unstable P_i values for VK and BFLY (Table 5.15).

Table 5.15. Lin & Binns' cultivar performance measurement values of milling characteristics for spring wheat cultivars under irrigation.

Cultivar	HLM	R	TKM	R	SKCS-G	R	SKCS-DIA	R	VK	R	SKCS-HI	R	FABS	R	BFLY	R	FLY	R
Marico	4.31	5	11.19	5	13.75	5	0.0701	5	17.80	1	22.53	4	11.75	5	0.55	1	0.68	1
Kariega	3.02	4	2.46	1	4.82	2	0.0194	4	41.14	4	78.48	5	3.53	3	0.68	2	0.70	2
SST825	2.26	3	3.08	2	3.56	1	0.0029	1	20.25	2	7.35	1	0.42	1	10.45	5	2.65	4
SST822	1.17	2	4.53	3	4.88	3	0.0180	2	34.45	3	11.22	2	2.47	2	2.13	3	3.43	5
SST876	0.16	1	5.18	4	5.59	4	0.0191	3	84.40	5	17.94	3	3.71	4	7.05	4	0.90	3

HLM = hectolitre mass, TKM = thousand kernel mass VK = Vitreous kernel, SKCS-G = SKCS weight, SKCS-DIA = SKCS diameter, SKCS-HI = SKCS hardness index, FABS = Farinograph water absorption, BFLY = break flour yield and FLY = flour yield.
R = ranking order

Lin and Binn's cultivar performance measurement values for the baking characteristics showed that the cultivar Marico was very stable for WGC-12 and MDT, it also showed intermediate stable values for GPC-Leco, SDS, AS, AD, ASTAB, P/L and LFV-12, while it was unstable for FLN, FPC-Leco and LFV (Table 5.16). Kariega showed stable P_i values for FPC-Leco, SDSS, AS and LFV-12, it had intermediate stable P_i values for GPC-Leco, WGC-12, MDT and LFV. Kariega was unstable for three baking traits namely FLN, ASTAB and LFV. SST 825 exhibited stable baking values for four baking characteristics namely AS, ASTAB, P/L and LFV, as well as intermediate stable P_i values for FLN, GPC-Leco, FPC-Leco, WGC-12, SDSS, MDT and LFV-12. SST 825 also had one unstable P_i namely AD. SST 822 was stable for FLN, GPC-Leco, FPC-Leco, WGC-12 and LFV-12, it displayed intermediate stable P_i values for SDSS, MDT, AS, AD, ASTAB and LFV, only one milling characteristic namely P/L was unstable. SST876 showed stable P_i values for WGC-12 and P/L, with one intermediate stable baking trait namely FLN. SST 876 had unstable P_i values such as GPC-Leco, FPC-Leco, SDSS, MDT, AS, AD, ASTAB, LFV and LFV-12 (Table 5.16).

Table 5.16. Lin & Binns' cultivar performance measurement values of baking characteristics for spring wheat cultivars under irrigation.

Cultivar	FLN	R	GPC-leco	R	FPC-leco	R	WGC-12	R	SDSS	R	MDT	R	AS	R	AD	R	ASTA B	R	P/L	R	LFV	R	LFV-12	R
	x 100								x 10				x 10		x 100		x 100				x 1000		x 1000	
Marico	10.67	5	0.41	4	0.48	4	14.98	5	2.15	2	0.01	1	2.11	2	3.44	3	2.80	2	0.050	3	7.31	4	1.76	4
Kariega	9.47	4	0.29	2	0.23	2	1.99	3	0.61	1	0.60	4	3.12	3	0.13	1	3.04	4	0.077	5	4.43	2	0.36	1
SST825	6.08	3	0.30	3	0.24	3	3.76	4	4.77	4	0.54	3	0.86	1	6.99	5	0.44	1	0.020	1	2.90	1	1.52	3
SST822	4.50	1	0.03	1	0.18	1	0.91	1	2.79	3	0.46	2	6.03	4	2.48	2	2.95	3	0.068	4	4.77	3	0.40	2
SST876	5.99	2	0.55	5	0.50	5	1.41	2	12.55	5	1.50	5	18.11	5	5.31	4	3.43	5	0.049	2	10.99	5	3.04	5

FLN = falling number, GPC-leco = grain protein content determined by the Leco, FPC-leco = flour protein content determined by the Leco, WGC-12 = Wet gluten content at 12% protein content, SDSS = SDS-sedimentation value, MDT = mixograph development time, AS = alveograph strength, AD = alveograph distensibility, ASTAB = alveograph stability, P/L = alveograph P/L index LFV = loaf volume and LFV-12% = loaf volume standardized at 12% protein content.

R = Ranking order

5.4.2.5 AMMI stability value (ASV)

AMMI stability value calculations for the milling as well as the baking characteristics can be seen in Tables 5.17 and 5.18. Genotypes with the lowest AMMI stability values are considered as more stable regarding their performance (Purchase, 1997).

According to the AMMI stability value a cultivar like Marico was very stable for the following milling characteristics namely; SKCS-DIA, VK, SKSCS-HI and BFLY. Marico had intermediate stable values for SKCS-G, TKM, VK and FABS, but was unstable for HLM and FLY (Table 5.17). Kariega showed stable ASV values for HLM, VK, FABS and FLY, but unstable VSA values only for TKM, SKSC-G, SKCS-DIA, SKSC-HI and BFLY. SST 825 however displayed stable VSA only for VK, while it had intermediate stable VSA values for TKM, SKCS-G and FABS. SST 825 was unstable for HLM, SKCS-DIA, SKCS-HI, BFLY and FLY. SST 822's VSA values were stable for SKCS-DIA and BFLY. It also had intermediate stable VSA values for HLM, TKM, SKCS-G and SKCS-HI, FLY and FABS, while it was unstable only for VK. SST876 showed stable VSA values for its milling traits such as TKM, SKCS-G, SKCS-DIA and SKCS-HI. It had intermediate stable values for HLM, FABS and BFLY, while it was unstable only for VK and FLY (Table 5.17).

Table 5.17. AMMI stability values of milling characteristics for spring wheat cultivars under irrigation.

Cultivar	HLM	R	TKM	R	SKCS-G	R	SKCS-DIA	R	VK	R	SKCS-HI	R	FABS	R	BFLY	R	FLY	R
Marico	2.52	5	2.24	4	2.47	4	0.42	3	2.56	3	1.83	1	1.92	3	0.59	2	1.71	4
Kariega	0.81	1	2.47	5	3.49	5	0.76	5	2.30	2	4.66	4	1.47	1	3.48	4	0.77	1
SST825	2.14	4	2.11	3	2.25	2	0.75	4	1.99	1	4.75	5	1.90	2	3.63	5	1.54	3
SST822	1.60	3	1.98	2	2.36	3	0.38	2	5.13	5	2.59	3	2.18	5	0.40	1	1.20	2
SST876	1.21	2	0.97	1	1.93	1	0.34	1	4.09	4	1.98	2	2.16	4	1.81	3	1.77	5

HLM = hectolitre mass, TKM = thousand kernel mass VK = Vitreous kernel, SKCS-G = SKCS weight, SKCS-DIA = SKCS diameter, SKCS-HI = SKCS hardness index, FABS = Farinograph water absorption, BFLY = break flour yield and FLY = flour yield.
R = ranking order

AMMI stability value for the baking characteristics showed that the cultivar Marico was very stable for the following traits namely; SDSS and ASTAB, it also showed intermediate stable values for GPC-Leco, AS, AD and P/L, while it was unstable for FLN, FPC-Leco, WGC-12, MDT, P/L and LFV and LFV-12 (Table 5.18). Kariega showed stable ASV values for FLN, FPC-Leco, WGC-12, ASTAB, LFV and LFV-12, it had intermediate stable ASV values for GPC-Leco, SDSS, MDT, AS, AD and P/L. SST 825 exhibited stable baking values for MDT and AD, as well as intermediate stable ASV values for FLN, WGC-12, AS and ASTAB. SST 825 also had unstable ASV values for GPC-Leco, FPC-Leco, SDSS, P/L, LFV and LFV-12. SST 822 was stable for GPC-Leco, FPC-Leco, WGC-12, SDSS, MDT, AS and P/L, it displayed intermediate stable asv values for AD, ASTAB, LFV and LFV-12, the only unstable milling characteristic for SST 822 was FLN. SST876 showed stable ASV values for FLN, GPC-Leco and FPC-Leco, with intermediate stable traits like WGC-12, SDSS, MDT and LFV. SST 876 showed unstable baking traits such as AS, AD, ASTAB, P/L and LFV-12 (Table 5.18).

Table 5.18. AMMI stability values of baking characteristics for spring wheat cultivars under irrigation.

Cultivar	FLN	R	GPC-leco	R	FPC-leco	R	WGC-12	R	SDSS	R	MDT	R	AS	R	AD	R	ASTA-B	R	P/L		LFV	R	LFV-12	R
Marico	13.79	5	1.27	4	1.23	4	2.81	5	2.43	2	2.67	5	3.35	2	5.42	4	1.33	1	0.39	2	19.64	5	14.94	4
Kariega	2.25	1	1.00	3	0.82	1	1.14	1	3.09	3	1.02	3	4.00	4	5.26	2	2.37	2	0.47	3	6.07	1	0.61	1
SST825	5.73	3	1.53	5	1.31	5	2.13	4	5.10	5	0.87	2	3.63	3	4.19	1	7.13	4	1.26	5	17.39	4	11.81	3
SST822	11.11	4	0.57	1	0.86	3	1.31	2	1.55	1	0.34	1	2.06	1	5.41	3	5.72	3	0.09	1	11.89	2	5.68	2
SST876	2.91	2	0.84	2	0.83	2	1.72	3	3.70	4	1.59	4	8.72	5	7.26	5	12.17	5	1.24	4	15.17	3	19.76	5

FLN = falling number, GPC-leco = grain protein content determined by the Leco, FPC-leco = flour protein content determined by the Leco, WGC-12 = Wet gluten content at 12% protein content, SDSS = SDS-sedimentation value, MDT = mixograph development time, AS = alveograph strength, AD = alveograph distensibility, ASTAB = alveograph stability, P/L = alveograph P/L index LFV = loaf volume and LFV-12% = loaf volume standardized at 12% protein content.

R = Ranking order

5.4.3 Combined comparison of stability analysis procedures

Tables 5.19 through to Table 5.29 indicate the results for Spearman's coefficient of rank correlations as determined for each of the possible pairwise comparisons of the different stability analysis procedures evaluated in this study.

5.4.3.1 Milling characteristics

Remarkable and total correspondence of significance for Spearman's rank correlation coefficients (highly significantly, $P=0.01$) regarding almost all the stability parameters had been noted for HLM and TKM (Table 5.19). Only the rank correlation between Shukla and Eberhart-Russell was below $r = 0.80$ for HLM ($r = 0.69$ at the $p=0.05$ significance level). For both HLM and TKM, the ASV stability measurement correlated almost a 100% with all the other stability measurement procedures. (Table 5.19)

Table 5.19. Spearman's ranking order correlation coefficient matrix for five G x E stability analysis procedures regarding hectolitre mass (HLM) and thousand kernel mass (TKM).

HLM					TKM						
Wrick					Wrick						
Eber	0.81**				Eber	1.00**					
Shuk	1.00**	0.81**			Shuk	1.00**	1.00**				
Lin	0.98**	0.69*	0.98**		Lin	0.96**	0.96**	0.96**			
ASV	1.00**	0.81**	1.00**	0.98**	ASV	1.00**	1.00**	1.00**	0.96**		
	Wrick	Eber	Shuk	Lin	ASV		Wrick	Eber	Shuk	Lin	ASV

* Significant according to Student's *t* test at the P=0.05 level

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

Wrick = Wricke's (1962) ecovalence

Eber = Eberhart and Russell's (1966) deviation parameter

Shuk = Shukla's (1972) stability variance

Lin = Linn and Binn's (1988) cultivar superiority performance

ASV = AMMI stability value (Purchase, 1997)

Remarkable and total correspondence of significance for Spearman's rank correlation coefficients (highly significantly, P=0.01) regarding almost all the stability parameters had been noted for SKCS-G and SKCS-DIA again (Table 5.20). In the case of SKCS-DIA, Eberhart and Russell's stability measurement correlated poorly ($r = 0.48$ and lower) with all the other stability measurements. Except for SKCS-DIA's Eberhart and Russell stability measurement the ASV stability measurement correlated almost a 100% with all the other stability measurement procedures regarding SKCS-G and SKCS-DIA (Table 5.20).

Table 5.20. Spearman's ranking order correlation coefficient matrix for five G x E stability analysis procedures regarding SKCS-weight (SKCS-G) and SKCS-diameter (SKCS-DIA).

SKCS-G					SKCS-DIA						
Wrick					Wrick						
Eber	1.00**				Eber	0.48					
Shuk	1.00**	1.00**			Shuk	1.00**	0.48				
Lin	0.98**	0.96**	0.97**		Lin	0.97**	0.32	0.97**			
ASV	1.00**	1.00**	1.00**	0.97**	ASV	1.00**	0.48	1.00**	0.97**		
	Wrick	Eber	Shuk	Lin	ASV		Wrick	Eber	Shuk	Lin	ASV

* Significant according to Student's *t* test at the P=0.05 level

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

Wrick = Wricke's (1962) ecovalence

Eber = Eberhart and Russell's (1966) deviation parameter

Shuk = Shukla's (1972) stability variance

Lin = Linn and Binn's (1988) cultivar superiority performance

ASV = AMMI stability value (Purchase, 1997)

Highly significant ($r=1.00$ at the $P=0.01$ level) Spearman's rank correlation coefficients regarding almost all the stability parameters had been noted for VK and SKCS-HI (Table 5.21). As in the case of SKCS-DIA the Eberhart and Russell's stability measurement of VK correlated poorly ($r = 0.58^*$ and lower) with all the other stability measurements. Except for SKCS-DIA's Eberhart and Russell's stability measurement, the ASV stability measurement correlated again almost a 100% with all the other stability measurement procedures regarding VK and SKCS-HI (Table 5.21).

Table 5.21. Spearman's ranking order correlation coefficient matrix for five G x E stability analysis procedures regarding vitreous kernels (VK) and SKCS-hardness index (SKCS-HI).

VK					SKCS-HI					
Wrick					Wrick					
Eber	0.58*				Eber	1.00**				
Shuk	1.00**	0.58*			Shuk	1.00**	1.00**			
Lin	0.99**	0.57*	0.99**		Lin	0.96**	0.97**	0.96**		
ASV	1.00**	0.54*	1.00**	0.98**	ASV	1.00**	1.00**	1.00**	0.96**	
	Wrick	Eber	Shuk	Lin	ASV	Wrick	Eber	Shuk	Lin	ASV

* Significant according to Student's t test at the $P=0.05$ level

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

Wrick = Wricke's (1962) ecovalence

Eber = Eberhart and Russell's (1966) deviation parameter

Shuk = Shukla's (1972) stability variance

Lin = Linn and Binn's (1988) cultivar superiority performance

ASV = AMMI stability value (Purchase, 1997)

Highly significant ($r=1.00$ at the $P=0.01$ level) Spearman's rank correlation coefficients regarding almost all the stability parameters had been noted for FABS and BFLY again (Table 5.22). The ASV stability measurement correlated again almost a 100% with all the other stability measurement procedures regarding FABS and BFLY (Table 5.22).

Table 5.22. Spearman's ranking order correlation coefficient matrix for five G x E stability analysis procedures regarding farinograph waterabsorption (FABS) and break flour yield (BFLY).

FABS					BFLY						
Wrick					Wrick						
Eber	1.00**				Eber	1.00**					
Shuk	1.00**	1.00**			Shuk	1.00**	1.00**				
Lin	0.95**	0.95**	0.95**		Lin	0.99**	0.98**	0.99**			
ASV	0.99**	0.99**	0.99**	0.96**	ASV	1.00**	1.00**	1.00**	0.99**		
	Wrick	Eber	Shuk	Lin	ASV		Wrick	Eber	Shuk	Lin	ASV

* Significant according to Student's *t* test at the P=0.05 level

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

Wrick = Wricke's (1962) ecovalence

Eber = Eberhart and Russell's (1966) deviation parameter

Shuk = Shukla's (1972) stability variance

Lin = Linn and Binn's (1988) cultivar superiority performance

ASV = AMMI stability value (Purchase, 1997)

Spearman's rank correlation coefficients as high as 100% regarding almost all the stability parameters had been noted for FLY (Table 5.23). The ASV stability measurement correlated again almost a 100% with all the other stability measurement procedures regarding FLY (Table 5.23).

Table 5.23. Spearman's ranking order correlation coefficient matrix for five G x E stability analysis procedures regarding flour yield (FLY).

FLY					
Wrick					
Eber	0.98**				
Shuk	1.00**	0.98**			
Lin	0.95**	0.97**	0.95**		
ASV	0.99**	0.98**	0.99**	0.96**	
	Wrick	Eber	Shuk	Lin	ASV

* Significant according to Student's *t* test at the P=0.05 level

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

Wrick = Wricke's (1962) ecovalence

Eber = Eberhart and Russell's (1966) deviation parameter

Shuk = Shukla's (1972) stability variance

Lin = Linn and Binn's (1988) cultivar superiority performance

ASV = AMMI stability value (Purchase, 1997)

5.4.3.2 Baking characteristics

Highly significant ($r=1.00$ at the $P=0.01$ level) Spearman's rank correlation coefficients regarding almost all the stability parameters had been noted for the baking characteristics namely FLN and GPC-leco (Table 5.24). In the case of FLN, the Eberhart

and Russell's stability measurement had lower correlations although still above 75% with all the other stability measurements, than the rest of the combinations. Except for SKCS-DIA's Eberhart and Russell stability measurement the ASV stability measurement again correlated almost a 100% with all the other stability measurement procedures regarding FLN and GPC-Leco (Table 5.24).

Table 5.24. Spearman's ranking order correlation coefficient matrix for five G x E stability analysis procedures regarding falling number (FLN) and grain protein content (GPC-Leco).

FLN					GPC-LECO					
Wrick					Wrick					
Eber	0.81**				Eber	0.95**				
Shuk	1.00**	0.81**			Shuk	1.00**	0.95**			
Lin	0.98**	0.75**	0.98**		Lin	0.98**	0.93**	0.98**		
ASV	1.00**	0.77**	1.00**	0.98**	ASV	1.00**	0.95**	1.00**	0.98**	
	Wrick	Eber	Shuk	Lin	ASV	Wrick	Eber	Shuk	Lin	ASV

* Significant according to Student's *t* test at the P=0.05 level

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

Wrick = Wricke's (1962) ecovalence

Eber = Eberhart and Russell's (1966) deviation parameter

Shuk = Shukla's (1972) stability variance

Lin = Linn and Binn's (1988) cultivar superiority performance

ASV = AMMI stability value (Purchase, 1997)

Remarkable high significant Spearman's rank correlation coefficients ($r=1.00$ at the $P=0.01$ level) regarding almost all the stability parameters had been noted for FPC-Leco and WGC-12 again (Table 5.25). In the case of WGC-12, Eberhart and Russell's stability measurement showed lower correlations ($r = 0.58$, at the 95% significant level) with all the other stability measurements. Except for the Eberhart and Russell's correlation with the ASV stability measurement, the ASV stability measurement again showed almost a 100% correlation with all the other stability measurement procedures regarding both FPC-Leco and WGC-12 (Table 5.25).

Table 5.25. Spearman's ranking order correlation coefficient matrix for five G x E stability analysis procedures regarding flour protein content (FPC-Leco) and wet gluten content (WGC-12).

FPC-LECO					WGC-12						
Wrick					Wrick						
Eber	1.00**				Eber	0.58*					
Shuk	1.00**	1.00**			Shuk	1.00**	0.58*				
Lin	0.98**	0.98**	0.98**		Lin	0.99**	0.54*	0.99**			
ASV	0.99**	0.99**	0.99**	0.97**	ASV	1.00**	0.58*	1.00**	0.99**		
	Wrick	Eber	Shuk	Lin	ASV		Wrick	Eber	Shuk	Lin	ASV

* Significant according to Student's *t* test at the P=0.05 level

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

Wrick = Wricke's (1962) ecovalence

Eber = Eberhart and Russell's (1966) deviation parameter

Shuk = Shukla's (1972) stability variance

Lin = Linn and Binn's (1988) cultivar superiority performance

ASV = AMMI stability value (Purchase, 1997)

Some of the pairwise correlations between the different stability parameters again showed remarkable high significant Spearman's rank correlation coefficients, for both SDSS and MDT (Table 5.26). In the case of both SDSS and MDT, lower correlations were observed (in the order of $r = 0.64^*$ up to $r = 0.80^{**}$) for combinations between Eberhart and Russell's, as well as Linn and Binn's cultivar superiority measurement with the other stability parameters included in this study. The ASV stability measurement again showed almost a 100% correlation with some of the other stability measurement procedures regarding SDSS (Table 5.26).

Table 5.26. Spearman's ranking order correlation coefficient matrix for five G x E stability analysis procedures regarding SDS-sedimentation test (SDSS) and mixograph developing time (MDT).

SDSS					MDT						
Wrick					Wrick						
Eber	0.80**				Eber	0.79**					
Shuk	1.00**	0.80**			Shuk	0.81**	0.99**				
Lin	0.99**	0.71*	0.99**		Lin	0.86**	0.64*	0.64*			
ASV	1.00**	0.80**	1.00**	0.99**	ASV	1.00**	0.80**	0.80**	0.86**		
	Wrick	Eber	Shuk	Lin	ASV		Wrick	Eber	Shuk	Lin	ASV

* Significant according to Student's *t* test at the P=0.05 level

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

Wrick = Wricke's (1962) ecovalence

Eber = Eberhart and Russell's (1966) deviation parameter

Shuk = Shukla's (1972) stability variance

Lin = Linn and Binn's (1988) cultivar superiority performance

ASV = AMMI stability value (Purchase, 1997)

Spearman's rank correlation coefficients as high as 100% regarding almost all the stability parameters had been noted for AS and AD (Table 5.27). The ASV stability measurement again correlated almost a 100% with all the other stability measurement procedures regarding AS and AD (Table 5.27).

Table 5.27. Spearman's ranking order correlation coefficient matrix for five G x E stability analysis procedures regarding aveleograph strength (AS) and alveograph distensibility (AD).

AS					AD					
Wrick					Wrick					
Eber	0.98**				Eber	0.99**				
Shuk	1.00**	0.98**			Shuk	0.99**	0.99**			
Lin	0.98**	0.98**	0.98**		Lin	0.97**	0.96**	0.97**		
ASV	1.00**	0.98**	1.00**	0.98**	ASV	1.00**	0.99**	1.00**	0.97**	
	Wrick	Eber	Shuk	Lin	ASV	Wrick	Eber	Shuk	Lin	ASV

* Significant according to Student's *t* test at the P=0.05 level

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

Wrick = Wricke's (1962) ecovalence

Eber = Eberhart and Russell's (1966) deviation parameter

Shuk = Shukla's (1972) stability variance

Lin = Linn and Binn's (1988) cultivar superiority performance

ASV = AMMI stability value (Purchase, 1997)

Some of the pairwise correlations between the different stability parameters again showed remarkable high significant Spearman's rank correlation coefficients, for both ASTAB and P/L (Table 5.28). In the case of ASTAB, lower correlations were observed (in the order of $r = 0.46^*$ up to $r = 0.58^*$) for combinations between Eberhart and Russell's stability measurement with the other stability parameters included in this study. Lower correlation coefficients between Lin and Binn's cultivar superiority performance measurement with Eberhart and Russell's ($r = 0.66^{**}$) as well as Shukla's stability variance ($r = 0.66^{**}$) parameters has been noted for P/L (Table 5.28). The ASV stability measurement again showed almost a 100% correlation with some of the other stability measurement procedures regarding ASTAB and P/L (Table 5.28).

Table 5.28. Spearman's ranking order correlation coefficient matrix for five G x E stability analysis procedures regarding avleograph stability (ASTAB) and alveograph P/L ratio (P/L).

ASTAB					P/L						
Wrick					Wrick						
Eber	0.58*				Eber	0.80**					
Shuk	1.00**	0.58*			Shuk	0.81**	1.00**				
Lin	0.98**	0.46	0.98**		Lin	0.94**	0.66*	0.66*			
ASV	1.00**	0.58*	1.00**	0.98**	ASV	1.00**	0.80**	0.80**	0.95**		
	Wrick	Eber	Shuk	Lin	ASV		Wrick	Eber	Shuk	Lin	ASV

* Significant according to Student's *t* test at the P=0.05 level

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

Wrick = Wricke's (1962) ecovalence

Eber = Eberhart and Russell's (1966) deviation parameter

Shuk = Shukla's (1972) stability variance

Lin = Linn and Binn's (1988) cultivar superiority performance

ASV = AMMI stability value (Purchase, 1997)

Some of the pairwise correlations between the different stability parameters again showed remarkable high significant Spearman's rank correlation coefficients, for both LFV and LFV-12 (Table 29). Lower correlations were observed (in the order of $r = 0.73^{**}$ up to $r = 0.80^{**}$) for combinations between Eberhart and Russell's stability measurement with the other stability parameters included in this study regarding LFV (Table 5.29). The ASV stability measurement again showed almost a 100% correlation with some of the other stability measurement procedures regarding LFV and LFV-12 (Table 5.29).

Table 5.29. Spearman's ranking order correlation coefficient matrix for five G x E stability analysis procedures regarding loaf volume (LFV) and loaf volume standardized at 12% protein content (LFV-12).

LFV					LFV-12						
Wrick					Wrick						
Eber	0.80**				Eber	0.81**					
Shuk	1.00**	0.80**			Shuk	0.81**	1.00**				
Lin	0.98**	0.73*	0.98**		Lin	1.00**	0.81**	0.81**			
ASV	1.00**	0.80**	1.00**	0.98**	ASV	1.00**	0.81**	0.81**	1.00**		
	Wrick	Eber	Shuk	Lin	ASV		Wrick	Eber	Shuk	Lin	ASV

* Significant according to Student's *t* test at the P=0.05 level

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

Wrick = Wricke's (1962) ecovalence

Eber = Eberhart and Russell's (1966) deviation parameter

Shuk = Shukla's (1972) stability variance

Lin = Linn and Binn's (1988) cultivar superiority performance

ASV = AMMI stability value (Purchase, 1997)

5.5 Conclusions

When summarizing the individual results from the different stability parameters (Tables 5.9, 5.11, 5.13, 5.15 and 5.17) it can be concluded that Marico is very unstable regarding its hectolitre mass (HLM) values with a consequent negative influence on the stability regarding its milling performance. Marico is however very stable regarding the expression of its inherent kernel hardness values (VK, SKCS-HI and BFLY). Kariega is however very unstable regarding the expression of its inherent kernel hardness value, but still able to produce remarkably stable flour yield levels. This could mainly be ascribed to the stable hectolitre mass values expressed by Kariega. Although SST 825 displays unstable hectolitre mass and hardness values, the resulting effect on the stability level of its flour yield is not too severe. SST 825 has very stable characteristics that influence kernel size. SST 822 expressed very stable flour yield as well as hardness values. Although SST 876 produced very stable values for hectolitre mass as well as the traits that influence kernel size it still produced an unstable flour yield.

From Tables 5.10, 5.12, 5.14 and 5.18 it is also evident that Marico is very unstable regarding its rheological as well as baking properties. Kariega on the other hand displays remarkable stable rheological as well as baking performance properties. SST 825 is unstable in the expression of its grain (GPC-Leco) and flour protein (FPC-Leco) levels, this however also had a negative influence on the stability of its baking performance (LFV and LFV-12). SST 825 produced stable alveograph strength (AS) and alveograph distensibility (AD) values. SST 822 however has very stable GPC-Leco as well as FPC-Leco values, which consequently had a positive effect on the stability of its rheological as well as baking performance characteristics. Although SST 876 showed very stable GPC-Leco as well as FPC-Leco values, its rheological properties is so weak that it could not induce a affirmative reaction on the stability of its rheological as well as baking performance characteristics.

In the study of Purchase (1997) where the Lin & Binns procedure showed the greatest deviation from the other procedures, generally having negative rank correlation coefficients, similar results had been obtained, however not to the same extent (no negative correlation coefficients had been observed). Lin & Binns (1988a) define stability as the deviation of a specific cultivar'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 its yields over sites will always be close to that of the top performer over the respective sites. Cultivars such as Marico and SST 876 with relatively lower milling and baking 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 is that the best performing cultivars in the different regions can differ considerably from trial to trial. This implies that stability in one trial is determined against a specific cultivar, but in another trial against another cultivar. In the case of crossover interaction, which has clearly been illustrated to exist in this study, this leads to contortion of the data. This method is unacceptable for the purpose of characterising genotype x environment interaction under wheat production in the irrigation areas.

According to Purchase (1997) 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 in his study. In this study similar results were obtained, but to a lesser extent. Their definition of stability is based on a cultivar'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 variety 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 & Leon'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. 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 analysis.

Purchase (1997) showed in his study that rank correlation coefficients of 1.0 exist between Shukla's and Wricke's procedures, from Tables 5.19 – 5.29 in this study it can be seen that most of the milling and baking characteristics verified the results obtained by Purchase (1997). As described by Purchase (1997), this indicates that the two procedures are equivalent for ranking purposes, as Wricke & Weber (1980) also noted. Purchase (1997) also reported that 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 & Leon (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 cannot 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 milling and baking characteristics for wheat production under irrigation.

According to Purchase (1997) the AMMI model can be described as the only multivariate analysis method that can be used because 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. His 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 to compute.

From his study, he showed that a single method of describing G X E interaction and the stability of a genotype had to be selected and that the AMMI model would be the most appropriate method. Becker & Leon (1988) stated that multivariate methods are too sophisticated to provide any simple measure of yield stability that allows ranking of genotypes. However, a relatively simple method has been proposed by Purchase (1997) using the IPCA1 and IPCA2 scores to determine an AMMI stability value (ASV), which can be ranked in order to identify superior genotypes. Both in his study and this study it has been shown to be highly correlated with the stability measures of Eberhart & Russell, Linn & Binn and especially Wricke and Shukla, with sources of instability that can be ascribed to the 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 the ASV model has considerable predictive value, the ASV model can be used for analysing genotype x environment interaction of wheat genotypes with regards to their milling and baking characteristics under irrigation. However, from this study, it would appear that all three the appropriate methods namely Wricke's ecovalence, Shukla's stability variance as well as the AMMI Stability Value can be used to describe the stability of a genotype.

5.6 References

- AACC, 1983. Falling number determination method 56-81B; Experimental milling Buhler method 26-21A; Mixograph method 54-40A; Farinograph method 54-2A using 50g of flour; Alveogram method 54-30A; SDS-sedimentation the method used to determine gluten strength, method 56-70. In Approved methods; 8th ed. American Association of Cereal Chemists Inc.; St Paul, MN, USA.
- AACC; 1995. Dumas Leco-FP200 method for protein determination, method 46-30. In Approved methods; 8th edn. American Association of Cereal Chemists Inc.; St Paul, MN, USA.
- AGROBASETM, 1999. Agronomic Software Inc., 71 Waterloo St. Winnipeg, Manitoba, R3N0S4, Canada.
- ALLARD, R.W. & BRADSHAW, A.D., 1964. Implication of genotype-environment interactions in plant breeding. *Crop. Sci.* 4: 503-508.
- BARTLETT, M.S., 1947. The use of transformations. *Biometrics* 2: 39-52.
- BECKER, H.C., 1981. Correlations among some statistical measures of phenotypic stability. *Euphytica* 30: 835-840.
- BECKER, H.C. & LÉON, J., 1988. Stability analysis in plant breeding. *Plant Breeding* 101: 1-23.
- CROSSA, J., 1990. Statistical analyses of multilocation trials. *Advances in Agronomy* 44: 55-86.

- CLARKE, J.M., CAMPBELL, C.A., CUTFORTH, H.W., DEPAUW, R.M. & WINKELMAN, E., 1990. Nitrogen and phosphorous uptake, translocation, and utilization efficiency of wheat in relation to environment and cultivar yield and protein levels. *Can. J. Plant Sci.* 70: 965-977.
- DE VILLIERS, O.T. & LAUBSCHER, E.W., 1995. Use of the SDSS test to predict the protein content and bread volume of wheat cultivars. *S. Afr. Tydskr. Plant Grond* 12(4): 140-142.
- EBERHART, S.A. & RUSSEL, W.A., 1966. Stability parameters for comparing varieties. *Crop Sci.* 6: 36-40.
- EGGITT, P.W.R. & HARTLEY, A.W., 1975. Extraction rates – milling processing implications. In: Spicer (Ed.) Bread. Social, Nutritional and agricultural aspects of wheaten bread. Applied Science Publishers, London, pp. 219-234.
- FINLAY, K.W. & WILKINSON, G.N., 1963. The analysis of adaptation in a plant-breeding programme. *Aust. J. Agric. Res.* 14: 742-754.
- FINNEY, K.F., 1984. An optimized straight-dough bread making method after 44 years. *Cereal Chem.* 61: 20-27.
- FINNEY, P.L., GAINES, C.S. & ANDREWS, L.C., 1987. Wheat quality: A quality assessor's view. *Cereal Foods World* 32: 313.
- GAINES, S.G., FINNEY, P.L. & RUBENTHALER, G., 1996. Milling and baking of some wheats developed for Eastern or Northwestern regions of the United States and grown at both locations. *Cereal Chem.* 73(5): 521-525.
- GAUCH, H.G., 1982. In: Multivariate analysis in community ecology. 1st ed. Cambridge Univ. Press, London and New York.
- GAUCH, H.G., 1988. Model selection and validation for yield trials with interaction. *Biometrics* 44: 705-715.
- GAUCH, H.G. & ZOBEL, R.W., 1988. Predictive and positive success of statistical analyses of yield trials. *Theor. Appl. Genet.* 76: 1-10.
- HOHLS, T., 1995. Analysis of genotype-environment interactions. *S. Afr. J. of Sci.* 91: 121-124.
- JÁNOS, M., 1998. Inheritance of SDS sedimentation volume of flour in crosses of winter wheat (*Triticum aestivum* L.). *Cereal Research Comm.* 26(2): 203-210.
- KASA, T.G., 2002. Genetic diversity analysis and genotype x environment interaction in Ethiopian mustard (*Brassica carinata* A. BRUAN). PhD Thesis, University of the Free State.
- KOEKEMOER, F.P., 1997. Inheritance of protein related characteristics in spring wheat. MSc. Thesis, Orange Free State.
- LIN, C.S. & BINNS, M.R., 1988a. A superiority measure of cultivar performance for cultivar x location data. *Can. J. Plant Sci.* 68: 193-198.
- LIN, C.S. & BINNS, M.R., 1988b. A method of analyzing cultivar x location x year experiments: A new stability parameter. *Theor. Appl. Genet.* 76: 425-430.
- LIN, C.S., BINNS, M.R. & LEFKOVICH, L.P., 1986. Stability analysis: where do we stand?. *Crop Sci.* 26: 894-900.
- LUKOW, O.M. & McVETTY, P.B.E., 1991. Effect of cultivar and environment on quality characteristics of spring wheat. *Cereal Chem.* 68(6): 597-601.
- McDONALD, A.A., 1994. Classification and grading. In: BUSHUK, W. & RASPER, V.F. (Eds). Wheat production: Properties and quality. Chapman & Hill, London, pp 37-46.
- NASSAR, R. & HÜHN, M., 1987. Studies on estimation of phenotypic stability: Test of significance for nonparametric measures of phenotypic stability. *Biometrics* 43: 45-53.

- NEL, M.M., AGENBAG, G.A. & PURCHASE, J.L., 1998. Sources of variation for yield, protein content and hectoliter mass of spring wheat (*Triticum aestivum* L.) cultivars of the Western and Southern Cape. *S. Afr. Tydskr. Plant en Grond* 15(2): 72-79.
- NEL, M.M., AGENBAG, G.A. & PURCHASE, J.L., 2000a. Sources of variation in spring wheat (*Triticum aestivum* L.) cultivars of the Western and Southern Cape. I. Milling and dough development characteristics. *South African Journal Plant and Soil* 17(1): 30-39.
- NEL, M.M., AGENBAG, G.A. & PURCHASE, J.L., 2000b. Sources of variation in spring wheat (*Triticum aestivum* L.) cultivars of the Western and Southern Cape. II. Baking characteristics. *South African Journal Plant and Soil* 17(1): 40-48.
- PERKINS, J.M. & JINKS, J.L., 1968. Environmental and genotype-environmental components of variability. III. Multiple lines and crosses. *Heredity* 23: 339-356.
- POMERANZ, Y. & MATTERN, P.J., 1988. Genotype and environment interaction effects on hardness estimates in winter wheat. *Cereal Foods World* 33(4): 371-374.
- PURCHASE, J.L., 1997. Parametric analysis to describe genotype x environment interaction and yield stability in winter wheat (*Triticum aestivum* L.). PhD Thesis, University of the Orange Free State.
- PURCHASE, J.L., HATTING, H. & VAN DEVENTER, C.S., 2000a. Genotype x environment interaction of winter wheat (*Triticum aestivum* L.) in South Africa: I. AMMI analysis of yield performance. *South African Journal Plant and Soil* 17(3): 95-101.
- PURCHASE, J.L., HATTING, H. & VAN DEVENTER, C.S., 2000b. Genotype x environment interaction of winter wheat (*Triticum aestivum* L.) in South Africa: II. Stability analysis of yield performance. *South African Journal Plant and Soil* 17(3): 102-107.
- ROMAGOSA, I. & FOX, P.N., 1993. Genotype x environment interaction and adaptation, pp. 373-390. In: M.D. Hayward, N.O. Bosemark & I. Romagosa, (eds.). *Plant Breeding: principles and prospects*, Chapman and Hall, London.
- SHOGREN, M.D. & FINNEY, K.F., 1984. Bread-making test for 10 grams of flour. *Cereal Chem.* 61: 418-423.
- SHUKLA, G.K., 1972. Some statistical aspects of partitioning genotype-environmental components of variability. *Heredity* 29: 237-245.
- STEEL, R.G. & TORRIE, J.H., 1980. *Principles and procedures of statistics*. McGraw-Hill, New York.
- TERMAN, G.L., 1979. Yields and protein content of wheat grain as effected by cultivar, N, and environmental growth factors. *Agron. J.* 71: 437-440.
- VAN ARK, H., 1995. *The introduction to linear correlation and regression*. Agricultural Research Council: Agrimetrics Institute.
- VAN DEVENTER, C.S., 1985. Die bepaling van genotipe x omgewinginteraksie by winterkoring. PhD Thesis, University of the Orange Free State.
- VAN LILL, D., PURCHASE, J.L., DE VILLERS, O.T. & SMITH, M.F., 1993. Effect of cropping systems on five South African wheat cultivars. II. Bread-making quality and quantitative protein composition. *Die SA Tydskrif vir Voedselwetenskap en Voeding* 5(1): 22-26.
- WRICKE, G., 1962. Über eine methode zur erfassung der ökologischen Streubreite in feldversuchen. *Z. Pflanzenzüchtg.* 47: 92-96

- WRICKE, G. & WEBER, W.E., 1980. Erweiterte analyse von wechselwirkungen in versuchsserien. In: Biometrie- heute und morgen. Eds Köpcke & Uberla. Springer-Verlag, Berlin.
- YUE, G.L., ROOZEBOOM, K.L., SCHAPAUGH, W.T. & LIANG, G.H., 1997. Evaluation of soybean cultivars using parametric and nonparametric stability estimates. *Plant Breeding* 116: 271-275.
- ZOBEL, R.W., WRIGHT, M.J. & GAUCH, H.G., 1988. Statistical analysis of a yield trial. *Agron. J.* 80: 388-393.

Table 5.3. Combined analysis of variance results for the milling characteristics regarding spring wheat cultivars under irrigation

		HLM	TKM	SKCS-G	SKCS-DIA	VK	SKCS-HI	FABS	BFLY	FLY
Source	DF	MS	MS	MS	MS	MS	MS	MS	MS	MS
Replications	30	1.19	5.42	4.76	0.02	69.78	8.82	1.62	0.69	0.71
Genotype	4	29.42*	51.33*	51.27*	0.57*	259.44*	521.93*	99.07*	120.99*	29.08*
Locality	14	63.28*	140.54*	139.03*	0.34*	3293.98*	934.31*	48.63*	134.75*	9.19*
Genotype x locality	56	4.19*	9.98*	13.40*	0.03*	91.26*	48.01*	5.31*	4.65*	3.06*
Error	120	2.11	4.53	4.10	0.02	48.88	14.15	1.32	0.91	0.63
Total	224									
CV%		1.85	5.33	5.18	5.27	9.07	5.77	1.84	4.55	1.04
R ²		0.84	0.84	0.86	0.79	0.90	0.91	0.90	0.96	0.85

* = Smallest significant difference at the p<0.05

MS = Mean squares

CV% = Coefficient of variance

R² = Coefficient of determination

S.E.D. = Standard error of difference

Table 5.4. Combined analysis of variance results for the baking characteristics regarding spring wheat cultivars under irrigation

		FLN	GPC-Leco	FPC-Leco	WGC-12	SDSS	MDT	AS	AD	ASTAB	P/L	LFV	LFV-12
Source	DF	MS x 1000	MS	MS	MS	MS x 1000	MS	MS x 1000	MS x 1000	MS x 1000	MS	MS x 1000	MS X 1000
Replications	30	0.51	0.46	0.61	5.41	12.12	0.06	43.64	0.20	0.06	0.25	5.80	1.24
Genotype	4	2.35*	3.79*	2.08*	132.81*	1.07*	13.72*	1.58*	7.17*	3.73*	0.61*	31.20*	12.07*
Locality	14	131.70*	4.08*	12.64*	35.05*	1.99*	5.05*	1.05*	8.44*	1.19*	0.25*	140.92*	20.93*
Genotype x localities	56	1.46*	0.60*	0.87*	6.79*	0.05*	0.46*	0.08*	0.49*	0.20*	0.06*	13.04*	4.33*
Error	120	0.56	0.31	0.43	4.06	19.34	0.10	0.02	0.23	0.04	0.01	4.11	1.50
Total	224												
CV%		8.01	4.39	5.58	6.07	5.87	11.44	11.91	11.34	9.35	21.40	6.73	4.12
R ²		0.97	0.76	0.78	0.76	0.94	0.93	0.92	0.87	0.89	0.85	0.86	0.77

* = Smallest significant difference at the p<0.05

** = Smallest significant difference at the p<0.01

MS = Mean squares

CV% = Coefficient of variance

R² = Coefficient of determination

S.E.D. = Standard error of difference

CHAPTER 6

A comparison between different selection methods to improve wheat quality.

6.1 Abstract

Five spring wheat cultivars (*Triticum aestivum* L.) were grown in five environments from 1997 through to 1999. Two test lines were also used in order to verify the accuracy of the evaluation methods, which were the combination of the independent culling with absolute limits of acceptability relative to a check method from the SAGL, Lukow's (1991) multiple linear regression analysis method, Howard's (2003) milling and baking worth procedure, canonical variate analysis (CVA) and cluster analysis. Some shortages do exist currently in the South African wheat cultivar release system such as: (i) The system does not take the consistency regarding the new candidate in comparison to that of the biological standard into consideration. (ii) The system combines two diverse methods in order to evaluate new genotypes which complicates interpretation of the data. (iii) The system puts too much emphasis on characteristics that are mainly under environmental influence. It can be concluded that Lukow's method has the tendency to identify lines that has stronger gluten strength characteristics, which makes sense because it was developed for the Canadian wheat market. Howard's milling and baking worth procedure has relative value for ranking cultivars, but the weighted contributions should be changed according to environmental influence on milling and baking characteristics. The CVA analysis is an objective and efficient procedure to evaluate new breeding lines regarding their milling and baking potential in comparison to a biological quality standard. The cluster analysis gave similar clusters when compared with the groupings of the CVA for baking results but not for the milling characteristics.

6.2 Introduction

Similar to the scenario described by Eskridge *et al.* (1994), the modern milling and baking industry in South Africa is also characterized by high-volume, highly automated

plants with little inherent flexibility in processing methods or procedures. In South Africa, the main production of commercial flour and bread is centralized in highly mechanized plants. Commercial mills are able to process more than 30 tons of wheat per hour, and commercial bakeries develop nearly six tons of dough per hour in order to produce 8000 loaves per hour (Van Lill *et al.*, 1995a). Consistency in quality and performance of wheat grain and flour is critical to the output of high-quality products. For the plant breeder, this means that wheat genotypes with normal end-use quality must be consistent across environments and have acceptable mean performance in milling and baking tests (Eskridge *et al.*, 1994).

Inconsistency of wheat end-use quality has also been described by Peterson *et al.* (1997) as a long term problem confronting the milling and baking industries, which require high levels of uniformity for modern, high speed, processing. Extensive research projects have been conducted world wide in order to characterize genetic, environmental, and biochemical factors that contribute to variation in wheat quality (Peterson *et al.*, 1997; Finney *et al.*, 1987). Therefore, the definition of biochemical factors responsible for genetically controlled quality variation could provide breeders with alternative selection procedures, or an understanding of deficiencies present in certain key genotypes (Graybosch *et al.*, 1996). Variation in wheat quality can interrupt production schedules, increase processing costs, require additional storage capacity, or reduce product quality (Wilson and Preszler, 1992). Milling and baking tests provide information on a number of intercorrelated variables, which makes interpretation difficult.

Osborne *et al.* (1993) reported that systems exist internationally, for a comparative assessment of new plant varieties in order to identify the varieties that will be more suitable for both the grower and the end-user. Bushuk (1998) also reported that in Australia and Canada new wheat cultivars must also meet a prescribed level of quality before it can be registered for commercial production. Salmon (1998) stated that the development of new and improved wheat varieties is an essential component of economic progress of the agricultural sector within the European Union (EU) member states. In most of these countries legislation exists that provides for the official testing of new plant varieties (Osborne *et al.*, 1993). Jones *et al.* (2003) states that prior to marketing, new varieties have to be included on a National List (NL) of one of the EU member states. Part of the testing for NL purposes requires that new varieties must be distinct from existing varieties, uniform and stable with regard to the characteristics used

to demonstrate distinctness. In the interest of uniformity, a new variety should not be released for distribution unless it is superior to the present varieties in one or more agronomic characteristics and disease resistance and should be satisfactory in all other aspects (Geddes, 1941). Salmon (1988) documented that there is normally a yield penalty when growing a bread making quality wheat, which indicates that such wheat varieties are invariably deficient in yield compared to the best yielding varieties, which often has no other market than animal feed production in the EU. Recently wheat breeders had been able to develop new cultivars with good yields without sacrificing quality (Cox *et al.*, 1989; Cline and Esfeld, 1998; Bruckner & Finney, 1992; Baker *et al.*, 1999; Kadar and Moldovan, 2003). Baker *et al.* (1999) also found that the present marketing system for their hard red winter wheat (HRW) grown in the Southern Plains of the USA fails to reward farmers who deliver superior quality wheat to the elevators. Therefore, they constructed a dough factor system, which uses the single kernel characterization system and the whole grain near-infrared analyser to evaluate the milling and baking quality of wheat using a single value called the dough factor.

Understanding the physio-chemical, rheological and compositional (particularly protein) basis for variation in spring wheat quality would enable the development of a rapid, predictive test for end-use quality. Such predictive tools would allow bakers to make adjustments to bakery formulations and equipment settings before the flour lot would reach the bakery floor. There is a need to identify which of the key variables have an effect on the quality and which are genetically controlled and amenable to alteration through selection (Butt *et al.*, 2001). In early segregating generations (F1 to F4), breeding programmes select for the basic criteria that define a market class (e.g. grain hardness, colour, kernel shape and gluten strength). In advanced generations (F5 to cultivar release), baking tests and rheological measures identify breeding lines fitting the subtle characteristics of a market class. However, breeding programmes favour rapid measures of end-use quality to rank breeding lines for relative end-use quality rather than time consuming protocols that would precisely measure the rheology of flour. Integration of genetic, biochemical, and rheological factors with breeding goals and realistic selection protocols results in the improvement of end-use quality for new cultivars (Souza *et al.*, 2002). Identification of variables that are highly influenced by the environment would assist in the development of wheats with enhanced quality when grown in diverse environmental conditions (Butt *et al.*, 2001).

Because quality testing involves the analyses of a large number milling and baking traits that are intercorrelated, most breeders either analytically or intuitively, practice multiple trait selection when developing cultivars (Henning and Teuber, 1996). Those using the analytical approach have numerous methods at their disposal. In general three multiple trait selection procedures are recognized namely, (i) tandem selection, (ii) index selection, and (iii) independent culling levels. Multivariate techniques are also widely applied to provide further information on real multivariate response of genotypes to environments. According to Eskridge *et al.* (1994) milling and baking industries in the USA desire genotypes that have high probabilities of meeting quality standards, as specified by upper and lower limits of acceptability, for multiple quality traits when grown across an array of environments. Statistical description of genotypic response to environmental conditions, as provided by regression or cluster analysis, is of limited value to the industry and is often difficult to interpret. A breeder however, may have difficulty defining limits of acceptability due to many different milling and baking characteristics used. Therefore, breeders often identify long term checks or genotypes to establish minimum values of acceptability for important quality traits. Germplasm is selected that equals or exceeds the check for individual quality traits.

6.2.1 *Tandem selection*

The tandem selection entails sequential selection on a series of traits. Repeated cycles of selection for a single trait are practiced until a desirable expression of the trait is reached. Then repeated selection for the next trait is performed until the desired expression within the population is accomplished. The breeder simply repeats the process until all the traits have undergone selection. Loss of genetic variability due to too high selection pressure on the first and second traits may limit progress in later generations. The tandem procedure offers little control over correlated selection responses. Therefore, one must have prior knowledge of correlated responses between traits undergoing selection and any undesirable traits before selection is initiated (Henning and Teuber, 1996). Because milling and baking characteristics show numerous correlated and intercorrelated responses this method of selection was not considered.

6.2.2 *Independent culling*

Independent culling is another method used for multiple trait selection. Under this protocol, breeders sequentially select for a series of independent traits in the same population. The ultimate selection intensity is reached after all traits have undergone selection. One primary advantage of this method is that breeders do not have to carry large populations throughout the multi-selection process. Independent culling was described as particularly useful when traits under consideration were expressed at different ages, however index selection was described as more efficient for multiple trait selection than independent culling, yet it required the handling of large populations throughout the selection process (Henning and Teuber, 1996). Because quality testing is very expensive, testing of genotypes regarding the above -mentioned methods will be very costly. The current system being used by the South African Wheat Technical Committee is based on a combination of independent culling as well as absolute limits of acceptability relative to a check.

Historically, the technology in South African bakeries is based on European designs that were developed to process weaker quality types (Chorleywood Breadmaking Process). Stronger dough types are known to produce more bread per unit flour, but processing problems outweigh the advantages of stronger flour types. These problems include increased dough temperature; increasing batch-batch cycle time and loaf volumes that exceed pan capacity in the modern plant bakeries (Van Lill and Purchase, 1995). Therefore Van Lill and Purchase (1995) concluded that care must be taken to maintain current levels of dough strength to avoid the release of wheat cultivars of which the dough strength exceeds the levels required for the Chorleywood breadmaking process for winter wheat cultivars under dryland production.

During 1996, the South African wheat market was deregulated from a single channel wheat marketing system to a liberal wheat-marketing environment. This had a drastic effect on the purchasing patterns of the processors regarding wheat grain. In the single channel marketing system, wheat cultivars were released for commercial production after meeting the minimum quality requirements (11 primary and 11 secondary parameters) set by the Wheat Technical Committee, functioning under the auspices of the former Wheat Board and comprising representatives from all the sectors of the industry. However, once these cultivars had been released for production purposes, they were

deemed to be of equal quality worth and the grain was mixed at the point of receipt (silo's). Buyers were then obliged to receive and accept grain of these mixtures of cultivars for milling and baking purposes, irrespective of the quality of the grain. It thus follows that these released wheat cultivars with superior quality characteristics were never scientifically and objectively identified and was thus also never in demand by the processing industry.

The new liberal wheat-marketing environment lends itself to buying on an individual cultivar basis, as is the common practice in many countries, which have deregulated wheat-marketing systems. However, only limited and unscientific information on the relative milling and baking worth of the different South African wheat cultivars is available to breeders, producers, buyers and processors of grain. The release of South African wheat cultivars is still being controlled by the Wheat Technical Committee, now under auspices of the Winter Cereal Trust. The committee consists of a panel of experts representing the farmers, millers, bakers and wheat breeders. New candidates are being submitted to an evaluation period of three years, which means that wheat samples from a total of 15 growth environments are being subjected to a composite analysis of 21 milling, mixing and baking characteristics. Thus the acceptability of an entry depends on the committee's belief whether the quality data lies within the specified margins when compared to a biological standard. Different biological standards are being set for each of the different breeding regions. Kariega is the designated biological standard for the irrigation areas. The National Chamber of Milling and Baking releases a list annually, which includes all the cultivars that will be accepted at the point of the delivery. This list will include all the cultivars that have been released, which still should exhibit acceptable bread making quality. Their quality data is mostly based on obsolete data originating from the time when they were released as cultivars. Moreover, the wheat industry had withdrawn several cultivars in the past based on unacceptable quality performance once grown commercially, mostly such cultivars had obvious problems with their milling or baking performance and were released during the period when the evaluation system was not so stringent. Mostly a cultivar's longevity depends also primarily on its overall adaptability and rapidity and degree of change of specific diseases or insects, races of individual diseases or biotypes of individual insects and the speed with which breeders can offer higher yielding and equal- or better quality new cultivars (Finney *et al.*, 1987).

6.2.3 *Absolute limits of acceptability relative to a check*

Multilocation trials are a common means for evaluating new cultivars or strains. Their statistical analysis is often based on multiple comparisons with one or more controls (Piepho, 1995). Butt et al. (2001) also reported that the milling and baking industry in Pakistan desires genotypes that have high probabilities of meeting quality standards, as specified by upper and lower limits of acceptability, for multiple quality traits when grown across an array of environments. Breeders often identify and use a long-term check genotypes to establish minimum values of acceptability for important quality traits. Germplasm is then selected that equals or exceeds the check for individual quality traits (Eskridge et al., 1994). A breeder, however, may find it difficult to defining these limits of acceptability due to the many different milling and baking processes used, and wide diversity in end-use products. Accumulating desirable quality genes will help reduce genotype x environment effects on quality – presently among the major challenges confronting breeders (Pena et al., 2002).

According to Eskridge et al. (1994), decision making models based on the assumption of safety-first behavior (Eskridge, 1990) may provide a method to quantify both acceptability and stability of multiple quality traits for genotype selection. Safety-first models could be quite useful with advanced trials where promising experimental genotypes are evaluated in multiple environments. A natural application of these models would be to base selection decisions on the probability of obtaining acceptable end-use quality for all traits under consideration when tested across multiple environments. A genotype with high probability of all traits falling within acceptable limits would be more reliable, and thus preferred, compared with those with lower probability values. Such an approach would provide substantial flexibility in statistical analyses as definitions of acceptability can be easily modified and results easily interpreted in terms of probabilities of success.

6.2.4 *Index selection*

Many multiple trait selection protocols utilize an aggregate score or an index, as means of differentiating genotypes possessing superior trait combinations. Index selection protocols utilize simultaneous selection on a series of traits as opposed to sequential selection. Some indices require the estimation of genetic variances, co-variances, and

the economic value for all the traits undergoing selection. The optimum index proposed by Hazel (1943) allows one to take genetic correlations into account and adjust selection pressures for each trait accordingly. Kempthorne and Nordskog (1969) had made modifications to the optimum index in order to enhance genetic gain due to the selection for specific traits while holding genetic gain in other traits constant.

6.2.4.1 *Lukow's index selection*

During the 1990's goals for the Canadian bread wheat were excellent milling quality, high inherent baking quality, blending quality, uniformity of export shipments and availability at different guaranteed protein levels for the two top milling grades. Particularly for baking, good all around quality or performance under many different baking conditions is more desirable than the ability to produce one specific product. They obtained this uniformity and consistency within the bread wheats by means of having cultivars that are similar in quality within specified limits (Lukow, 1991). In order to achieve the above-mentioned goal, Lukow (1991) developed a set of formulas that calculates scores for lines in order to distinguish between lines with poor and good quality traits at early as well as advanced generations. Due to small samples at early generations where it is not possible to measure loaf volume, multiple linear regression analysis was used to generate prediction equations for loaf volume and baking strength index (BSI) for early as well as advanced lines. This method developed by Lukow (1991) can be described as a selection index.

6.2.4.2 *Howard's index selection*

Locally a cultivar project grew out of the need to standardize the quality of the milling wheats in South Africa in order to determine the actual worth of each cultivar when compared with others, or in other words to determine a ranking order, if possible, for the wheat cultivars in a specific region. Mathematical models were used to develop the complex equations when comparing the qualities of the cultivars among each other. Other values were also calculated on an empirical formulation based upon potential worth of that property in the industry. Hence a milling worth and a baking worth factor was established which take the weighted contributions for the relevant milling and baking characteristics into consideration. Table 6.1 summarizes the nominal values together

with their milling and baking worth contributions for the relevant milling and baking characteristics (Howard, 2003).

Table 6.1. Milling and baking worth contributions developed by Howard (2003).

Worth	Nominal value	Contribution (%)
Milling worth:		
Buhler extraction (FLY)	78%	35
Hectilitre mass (HLM)	78kg/hl	15
1000 kernel mass (TKM)	42g	15
Buhler break flour yield (BFLY)	15%	10
Flour Colour (FCL)	-3 KJ units	15
Falling number (FLN)	300 s	10
Total		100
Baking worth:		
Loaf volume (LFV)	950cm ³	35
Flour protein content (FPC)	11.50%	8
Farinograph water absorption (FABS)	66%	16
Alveograph P/L ratio (P/L)	0.8	12
Alveograph strength (AS)	35cm ²	13
Mixograph development time (MDT)	2.6 min	16
Total		100

6.2.5 Multivariate selection

Multivariate statistical techniques can also be used to compute user-friendly models for objective characterization of variation in milling and rheological quality of wheat lines. The interpretation of genotypic and environmentally related variation can then be improved through the obtained graphical presentations (Van Lill and Smith, 1997).

Statistical description of genotypic response to environmental conditions, as provided by regression or cluster analyses, is of limited value to the industry and often difficult to interpret. In contradiction to the previous statement, Butt *et al.* (2001) reported that the application of canonical analyses, has shown that the measurement of some biological components explains more than 90% of the variation in major quality attributes such as dough handling and loaf characteristics. Graybosch *et al.* (1993a) highlighted the grouping of numerous biochemical components together with the usage of multivariate analysis may be required to develop effective predictive models to explain the variation

observed in the end-use quality of wheat. When the relationships of two sets of variables are to be considered, within and among the sets, the principal component analysis is not useful. In such a case an alternative approach must be used for instance the method developed by Hottelling (1936), also known as the canonical correlation analysis.

6.2.5.1 *Canonical Variate Analysis*

The Canonical Variate Analysis (CVA) is a method with certain maximal properties similar to those of the principle component analysis and in a way is an extension of the multiple regression analysis (Butt *et al.*, 2001). The CVA is a test used when it is of more interest to show differences between groups than between individuals. The objective of this approach is to determine the linear functions of the variables for each of the sets such that the correlation between these linear functions is as high as possible (Butt *et al.*, 2001). Therefore, the difference between a large number of variables is firstly reduced to a smaller set of variables that account for most of the variance in that range. This new set is called canonical variates, which is linear combinations of the original measurements, and is thus given as vectors of loading for the original measurements. With this approach, a set of directions is obtained in such a way that the ratio of between-group variability to within-group variability in each direction is maximized. (Digby *et al.*, 1989; Van Lill and Purchase, 1995). Van Lill and Smith (1997) clearly demonstrated in their study for winter wheat cultivars under dryland production, that the CVA analyses have the potential to compare independent data sets. They also showed that this approach does not apply to the comparison of data sets from independent wheat breeding institutions within harvest seasons, but also to comparisons of samples over seasons. Moreover, the reliability of the interpretation could be improved by allowing new data to be entered in a national wheat quality data bank to be used for computation and incorporation of new equations on a manual basis.

Van Lill *et al.* (1995b) also proved that multivariate statistical techniques (like the canonical variate analysis) are best suited to evaluate the magnitude and contribution of several factors to variation in bread-making quality. Graybosch *et al.* (1993b) also used the canonical variate analysis to ascertain the extent to which a set of biochemical measurements was related to a set quality measurements and to determine the

particular components that have been responsible for these correlations. For discrimination between quality types in breeding material, where differences between groups are of more significance than differences between individual breeding lines, canonical variate analyses was employed by Osborne *et al.* (1993). Labuschagne *et al.* (2002) also showed that the canonical variate analysis as a multivariate analysis can be used by wheat breeders, to assess quality of wheat cultivars, and to improve the effectiveness of selection.

6.2.5.2 *Cluster analysis*

Cluster analysis is a numerical classification technique that defines groups or clusters of individuals. Two types of classification can be distinguished. The first is nonhierarchical classification, which assigns each item to a class. The second type is hierarchal classification, which groups individuals into clusters and arranges these into a hierarchy for the purpose of studying relationships in the data (Crossa, 1990). Comprehensive reviews of the applications of cluster analysis to study genotype x environment interactions can be found in Lin *et al.* (1986) and Westcott (1986).

6.2.6 *Objectives of the study*

The objectives of this research were to: (i) evaluate the different existing methods available regarding their suitability for grouping different genotypes into homogeneous groups according to their milling and baking characteristics respectively. (ii) The effectiveness of these methods to identify superior genotypes according to their milling and baking characteristics will also be determined. (iii) Illustrate the success with which the abovementioned approaches can be used to evaluate the milling and baking quality characteristics from multilocation field trials for new testing lines to be considered for release.

6.4 **Materials and methods**

Evaluation of wheat quality involves the measurement of a large number of characteristics. Since many of the tests for quality evaluation are time-consuming and expensive, they have been performed traditionally on a limited number of samples. The number of samples to be evaluated may be reduced by combining samples over replicates, locations or years. However, this procedure reduces the precision with which quality characteristics are estimated and may lead to erroneous conclusions if large cultivar by environment interactions do occur (Lukow and McVetty, 1991). Therefore, in order to improve the precision of the analysis the number of cultivars, localities, replications and years were maintained throughout the study.

6.3.1 Field trials

Five genetically diverse spring wheat cultivars namely, Kariega, Marico, SST825, SST822 and SST876 were the genotypes common in all three years of testing. Small Grain Institute (Agricultural Research Institute) released Kariega and Marico, while Monsanto owns the Plant Breeders Rights on the latter three cultivars. The term "spring wheat" implies that such cultivars do not need a certain degree of vernalization requirements in order to reach full maturity. The genotypes, year of release, status and origin for the genotypes used in this study are indicated in Table 3.1.

Most of the cultivars are semi-dwarf cultivars except for SST822, which is a short growth period double dwarf. Double dwarf wheat cultivars tend to have lower yield potential than semi dwarf wheat cultivars in South Africa. SST876 possesses the solid stem characteristic originating from *Aegilops ventricosa*. The solid stem characteristic improved lodging tolerance dramatically, with resultant higher grain yield. Kariega is the biological quality standard being used by the South African Wheat Technical Committee as a reference cultivar. This implies that all new lines are compared against Kariega for possible release as new cultivars in the irrigation areas. Kariega and Marico are long growth period cultivars while SST 825 and SST 876 are classified as medium growth period cultivars. Seed for the given quality analysis, were obtained from trials conducted in the irrigation areas by the National Cultivar Evaluation Department of Small Grain Institute during 1997,1998 and 1999.

Table 6.2. Genotypes and their pedigrees, year of release, status and origin.

Genotype		Year	Status	Origin
Marico	BROADBILL'S"	1992	Cultivar	CIMMYT, Mexico
Kariega	SST44//K45400/SAPSUCKER'S'	1993	Cultivar	SIG, RSA
SST822	Not available	1992	Cultivar	Monsanto, RSA
SST825	TUI'S"	1992	Cultivar	CIMMYT, Mexico
SST876	SST57/ADAT TAS//SST 825	1997	Cultivar	Monsanto, RSA
BPT01/07	SST876/KARIEGA/SST886	Na	Line	Monsanto, RSA
BSP02/06	97BPT11/SST875//KARIEGA	Na	Line	Monsanto, RSA

SIG = Small Grain Institute
 RSA = Republic of South Africa
 Na = Not applicable

Wheat production under irrigation in the summer rainfall region entails the production of spring wheat types, which are planted in the fall and winter. There are five main irrigation areas, namely the cooler central irrigation areas (situated next to the Orange, Vaal, Sand and Vet rivers), the warmer northern irrigation areas (along the Eliphants and Crocodile rivers, the Loskop dam irrigation area is also included here), Kwazulu-Natal, Eastern Free State and the Eastern Cape (Cradock). The warmer northern irrigation regions have a lower yield potential compared to that of the cooler central irrigation areas, and this is mainly due to the warmer winter temperatures and therefore a shorter growing season. This leads to a higher growth and development rate, weaker tillering capacity and subsequently lower yields. The irrigation areas represent high yielding environments, which rely heavily on intensive cropping systems.

The region, location, coordinates and number of trials from 1997 until 1999 included for quality analysis can be seen in Table 3.2. Trials were conducted at experimental stations or farms of collaborators where the soil and climate are representative of a specific area.

Table 6.3. Regions with representative localities and the number of trials from 1997 until 1999.

Region	Locality	1997	1998	1999
Warmer areas	Loskop	1	1	1
Cooler areas	Bult Hill	1	1	1
	Prieska	1	1	1
	Hopetown	1	1	1
	Douglas	1	1	1

It is very important to bring cultivar performance in line with the weather conditions that prevailed during the growth cycle. For the 1997 season normal temperatures occurred during the period up to the middle of June in all the regions. Temperatures above average occurred during the second half of winter in all five regions. Above average temperatures were measured during the grain filling period from August through to October. This had a negative influence on the yield and hectolitre mass levels.

During the 1998 season normal to above average temperatures occurred in all the irrigation areas during the second part of the winter months up to the end of August. Below average temperatures were measured during September and October which had a positive influence on grain filling period resulting in higher yields and hectolitre masses. In some of the areas heavy rain showers were observed which lowered the hectolitre masses slightly.

Regarding the 1999 season normal to above normal temperatures occurred during the growth period up to the end of August in all the irrigation areas. Above average temperatures occurred in all five irrigation areas during the second half of the winter. Relatively low temperatures occurred during September and October, which had a positive effect on yield and hectolitre mass.

The cultivars were planted according to a randomised block design with four replicates. Trial plots consisted of eight rows 0.17 m apart and six meter in length, which were then later reduced to five meters length to produce a net plot size value of 6.8m². The seeding rate was standardized for each cultivar according to its 1000 kernel weight.

Therefore, the seeding rate for each cultivar differed in order to establish a uniform stand of plants per square meter.

Fertilization was applied according to target yield recommendations for each region. Applications on the trial plots were done according to recommendations based on individual soil analyses obtained from soil samples. Weed and pest control was performed when necessary. At harvesting, the two side rows were cut out in order to reduce the side-row effect, which can influence yield positively, thus the net plot size harvested for the quality analysis was 5.1 m². The plots were harvested with a Wintersteiger plot combine.

The soil profiles in the cooler central irrigation areas are mostly sandy and red in colour. Soils with high clay contents are found in the warmer northern irrigation regions. Maximum temperatures above 30°C during kernel filling period are a common phenomenon that eventually increases the risk for drought stress with consequently low hectolitre masses and high protein contents (Koekemoer, 1997). Mostly the total rainfall figures in all the irrigation areas except Kwazulu-Natal do not exceed 200mm during the growth cycle.

6.3.2 *Quality analysis*

Test weight or hectolitre mass (HLM, kg/hl) was determined using a Franklin chondrometer. The mass of a thousand kernels counted with a Numigral seed counter (Tripette et Renaud Paris France) was considered as the thousand kernel mass (TKM, g). After 50 grains had been cut with a farinator, vitreous kernels (VK, %) were determined as the total of two points per fully vitreous grain and one point per grain with at least 50% vitreousness. Grain samples of approximately 50 g were milled with a Falling Number KT-120 laboratory mill (1.0mm sieve) after which Hagberg Falling Numbers (FLN, s) were determined (AACC, 1983) from a 6.1 g sample to compensate for altitude (\pm 1340m). The grain protein contents (GPC-Leco, %) and flour protein contents (FPC-Leco, %) were determined with a Leco-FP2000 (AACC, 1995). Flour extraction rate (FLY, %) and break flour yields (BFLY, %) were calculated after experimental milling in a pneumatic Buhler MLU202 mill (Buhler-Miag, Uzwil, Switzerland), (AACC, 1983). A Kent Jones and Martin colour grader was used to

measure flour colour standardised at a 76% flour extraction rate (FCL76, kj units). Single kernel characteristics were determined using the SKCS 4100 (Perten Instruments, Springfield, IL), this instrument provides characteristics like kernel diameter (average diameter of 300 kernels), hardness index (the index as percentage of the pressure of two rollers to crush 300 kernels) and kernel weight (the average weight of 300 kernels in mg).

Mixograph dough development time (MDT, min) was determined with a 35g National Mixograph (National Mfg., Lincoln, Nebraska), (AACC, 1983). Other rheological analyses performed according to approved methods (AACC, 1983) included the Brabender Farinograph quality determinant water absorption (FABS, %), the Chopin Alveograph determinants: dough strength (AS, cm²), Alveograph stability (ASTAB, mm), Alveograph distensibility (AD, mm) and the ratio of stability to distensibility (P/L). In this study, micro loaves were baked from 100g of flour, using an optimized straight dough method (Finney, 1984). Loaf volumes were then determined by rapeseed displacement directly after baking, using a pup loaf volumeter. The SDS-sedimentation (sodium dodecyl sulphate –SDS) test was used to measure the relative gluten strength as it indicates the differences in the quantities of the polymeric glutenins (gel protein), (AACC, 1983). Wet-gluten content was determined with the glutomatic; the glutomatic is an automatic apparatus, which develops gluten of wheat flour from a 2% NaCl solution. The dough mixing and subsequent separation of starch and other solubles from the dough takes place in the same test chamber under controlled standardized conditions. The ball is then centrifuged to remove excess water and weighed as wet gluten.

In order to simplify the discussion, all the quality characteristics were divided into two groups namely milling and baking characteristics. The milling characteristics are represented by hectolitre mass (HLM), thousand kernel mass (TKM), Vitreous kernel (VK), SKCS weight (SKCS-G), SKCS diameter (SKCS-DIA), SKCS hardness index (SKCS-HI), Farinograph water absorption (FABS), break flour yield (BFLY) and flour yield (FLY). The baking characteristics are represented by falling number (FLN), grain protein content determined by the Leco (GPC-Leco), flour protein content determined by the Leco (FPC-Leco), Wet gluten content standardized at 12% protein content (WGC-12), SDS-sedimentation value (SDSS), mixograph development time (MDT), alveograph strength (AS), alveograph distensibility (AD), alveograph stability (ASTAB), alveograph P/L index (P/L), loaf volume (LFV) and loaf volume standardized at 12% protein content (LFV-12) in order to eliminate the positive effect of protein content on bread loaf volume.

6.3.3. *Statistical analysis*

6.3.3.1 *Combination of independent culling method with absolute limits of acceptability regarding to a relative check (SAGL, 2002)*

The classification of wheat cultivars is an attempt to provide the wheat industry with new cultivars that perform well agronomically and possess suitable milling, rheological and baking characteristics. The analytical procedures and classification norms are compiled in conjunction with wheat breeders, millers and bakers to ensure market-directed and quality-driven wheat production in the interest of the wheat producers and processors. The classification norms use cultivars as biological quality standards as a frame of reference against which new breeding lines are evaluated. Only cultivars that are successfully grown commercially and possess acceptable agronomical and quality characteristics may be considered as biological quality standards. As the breeding of wheat with the suitable quality characteristics is a long-term project, classification norms and quality standards are provided to breeders in an attempt to give them guidelines that should stand the test of time. Changing the classification norms and establishing new quality standards are for this reason thoroughly investigated and carefully considered to ensure that the long-term goals of breeding programs are achieved (SAGL, 2002). This method will be used as the reference method throughout this study.

The effect of the climate, rainfall, environmental interaction, cultivation practices and other factors on wheat quality makes the use of fixed criteria or norms for classification purposes impractical. For this reason cultivars are used as biological quality standards, and acceptable deviations from the standard are established as classification norms. It is important that the agronomical performance and yield potential of the chosen quality standard should be comparable with those of the breeders' lines, as lower yields in some quality standards are often connected to higher protein content. Big differences in the protein content of breeders' lines and the quality standard cause deviations, especially in rheological analysis results, which complicates the interpretation and evaluation of breeders' lines (SAGL, 2002).

Kariega is the cultivar that represents the quality standard for the irrigation areas against which wheat breeders' lines are evaluated for the bread wheat class. The quality norms

for classification are categorized in primary (P) and secondary (S) quality norms. The quality of new lines is judged by the primary criteria, which is non-negotiable. In borderline cases, a decisive answer is obtained by referring to secondary norms. Only red cultivars with medium hard to hard morphological characteristics will be allowed in the class.

A minimum of two years' analysed data from at least five localities per annum is required for provisional classification. If there is any doubt about any of the quality aspects, provisional classification is postponed. For final classification, analysed data over three years for the cultivar and the quality standards concerned from a minimum of five localities should be submitted. For classification in an area other than originally classified, two years' data from at least five localities is needed. The first year's data is valid for provisional classification and the second year's data for final classification. The norms together with the categories set by the SAGL for wheat classification purpose are summarized in Table 6.4 (SAGL, 2002).

Table 6.4. Quality standards for South Africa irrigation wheat cultivars.

Test	Category	Deviation
Hectolitre mass-clean (kg/hl)	P	"-1.5 units
* 1000 Kernel mass (g)	S	" +4g
Falling number (s)	P	"-15%
Grain protein content (%)	P	-1%
Extraction (%)	P	-1.2%
** Colour (KJ C76)	P	+0.5 units
Break Flour yield (%)	S	±5%
Mixograph peak time (min)	P	-20% to +10%
Farinograph water absorption (%)	P	±2%
Farinograph development time (min)	S	±20%
Farinograph stability (min)	S	-30% to +10%
Alveograph strength (cm ²)	P	±20%
Alveograph stability (mm)	S	-10% to +20%
Alveograph distensibility (mm)	S	-10% to +20%
Alveograph P/L ratio	P	±20%
*** Baking test 100g - corrected volume (cm ³)	P	-10%
Dough characteristics	P	none

Falling number values should not exceed 250 seconds and may not be more than 15 % lower than that of the quality standard.

** Colour is corrected to 76 % extraction based on 0.4 KJ units per 1 % extraction. E.g. If a line has an extraction to the value of 77 %, 0.4 KJ will be subtracted from the line's colour value. Should the line's extraction be 75 %, 0.4 KJ will be added to the line's colour value.

*** Bread volume is evaluated against the protein level of the line. A factor of 40 cm³ per 1 % protein difference is used to adjust the bread volume of the line against the standard. E.g. If a line has a

protein content of 11.0 % and the standard has a protein content of 12.0 %, 40 cm³ will be added to the line's bread volume and vice versa

The standard deviations were determined for each of the cultivars in order to verify if the minimum and maximum limits set for each line according to the deviation from the check are acceptable. The standard deviations was determined according to the following formula:

$$STD = \sqrt{\frac{n\sum x^2 - (\sum x)^2}{n(n-1)}}$$

STD = Standard deviation of the means

6.3.3.2 *Index selection*

6.3.3.2.1 *Lukow's index (1991) method*

One of the objectives in breeding wheat for baking purposes is to develop cultivars that will produce large loaves when baked by the remix method (Kilborn and Tipples, 1981). The baking strength index (BSI) expresses actual remix loaf volume (RLV) as a percentage of the volume that would be expected of top-quality Canadian red spring wheat flour of the same protein content (Tipples and Kilborn, 1974). The predicted RLV is being calculated according to the following equation:

$$\text{Predicted loaf volume (PLV)} = 62.5(\text{FLP}) + 58.1(\text{MDT}) - 119.6$$

$$\text{Predicted baking strength index} = \text{PLV}/(70(\text{FLP})-55)$$

To provide an overall indication of quality, a general score was developed and is calculated for every advanced test line:

$$\text{Overall score} = \Delta\text{FLP} + 0.2(\Delta\text{FLY}) + \Delta\text{MDT} + 0.2(\Delta\text{FAB}) + 0.02(\Delta\text{RLV}) + 0.01(\Delta\text{AACC})$$

[if ΔMDT is used when $\Delta\text{MDT} = 0.3$] or + [0.7 - ΔMDT] is used when $\Delta\text{MDT} > 0.3$

Where ΔFLP , ΔFLY , ΔMDT , ΔFAB , ΔRLV and ΔAACC are the actual differences between the test line and the mean of the check cultivar for flour protein content, flour yield and mixograph development time, farinograph absorption and AACC straight dough loaf volume with 10ppm bromate respectively (according to the AACC method) respectively.

6.3.3.2.2 *Howard's (2003) milling and baking worth index procedure*

The procedure developed by Howard (2003) is specifically aimed at the determination of the ranking order of various wheat cultivars, grown and tested under rigid standard conditions, and not to the actual monetary worth per se. This wheat cultivar quality model is primarily aimed at assisting the cereal technologist in the determination of the ranking order of the cultivars in the South African market. The procedure was achieved with the utilization of mathematical models in order to develop the complex equations when comparing the quality of cultivars with each other. Some of the milling and baking worth contributions were developed from the genetic contribution and other values were calculated on an empirical formulation based upon the potential worth of that property to the industry. The equations used in order to determine the contributions of each quality trait should have an acceptable nominal value and an acceptable range so that the penalty for poor quality is severe. This procedure will work 1) if the wheat samples are grown in the same test plot and 2) if tested in the same laboratory using standardized methods. Ideally each cultivar should be tested the same number of times in the trial. The nominal values were also chosen to represent the ideal values as they are presently understood and accepted in the Milling and Baking Industries. In order to accommodate the ultimate requirements for superior Milling and Baking wheat cultivars in South Africa, the nominal values chosen are higher than expected. From a study of the actual use of this equation carried out by Howard (2003) to demonstrate the milling and baking worth procedure, it was found that not many South African wheats obtain scores of 100% or better (Howard, 2003).

6.3.3.2.2.1 *Milling worth calculations*

The calculations for the individual milling worth (mw) factors have been added together to add up to 100%. The actual contribution of each value together with its milling worth is summarized in Table 6.1. Six factors were selected to represent the measurable items that contribute to the milling worth of a wheat cultivar. Many of these nominal values have been increased at the request of the Milling Industry representatives. Although hardness, as measured by the Single Kernel Hardness Tester, is a significant value, the Milling Industry felt that more experience is required on the interpretation of these results

before they are included in the overall equation. The falling number has been included, for the first time, into the equation (Howard, 2003).

The extraction contribution ($EX-FLY_{mw}$) is calculated according to a polynomial equation fixed to give a value of 35% when the extraction is 78% on the Buhler MLU 202 laboratory mill. The development of the equation took cognizance of the request that the penalty for under achieving is of the order required by the sub-committee. The equation is:

$$EX-FLY_{mw} = (0.534*FLY^2 - 67.9*FLY + 2147.345)*35/100$$

Thus, an extraction value of 74% gives a contribution value of 16.4%, while an extraction of 80% contributes 46.5% to the total milling worth value. The results indicate the spread of the varying extraction flour yields and the effect upon the milling worth value. Because of the importance of the extraction value the rapid decrease in the worth value when the extraction is lower than 78% comes into effect (Howard, 2003).

The hectolitre mass contribution (HLM_{mw}) was calculated from a straight line graph. The equation was adapted in such a way that the hectolitre mass of 80kg/hl produced a contribution value 15% to the overall milling worth. The equation is as follows:

$$HLM_{mw} = (10*HLM-700)*15/100$$

A hectolitre mass of 76kg/hl contributes a total of 9 %, while a line with a hectolitre mass of 82 kg/hl produces a contribution value of 18% (Howard, 2003).

The thousand kernel mass contribution (TKM_{mw}) is calculated with a polynomial equation ($y = ax^3 + bx^2 + cx + d$). The equation is:

$$TKM_{mw} = (0.0052*TKM^3 - 0.852*TKM^2 + 44.345*TKM - 644.82)*15/100$$

The results (46g = 14.80%, while 32g = 10.8%) indicate the spread of the varying thousand kernel masses and the effect upon the milling worth value. The reason that values greater than 42g are penalized is that it is always beneficial to have as even as possible wheat size in a milling mixture (grist) (Howard, 2003).

The break flour yield contribution ($BFLY_{mw}$) is calculated by using also a polynomial equation, where the minimum break flour yield value for bread wheat is being set at 15 %. According to Howard (2003), the break flour yield, as a measurement is the best component available at present to measure the hardness of wheat and therefore represents an important factor in the overall equation. Presently most of South African wheat has BFLY value of around 22% to 25% indicating that South African wheat, on a hardness scale, can only be considered as medium hard wheat. The equation for the $BFLY_{mw}$ is:

$$BFLY_{mw} = (-0.444*BFLY^2 + 13.322*BFLY + 0.07)*10/100$$

When $BFLY = 15\%$ the $BFLY(mw) = 10\%$ (in the milling worth equation). This means that given the BFLY values the corresponding $BFLY_{mw}$ values are (18% = 9.6% and 12% = 9.6%). The results indicate that the optimal break flour yield is set at 15%, on either side of the optimum value of 15%, the milling worth value decreases in regular increments. This low break flour figure of 15% will tend to increase the hardness of South African wheat with time (Howard, 2003).

The Kent Jones colour value was chosen with an absolute ideal value $-3KJ$ units representing a very white flour colour. The equation is:

$$FCL_{mw} = (1.25*FCL^2 - 15*FCL + 43.75)*15/100$$

A Kent Jones flour colour of -3 produces a FCL_{mw} contribution of 15, while a KJ value of 2 produces a FCL_{mw} contribution value of 2.8

The equation for the falling number contribution (FLN_{mw}) is also a polynomial equation fixed to give a FLN_{mw} contribution of 10%, with a corresponding 300s falling number value. The equation is as follows:

$$FLN_{mw} = (0.0000025*FLN^3 - 0.00339*FLN^2 + 1.357*FLN - 69.5)*10/100$$

A falling number value of 60s produces an FLN_{mw} contribution value of 0%, while a FLN value of 400s produces an FLN_{mw} contribution of 9.1%. The decrease in milling worth

value for falling numbers greater than 300sec is associated with the fact that the bakers (or in some cases millers) have to add enzyme to compensate for low enzyme activity.

6.3.3.2.2 *Baking worth calculations*

The following calculations will represent the baking worth (bw) factors. The actual contribution of each value is summarized in Table 6.1. The factors considered to have a marked effect upon the baking worth equation are: flour protein (FPC), farinograph water absorption (FABS), mixograph peak (development) time (MDT), loaf volume (LFV), alveograph P/L ratio (P/L), and the alveograph strength (AS).

The nominal loaf volume value (LFV_{bw}) is set at 950cm^3 and its baking worth is fixed at 35%. Included in the equation is a factor that combines the effect of the flour protein content upon the volume of the bread. This factor compensates in the cases when the flour protein content is high, but without a proportional increase in bread volume. The information required for this compensatory part of the equation was calculated from two years of results done by the SAGL on three standard cultivars. This compensatory part of the equation is:

$$(0.222 (-47.842 (\text{FPC} - 14.909))).$$

The overall LFV_{bw} equation is:

$$LFV_{bw} = (((0.222 * LFV - 111.111) + (0.222 * (-47.842 * (\text{FPC} - 14.909) + 338.36) - 111.111))) * 35 / 100$$

The effect of this loaf volume equation on the baking worth is as follows: 950cm^3 LFV and 11.5% protein content = 35%, while 950cm^3 and 10.5% protein content = 38.7%. It can be noticed that when the bread volume is 950cm^3 and the flour protein is 11.5% then the $LFV_{bw} = 35\%$, with a resulting baking worth contribution is 35% (Howard, 2003).

According to Howard (2003), it is believed currently that protein content by itself should also be considered as contributing towards the baking worth of the wheat. A flour protein of 11.5% is considered the optimum for this test and a straight - line curve was developed. The equation is:

$$FPC_{mw} = (33.333 * FPC - 283.33) * 8 / 100$$

This means that the cultivar or the environment's ability to influence protein production can also have an influence on the baking worth result. However, this must refer to "protein content related to baking potential", although this has been taken care of by the loaf volume equation, which will penalize high protein lines without producing larger bread volumes (Howard, 2003).

The optimal farinograph water absorption ($FABS_{bw}$) value is taken as 66%. This high value is taken to encourage this quality aspect in South African wheat as well as kernel hardness and milling technique. The contribution for the farinograph water absorption in the baking worth equation is 16%. The equation is a polynomial and is calculated as follows:

$$FABS_{bw} = (1.239 * FABS^2 + 163.547 * FABS - 5297.02) * 16 / 100$$

A FABS value of 58% will produce a $FABS_{bw}$ contribution of 3.5%, while a FABS value of 70% = 12.7%, $FABS_{bw}$ contribution value (Howard, 2003).

The equation developed for the analyses of the alveograph P/L ratio (ideal value is 0.8) is a polynomial equation to the fourth power. The equation allows for complex calculations especially for values at the high range of the ratio, i.e. above 1.5. The contribution towards the baking worth is 12%. The equation is as follows:

$$P/L_{bw} = (-29.209 * P/L^4 + 233.822 * P/L^3 - 636.209 * P/L^2 + 626.537 * P/L - 101.808) * 12 / 100$$

A P/L value of 2.0 will produce a P/L_{bw} contribution of 1.2%, while a P/L value of 0.2 = 0%, P/L_{bw} contribution value (Howard, 2003).

The nominal for alveograph strength was set at 35cm^2 and a polynomial equation was developed calculate the relationship. The contribution towards the Baking Worth is 13%. The equation is:

$$AS_{bw} = (0.000767*AS^3 - 0.157*AS^2 + 10.703*AS - 115.168)*13/100$$

This gives corresponding AS_{bw} contributions of 5.5% and 16% for AS values of 20cm^2 and 50cm^2 respectively (Howard, 2003).

The mixograph baking worth contribution was developed through solving a polynomial equation. The ideal mixograph development (mixing) time of 2.6 min was used in the calculation of the equation. The nominal value for the MDT baking worth contribution is 16% when $MDT = 2.6$ min. The equation is as follows:

$$MDT_{bw} = (1.223*MDT^3 - 21.789*MDT^2 + 86.589*MDT + 0.667) 16/100$$

This gives corresponding MDT_{bw} contributions of 10.7% and 0% for MDT values of 1.0min and 6.0min respectively (Howard, 2003).

In order to test if the milling and baking worth values differ significantly from one another a normal randomized complete block design was carried out on the averages of both the milling and baking worth values in order to determine the least significant difference value at the 95% confidence level.

6.3.3.3 *Multivariate analysis*

6.3.3.3.1 *Canonical correlations and variate analysis*

Canonical variate correlations were determined between the milling (representing 10 variables) and baking characteristics (representing 12 variables) separately. Canonical analysis was used to examine whether combinations of one set of related variables could effectively account for the observed variation in a second set of variables (Gittens, 1985). This approach allows the elucidation of relationship in a common data set among two large sets of variables, through the reduction into a relatively small number of highly correlated hypothetical canonical variates. Canonical variates are constructed from linear combinations of a set variables selected to maximize covariance with the canonical variates of a second set of variables. The canonical correlation then expresses the overall degree of relationship (response domain) between two constructed variates. The

CVA analysis was performed with the Genstat 5 statistical programme (Genstat 5 Committee, 1987).

To discriminate between the groups, 95% and 90% confidence circles were drawn around the biological standard Kariega. The radius of the circle (2.45) and (3.03) are given by the square root of the 95% and 90% point of a chi-square variable respectively at two degrees of freedom, since the plot is two dimensional, the degrees of freedom equals two. When cultivars fall within the circle around Kariega, it implies that quality characteristics do not differ significantly from that of Kariega. At 90% confidence level, the consistency levels of cultivars grouped together will improve drastically when compared to the current situation where all the cultivars are being mixed at the receiving point. The size of the latent roots for the different canonical variates (CV_1 and CV_2) indicates if variation exists within or between groups. When the latent root is bigger than one it thus indicates that variation exists between groups than within groups (Digby *et al.*, 1989).

6.3.3.3.2 Cluster analysis

Cluster analysis of genotypes and environments based on actual means was performed using the NCSS 2000 software computer programme (Hintze, 2000). For the purpose of classification, cluster analysis with unweighted pair group method with arithmetic average (UPGMA) clustering method has been applied with the NCSS software programme (Hintze, 2000). The Euclidean distance matrix was computed. Before computing the distance between genotypes, the data were standardized as recommended by Fox and Rosielle (1982). By standardizing the data, each genotype will have a mean of zero and unit variance, and the effect variability in phenotypic variance (as well as the mean) should be reduced.

6.4 Results and discussion

6.4.1 Combination of independent culling method with absolute limits of acceptability regarding to a relative check (SAGL, 2002)

The average mean values for three years over five localities regarding the milling characteristics in comparison to that of Kariega can be seen in Table 6.5. The deviations that exceed the allowed limits in comparison to that of Kariega are being displayed in bold.

Table 6.5. Means and limits for milling characteristics in comparison to the quality check Kariega.

	HLM	TKM	VK	FABS	BFLY	FCL	FLY
Cultivar	(Kg/hl)	(g)	(%)	(%)	(%)	(C76)	(%)
Kariega	78.05	41.08	79.22	62.15	22.69	-0.25	76.83
Marico	77.86	38.27	76.56	59.86	22.30	0.24	76.87
SST 825	78.50	40.46	78.33	63.91	18.96	1.29	75.59
SST 822	78.89	40.30	78.27	62.83	21.38	1.43	75.06
SST 876	79.90	39.64	73.18	62.07	19.62	0.44	76.47
Tolerance (min)	-1.50			-2.00	-5.00		-1.20
Tolerance (max)		+4.00		+2.00	+5.00	+0.50	
Limit (minimum)*	76.55			60.15	17.69		75.63
Limit (maximum)*		45.08		64.15	27.69	0.25	

* Minimum and maximum limits calculated according to set tolerances

From Table 6.5 it is evident that Marico's FABS value (59.86%) was outside the allowed limit of 60.15%. SST 825 (1.29), SST 822 (1.43) and SST 876 (0.44) produced darker flour colours (FCL C76) values than allowed. SST 825 (75.59) and SST 822 (75.06) also produced flour yield (FLY) levels lower than the allowed minimum value of 75.63%. From Table 6.5 it is clear that if Marico, SST 825, SST 822 and SST 876 were to be presented again for release none of them will actually be good enough when compared to Kariega regarding their milling characteristics.

The mean values for three years over five localities regarding the baking characteristics in comparison to that of Kariega can be seen in Table 6.6. The deviations that exceed the allowed limits in comparison to that of Kariega are again being displayed in bold.

Marico's mixograph mixing time (MDT) of 3.52 min exceeded the acceptable limit of 2.86 min, while on the other hand, although it is marginal, SST 876 produced a lower MDT value than the lower limit of 2.08 min. Marico, SST 825 and SST 876 showed less extensible dough characteristics than the lower limit set by Kariega of 135 mm for alveograph distensibility. SST 825 showed values that exceeded that of the upper limit set by Kariega for both ASTAB and P/L (Table 6.6). Only SST 822 has baking quality characteristics that fall into the acceptable limits when compared to Kariega. From Table 6.6 it is clear that SST 825 is the cultivar with the hardest kernel characteristics (showed the lowest BFLY value) and due to improper conditioning, there was too much starch damage during the milling process with detrimental influence on its distensibility capability of its dough.

Table 6.6. Means and limits for baking characteristics in comparison to quality check Kariega.

	FLN	GPC-Leco	FPC-Leco	MDT	AS	AD	ASTAB	P/L	LFV-12
Cultivar	(s)	(%)	(%)	(min)	(cm ²)	(mm)	(mm)		(cm ³)
Kariega	316.80	12.73	11.97	2.60	39.27	150.47	63.24	0.46	957.40
Marico	309.22	12.53	11.60	3.52	40.60	131.44	64.87	0.54	928.69
SST 825	325.42	12.72	11.92	2.78	44.00	117.02	84.07	0.75	933.02
SST 822	329.09	13.15	12.10	2.76	36.09	138.96	65.73	0.47	958.58
SST 876	320.87	12.38	11.64	1.98	28.36	126.73	62.42	0.54	924.22
Tol (min)	-15.00	-1.00		-20.00	-20.00	-10.00	-10.00	-20.00	-10.00
Tol (max)				+10.00	+20.00	+20.00	+20.00	+20.00	
Limit (minimum)*	269.28	11.73		2.08	31.42	135.42	56.92	0.37	861.66
Limit (maximum)*				2.86	47.12	180.56	75.89	0.55	

* Minimum and maximum limits calculated according to set tolerances

The laboratory procedure only allows for a 16-hour period at 16% moisture content conditioning. For harder wheat this conditioning period may not be enough because the moisture takes longer to reach the centre of the kernels. This problem can be solved by means of increasing the amount of water added or increasing period of conditioning at the same water levels.

In order to accommodate the observed variation for the biological standard namely Kariega, the standard deviations from the mean for each cultivar regarding its milling and baking characteristics were calculated and can be seen in Tables 6.7 and 6.8

respectively. Actual minimum and maximum limits were then recalculated from the observed standard deviations for Karioga for both milling and baking characteristics (Table 6.7 and 6.8).

From Table 6.7 it is evident that the minimum limit for hectolitre mass (HLM) should be lowered to 1.7kg/hl instead of 1.5 kg/hl to incorporate the observed variation for Karioga. The minimum and maximum limits for FABS should also be adjusted to $\pm 2.4\%$ instead of $\pm 2.0\%$. For BFLY the minimum and maximum limits can be changed to $\pm 3.0\%$. For FCL (C76) the maximum limit should be increased to +1.47 KJ units from +0.5 KJ units to accommodate the large variation around the means for Karioga. For FLY, the value can remain the same (Table 6.7). When taking the above changes into consideration it means, that Marico's FABS values do not exceed the lower limit anymore and SST876's, FCL also falls in the acceptable range. However, for BFLY, SST876 and SST825 exceeded the lower limit when the adjustments are taken into consideration.

Table 6.7. Standard deviations from the quality check Karioga for milling characteristics.

	HLM	TKM	VK	FABS	BFLY	FCL	FLY
Cultivar	(Kg/hl)	(g)	(%)	(%)	(%)	(C76)	(%)
Karioga	1.77	3.80	15.53	2.35	3.20	1.47	1.08
Marico	2.34	2.97	12.37	2.10	3.03	1.53	1.58
SST 825	2.41	3.92	13.75	2.34	3.68	1.18	1.87
SST 822	2.61	3.40	18.81	2.06	3.21	1.21	0.82
SST 876	2.38	3.16	16.80	1.80	2.80	1.02	0.95
Tolerance (min)	-1.50			-2.00	-5.00		-1.20
Tolerance (max)		+4.00		+2.00	+5.00	+0.50	
Actual (min)*	-1.77			-2.40	-3.00		-1.1
Actual (max)*		+4.00		+2.40	+3.00	+1.47	

* Minimum and maximum actual values were rounded off the nearest integer

From Table 6.8 it is evident that the minimum limit for falling number (FLN) should be lowered to -22% instead of -15% to incorporate the observed variation for Karioga. The minimum and maximum limits for AS should also be adjusted from $\pm 20\%$ to $\pm 29.0\%$. For AD the minimum and maximum limits can be changed to $\pm 18.0\%$. Regarding ASTAB the minimum limit should be lowered to -14% from -10.0% . In order to accommodate the large variation around the means for Karioga for P/L ratio the minimum and maximum limits should be lowered to $\pm 39.0\%$ from $\pm 20\%$. For LFV

standardized at 12% protein content the minimum limit can be increased from -10.0% to -4.0%. If the above changes are taken into consideration it means that SST876 does not fall outside the acceptable limits for AS. Only SST 825 does make it if the suggested changes are being made for AD (Table 6.8).

Table 6.8. Standard deviations from the quality check Kariega for baking characteristics.

	FLN	GPC- Leco	FPC- Leco	MDT	AS	AD	ASTAB	P/L	LFV-12
Cultivar	(s)	(%)	(%)	(min)	(cm ²)	(mm)	(mm)		(cm ³)
Kariega	69.00	0.66	0.84	0.51	11.69	27.05	9.03	0.18	35.42
Marico	58.46	0.59	0.87	1.02	9.97	20.09	10.01	0.14	61.83
SST 825	62.25	0.79	1.10	0.66	10.20	23.17	12.52	0.15	49.86
SST 822	57.71	0.70	0.74	0.65	8.01	27.37	11.03	0.16	47.50
SST 876	62.36	0.52	0.71	0.36	7.04	32.44	13.00	0.25	54.11
Tolerance (min)	-15.00	-1.00		-20.00	-20.00	-10.00	-10.00	-20.00	-10.00
Tolerance (max)				+10.00	+20.00	+20.00	+20.00	+20.00	
Actual (min)*	-22.00	-1.00		-20.00	-29.00	-18.00	-14.00	-39.00	-4.0
Actual (max)*				+10.00	+29.00	+18.00	+20.00	+39.00	

* Minimum and maximum actual values were rounded off the nearest integer

6.4.2 Index selection

6.4.2.1 Lukow's index selection (1991)

The overall score for Lukow's index selection is summarized in Table 6.9. Thus lines with scores better than Kariega's will be selected to continue. Marico produced the better baking strength value among all the cultivars, while SST 876 produced the lowest baking strength value. From Table 6.9 the cultivars that had higher scores than Kariega were SST 825 and SST 822. If needed culling levels with minimum and maximum acceptable values for the PBSI and OSCORE can be set to determine which lines will be advanced for possible release. For lines included in this study, it was not worthwhile to construct culling levels.

Table 6.9 Predicted loaf volume, baking strength and overall scores for five cultivars at five sites from 1997 until 1999.

Cultivar	PRLV	PBSI	OSCORE
MARICO	809.91	106.99	-0.75
KARIEGA	779.59	99.58	0.00
SST825	786.92	100.96	0.40
SST822	797.01	100.63	0.27
SST876	722.94	95.15	-2.73

PRLV = Predicted loaf volume

BSI = Baking strength index

OSCORE = Overall score

6.4.2.2 Howard's (2003) milling and baking worth index procedure

In the determination of the milling and baking worth values, flour yield and loaf volume is rated as the most important characteristics and also evidently have the highest nominal weights being linked to them (Table 6.1). If a cultivar has milling and baking worth values of 100% or higher, it means that the cultivar or line equals or exceeds the desired milling or baking worth goals set by the processing industry. The individual as well as the total milling and baking worth values for each of the cultivars include in this study can be seen in Tables 6.10 and 6.11 respectively. As found in the study of Howard (2003) almost none of the cultivars reached milling or baking worth values in the order of a 100%.

Table 6.10. Milling worth values of five wheat cultivars from 1997-1999.

Cultivar	FLY (%)	HLM (%)	TKM (%)	BFLY (%)	FCL (%)	FLN (%)	TOTAL (%)
MARICO	29.15	11.79	14.38	7.64	6.03	9.99	78.98
KARIEGA	28.95	12.08	14.93	7.38	7.14	9.97	80.44
SST825	23.09	12.75	14.86	9.30	3.97	9.93	73.90
SST822	20.77	13.35	14.84	8.19	3.73	9.90	70.78
SST876	27.19	14.85	14.72	9.05	5.61	9.95	81.37

LSD (0.05) = 3.69

From Table 6.10 the ranking in descending order for the milling worth is SST 876, Karioga, Marico, SST 825 and SST 822. The magnitude regarding all the cultivars is surprisingly very low. With the previous round of calculations cultivars like Karioga and SST 876 showed values in the order of between 90 and 100%. These lower values can be due to the recent introduction of a more severe penalization for break flour yield as a

measurement of hardness. Characteristics like, flour colour (FCL) showed such a large genotype x environment interaction that it was impossible to determine the different variance components for it. This means that genetic gain through breeding for this characteristic is almost impossible. For TKM the genetic contribution was in the order of 8.57% and the large genotype x year effect, implies that genetic improvement for this characteristic will be very slow (Table 3.12, Chapter 3). A similar pattern was observed for falling number (FLN), moreover the irrigation areas is a low risk area for low falling numbers and should therefore not be treated the same as the rest of the wheat production areas. Therefore the milling worth weights of 15% for both TKM and FCL and 10% for FLN respectively are definitely too high and should be reduced drastically. The weights of traits like BFLY and FLY with genetic variance component values in the order of 54.25% and 24.25% (Table 3.12 and 3.13, Chapter 3) respectively can be increased in order to speed up the efficiency of the genetic progress regarding the milling characteristics of cultivars.

From Table 6.10 it can be seen that Marico, Kariega and SST 876 did not differ significantly regarding the total milling worth values. SST 825 total milling worth value was significantly lower than that of the latter three cultivars and significantly higher than that of SST822.

From Table 6.11 the ranking in descending order for the baking worth is SST 825, Kariega, SST 822, SST 876 and Marico. The magnitude regarding all the cultivars is much higher than in the case of milling worth. These higher values can be ascribed to the fact that the goals for breeding cultivars in comparison to Kariega had not been shifted drastically. A lot of emphasis has been placed on bread loaf volume, but the influence of genetic contribution on the expression of LFV is less than one percent which mean that LFV is mainly controlled by environment interactions and genotype x year interactions. FLP also is mainly influenced by the environment (a genetic contribution of 8%) (Table 6.11). Therefore the weight given to LFV (35%) and FLP (8%) to a lesser extent, should be lowered and traits with high genetic contributions like MDT, AS, AD, ASTAB, P/L can be increased (Table 6.11). This change will improve the relevance of employing a baking worth value in wheat breeding programmes as a selection tool, and speed up the development of cultivars with superior dough handling characteristics.

Table 6.11. Baking worth values of five wheat cultivars from 1997-1999.

Cultivar	LFV (%)	FPC (%)	FABS (%)	APL (%)	AS (%)	MDT (%)	TOTAL (%)
MARICO	33.65	8.27	3.61	10.24	14.55	14.21	84.53
KARIEGA	34.73	9.25	12.93	8.79	14.23	16.00	95.93
SST825	36.10	9.12	13.29	11.96	15.23	15.88	101.58
SST822	34.49	9.60	13.07	9.00	13.35	15.90	95.40
SST876	31.63	8.37	12.91	10.24	10.35	15.39	88.89

LSD (0.05) = 4.06

SST 825's baking worth value was significantly higher than the rest of the cultivars included in this study. Karioga and SST 822 baking worth values were significantly similar, but significantly higher than that of Marico and SST 822. SST 822's produced a significantly higher baking worth value than Marico (Table 6.11).

6.4.3 Multivariate analysis

6.4.3.1 Canonical correlations and variate analysis

The canonical variates were calculated for the milling and baking characteristics separately in order to find the groupings among the genotypes. For milling, 10 quality characteristics (namely HLM, TKM, SKCS-G, SKCS-DIA, SKCS-HI, VK, FABS, FCL (C76), BFLY and FLY) and for the baking characteristics a total of 12 characteristics (namely, FLN, GPC-Leco, FPC-Leco, WG-12, SDSS, MDT, ASTAB, AD, AS, P/L, LFV and LFV-12) were measured for each of five genotypes at five localities from 1999 until 1999. The unimportant variates were then eliminated one-by-one from the analysis until only those with reasonable correlation coefficients were retained.

For the milling characteristics seven variates were retained, which included TKM, SKCS-G, SKCS-DIA, FABS, FCL (C76), BFLY and FLY. The CVA variates with their proportional contribution as well as the latent vectors for each of the axis's regarding five irrigation wheat cultivars, each cultivar can be seen in Table 6.12.

Table 6.12. Canonical variate percentage variation and mean scores of the first two canonical variates regarding the milling characteristics for five cultivars.

Variates	CV1	CV2
	91.70% (8.519*)	5.54% (0.515**)
Marico	3.29	0.48
Kariega	1.47	0.20
SST825	-4.38	0.28
SST822	0.31	-1.40
SST876	-0.88	0.45

* = Latent root for CVA₁ - axis

** = Latent root for CVA₂ - axis

The horizontal separation (CV₁) accounted for 91.70% of the total variation. The latent root for the first CV₁ was greater than one, indicating that more variation existed between groups than within the groups (Table 6.12). The correlation matrix for both the selected CVA1 and CVA2 variates can be seen in Table 6.13. A canonical coefficient provides a measure of association between a factor and the canonical variate mean. Therefore, the characteristics with correlations above 45% were seen as the characteristics that explain most of the observed variation for both axes' regarding the milling characteristics. From Table 6.13 it is evident that SKCS-DIA, SKCS-FABS and BFY showed the highest correlations and thus explained most of the variation observed between the cultivars for CVA₁-axis. From the latter SKCS-DIA was the dominant contributor to the variance within this response domain. The negative coefficients for SKCS-DIA and FABS indicated that the data pattern would be inverse to that of BFY. This implies that, increases for SKCS-DIA and FABS values will cause decreases in BFY values. It is interesting to note that except for SKCS-DIA, FABS and BFY are characteristics involved in the expression of hardness levels of wheat genotypes.

Table 6.13. Correlation matrix for five cultivars at five localities from 1997 until 1999 for the milling characteristics.

	TKM	SKCS-G	SKCS-DIA	FABS	FCL (C76)	BFY	FLY
CVA ₁	-0.24	-0.24	-0.59	-0.53	-0.19	0.48	0.37
CVA ₂	-0.40	-0.06	-0.07	-0.29	-0.48	-0.08	0.79

The vertical separation (CV₂) accounted for 5.54% of the total variation. The latent root for the first CV₂ was smaller than one, indicating that more variation existed within groups

than between groups (Table 6.12). From Table 6.13 it is evident that FCL (C76) and FLY both showed correlations above 45% and thus explained most of the variation observed between the cultivars for the CVA₂-axis. From the latter FLY was the main contributor to the variance within this response domain. The negative coefficients for FCL (C76) indicated that the data pattern would be inverse to that of FLY. This implies that, lighter flour colour values (FCL-C76) can be expected when extraction values (FLY) are increased, but this will only be valid for optimum extraction values (79%), where after flour colour will darken, because too much bran will be included in the flour, in order to meet the higher extraction rates.

The grouping of the five cultivars according to their CVA₁ and CVA₂ variates for the milling characteristics are being illustrated in a plot of the two canonical variates mean scores for each cultivar (Figure 6.1). To discriminate between the groups, 95% and 90% confidence circles were drawn around the biological standard Kariega. When cultivars fall within the circles around Kariega it implies that quality characteristics do not differ significantly from that of Kariega regarding the various confidence levels.

From Figure 6.1 it is obvious that at the 90% confidence level all the cultivars included in this study were significantly similar regarding their milling characteristics, except for SST 825. At the 95% confidence level only SST822 and SST 825 differed significantly from the rest of the cultivars. Thus, SST 825 differed from the rest of the cultivars regarding its harder kernel texture, larger kernel diameter, higher farinograph water absorption level, and higher and whiter flour yield. At the 95 % confidence level SST 822 differed from the rest of the cultivars regarding its medium kernel texture, medium kernel diameter, medium farinograph water absorption level, medium flour yield and dark flour colour. SST 876 falls into the same quadrant representing the harder kernel characteristics, flour with higher water absorption levels, larger yield levels and whiter in colour, with increased kernel diameters. Kariega and Marico were plotted in the quadrant that represents softer kernels characteristics, flour with lower water absorption levels, and lower yield levels and whiter in colour. SST 822 falls into the quadrant indicating softer kernel characteristics, lower flour yield, with lower water absorption and darker colour. The CVA analysis thus actually shows that for SST 825 better flour yields with whiter flour colour can be generated when the seed is conditioned properly according to a suitable hardness class. Most of the variation experienced in the milling industry can be ascribed to the fact that most of the cultivars in the market today vary

significantly for their milling characteristics, if the variation is being reduced by means of grouping cultivars with similar milling characteristics together, improved milling potentials will be the resultant effect.

For the baking characteristics five variates were retained, which included MDT, ASTAB, AD, AS and P/L ratio. The CVA variates with their proportional contribution as well as the latent vectors for each of the axis's regarding five irrigation wheat cultivars, each cultivar can be seen in Table 6.14.

Table 6.14. Canonical variate percentage variation and mean scores of the first two canonical variates regarding the baking characteristics for five cultivars.

Variates	CV1	CV2
	63.32% (1.03*)	27.86% (0.45**)
Marico	1.71	-0.08
Kariega	0.04	-0.47
SST825	-0.39	1.30
SST822	0.04	-0.27
SST876	-1.40	-0.48

* = Latent root for CVA₁ - axis, ** = Latent root for CVA₂ - axis

The horizontal separation (CV₁) accounted for 63.32% of the total variation. The latent root for the first CV₁ was greater than one, indicating that more variation existed between groups than within the groups (Table 6.14). The correlation matrix for both the selected CVA1 and CVA2 variates can be seen in Table 6.15. A canonical coefficient provides a measure of association between a factor and the canonical variate mean. Therefore, the characteristics with correlations above 45% were seen as the characteristics that explain most of the observed variation for both axis's regarding the baking characteristics. From Table 6.15 it is evident that MDT showed a correlation above 45%, thus discriminating the most among the cultivars regarding the CVA₁-axis.

Table 6.15. Correlation matrix for five cultivars at five localities from 1997 until 1999 for the baking characteristics.

	MDT	ASTAB	AD	AS	P/L
CVA ₁	0.93	-0.09	0.09	0.36	-0.16
CVA ₂	0.27	0.98	-0.50	0.60	0.84

The vertical separation (CV_2) accounted for 27.86% of the total variation. The latent root for the first CV_2 was smaller than one, indicating that more variation existed within groups than between groups (Table 6.14). From Table 6.15 it is evident that ASTAB, AD, AS and P/L rations showed correlations above 45% and thus explained most of the variation observed between the cultivars for the CVA_2 -axis. From the latter ASTAB was the main contributor to the variance within this response domain. The negative coefficient for AD indicates that the data pattern will be inverse to that of ASTAB, AS and P/L, implying that dough will lose its distensibility capacity due to increases in dough strength (AS), dough stability (ASTAB) and the ratio between elasticity and stretching capacity (P/L ratio).

The grouping of the five cultivars according to their CVA_1 and CVA_2 variates for baking characteristics are being illustrated in a plot of the two canonical variates mean scores for each cultivar (Figure 6.2). To discriminate between the groups, 95% and 90% confidence circles were drawn around the biological standard Kariega again.

From Figure 6.2 it is obvious that for the 90% confidence level Kariega, SST 822 and SST 825 were significantly similar regarding the five cultivars included in this study according to their baking characteristics. For the 95% confidence level only Kariega and SST 822 were significantly similar. SST 876 differed significantly because it showed shorter mixing times with medium dough strength and distensibility, while Marico displayed longer mixing times with medium dough strength and distensibility. As in the case of the milling characteristics too much variation exists among current irrigation wheat cultivars in the South African market, and classification of cultivars according to their gluten strength will decrease the variation, with a resultant improvement regarding consistency. The dough characteristics of SST 825 could also improve when it is properly conditioned before milling, thus lowering the current observed variation for baking characteristics.

A CVA analysis was carried out for a scenario where the milling and baking characteristics were combined. A total of 22 characteristics were then included (namely, HLM, TKM, SKCS-G, SKCS-DIA, SKCS-HI, VK, FABS, FCL (C76), BFLY, FLY, FLN, GPC-Leco, FPC-Leco, WG-12, SDSS, MDT, ASTAB, AD, AS, P/L, LfV and LfV-12). However, only five variates were retained, which included MDT, AS, SKCS-DIA, FABS and FLY. The CVA variates with their proportional contribution as well as the

latent vectors for each of the axis's regarding five irrigation wheat cultivars can be seen in Table 6.16.

Table 6.16. Canonical variate percentage variation and mean scores of the first two canonical variates regarding the both milling and baking characteristics for five cultivars.

Variates	CV1	CV2
	58.67% (1.64*)	28.10% (0.79**)
Marico	-2.03	-0.76
Kariega	-0.59	0.17
SST825	1.58	-0.80
SST822	1.03	-0.21
SST876	0.02	1.60

* = Latent root for CVA₁ - axis

** = Latent root for CVA₂ - axis

The horizontal separation (CV₁) accounted for 58.67% of the total variation. The latent root for the first CV₁ was greater than one, indicating that more variation existed between groups than within the groups (Table 6.16). The correlation matrix for both the selected CVA1 and CVA2 variates can be seen in Table 6.17. Because a canonical coefficient provides a measure of association between a factor and the canonical variate mean, the characteristics with correlations above 45% were seen as the characteristics that explain most of the observed variation for both axis's regarding the combined milling and baking characteristics. From Table 6.17 it is evident that SKCS-DIA, FABS and FLY showed a correlation above 45%, thus discriminating the most among the cultivars regarding the CVA₁-axis. Thus, long term data suggests that a breeding programme can only incorporate the mixograph test, alveograph test, Buhler flour extraction, farinograph water absorption and SKCS test in order to improve milling and baking characteristics efficiently. From Table 6.17 it is also clear that the influence of the milling characteristics regarding discriminating among spring wheat cultivars under irrigation was 30.57% higher than in the case of baking characteristics. Therefore, if cultivars are to be classified according to their different hardness classes, the current observed variation for milling and even baking characteristics could be drastically lowered for South African wheat cultivars produced under irrigation.

Table 6.17. Correlation matrix for five cultivars at five localities from 1997 until 1999 for both milling and baking characteristics.

	MDT	AS	SKCS-DIA	FABS	FLY
CVA ₁	-0.41	0.05	0.66	0.67	-0.66
CVA ₂	-0.89	-0.65	-0.06	0.06	0.07

The vertical separation (CV₂) accounted for 28.10% of the total variation. The latent root for the first CV₂ was smaller than one, indicating that more variation existed within groups than between groups (Table 6.16). From Table 6.17 it is evident that SKCS-DIA, FABS and FLY showed correlations above 45% and thus explained most of the variation observed between the cultivars for the CVA₂-axis. All three the latter characteristics contributed equally to the variance within this response domain. The negative coefficient for FLY indicates that the data pattern will be inverse to that of SKCS-DIA and FABS, implying that higher FLY values will produce lower SKCS-DIA and FABS values.

The grouping of the five cultivars according to their CVA₁ and CVA₂ variates for the combined milling and baking characteristics are illustrated in a plot of the two canonical variates mean scores for each cultivar (Figure 6.3). To discriminate between the groups, 90% and 95% confidence circles were drawn around the biological standard Kariega.

Figure 6.3 shows that none of the five cultivars are significantly similar according to their combined milling and baking characteristics at both 90% and 95% confidence levels. Marico produced flour with low water absorption and higher extraction from kernels with smaller diameters and a dough with longer mixing time and stronger gluten strength. SST 825 produced flour with high water absorption and lower extraction from kernels with larger diameters and a dough with longer mixing times and stronger gluten strength. Kariega produced medium mixing times, with medium dough strengths with medium flour yields smaller kernel diameter and medium water absorption levels. SST 822 also produced medium mixing times, with medium dough strengths, but flour with medium to low flour yields originating from higher kernel diameters and water absorption levels. SST 876 produced dough with shorter mixing times and lower gluten strengths, with a medium flour yield, medium water absorption and medium kernel diameters (Figure 6.3). To evaluate the milling and baking characteristics separately simplify the discrimination of wheat genotypes regarding their milling and baking characteristics.

6.4.3.2 Cluster analysis

Cluster analysis is the most widely used technique for classifying genotypes into homogeneous groups. It operates on a matrix of dissimilarity (or similarity) indexes for all possible pairs of genotypes (Ghaderi *et al.*, 1980).

A cluster analysis was performed to study the patterns of possible groupings that is possible for the genotypes included in this study. The dendrograms (Figures 6.6 and 6.7) for the milling and baking characteristics were generated from the UPGCMA clustering method of genotypes, based on Euclidean distances using the mean values of genotypes respectively. Clustering of genotypes was executed at a cut-off value of 25 for the milling characteristics and it produced four clusters where three of them were singletons (Figure 6.6). SST 822 and Kariega can be grouped together because they have similar distances, while SST 876 displayed the smallest and Marico the largest distance.

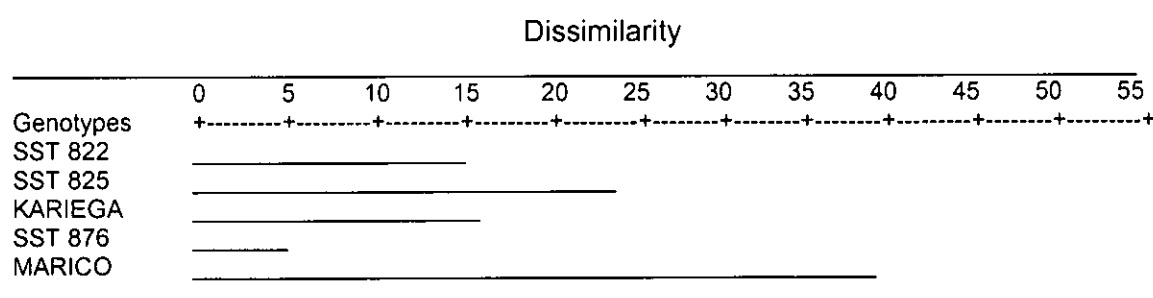


Figure 6.6. Dendrogram depicting the clustering of five genotypes using average means at five localities over three years for milling characteristics.

Clustering of genotypes was executed at a cut-off value of 35 for the baking characteristics and it produced three clusters where two of them were singletons (Figure 6.7). SST 822, SST 825 and Kariega can be grouped together because they have similar distances, while SST 876 displayed the smallest and Marico the largest distance.

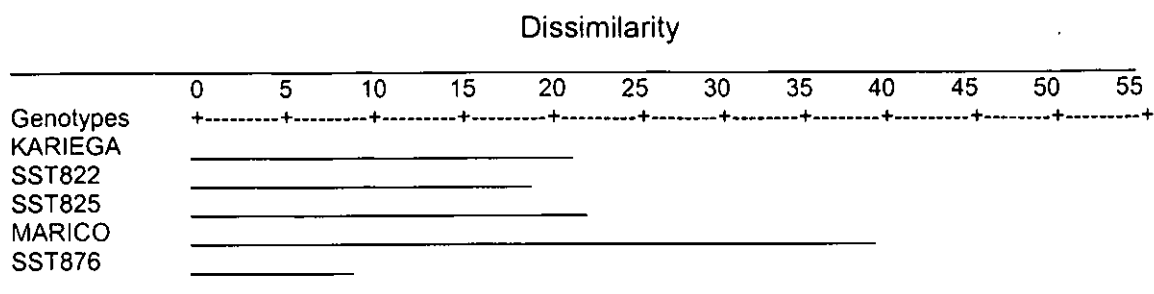


Figure 6.7. Dendrogram depicting the clustering of 5 genotypes using average means at five localities over three years for milling characteristics.

6.4.4 Evaluation of new test lines with regard to some of the different selection methods

Only the methods of the combined independent culling levels with absolute acceptable limits used by the SAGL, Howard's milling and baking worth selection index as well as the CVA analysis for both milling and baking characteristics separately will be compared with each other according to the test lines included in this study namely BPT01/7 and BPT02/06

The mean values for independent culling levels with absolute limits regarding two years over five localities for the milling characteristics in comparison to that of Kariega can be seen in Table 6.18 for BPT01/07 as well as the one year quality data for BPT02/06. The deviations that exceed the allowed limits in comparison to that of Kariega are displayed in bold. Each of the lines was compared against Kariega (Table 6.18).

From Table 6.18 it is evident that BPT01/07 milling characteristics compare favourably with that of Kariega. BPT02/06 displays much harder kernel characteristics than Kariega and has darker flour colour and flour extraction value (FLY) than Kariega, normally this line will be discarded due to its inferior milling characteristics.

Table 6.18. Independent culling levels set at absolute limits for milling characteristics in comparison to Kariega regarding BPT01/07 and BPT02/06.

Cultivar	HLM (Kg/hl)	TKM (g)	VK (%)	FABS (%)	BFLY (%)	FCL (C76)	FLY (%)
Kariega#	77.70	42.00	76.00	62.70	22.30	-0.60	76.50
BPT01/07	78.90	41.10	78.00	63.50	21.50	-0.20	76.70
Tolerance (min)	-1.50			-2.00	-5.00		-1.20
Tolerance (max)		+4.00		+2.00	+5.00	-0.50	
Limit (minimum)*	76.00			60.70	17.30		75.30
Limit (maximum)*		46.00		64.70	26.50	-0.10	
Kariega\$	79.90	41.08	59.00	64.90	17.70	-2.00	77.80
BPT02/06	80.70	43.27	91.00	66.80	14.10	-1.00	74.90
Tolerance (min)	-1.50			-2.00	-5.00		-1.20
Tolerance (max)		+4.00		+2.00	+5.00	+0.50	
Limit (minimum)*	78.00			62.90	12.70		76.60
Limit (maximum)*		45.08		68.80	19.10	-1.50	

* Minimum and maximum limits calculated according to set tolerances

= Kariega as biological standard for BPT01/07

\$ = Kariega as biological standard for BPT02/06

The average mean values for two years over five localities regarding the baking characteristics in comparison to that of Kariega can be seen in Table 6.19 for BPT01/07 as well as the one year quality data for BPT02/06. The deviations that exceed the allowed limits in comparison to that of Kariega are again being displayed in bold. Each of the lines was again compared against Kariega.

Table 6.19. Independent culling levels set at absolute limits for baking characteristics in comparison to Kariega regarding BPT01/07 and BPT02/06.

	FLN	GPC-Leco	FPC-Leco	MDT	AS	AD	ASTAB	P/L	LFV-12
Cultivar	(s)	(%)	(%)	(min)	(cm ²)	(mm)	(mm)		(cm ³)
Kariega#	336.00	13.40	12.70	2.50	45.60	134.80	82.60	0.64	940.00
BPT01/07	350.00	14.10	13.30	2.20	39.30	136.10	78.80	0.58	904.00
Tolerance (min)	-15.00	-1.00		-20.00	-20.00	-10.00	-10.00	-20.00	-10.00
Tolerance (max)				+10.00	+20.00	+20.00	+20.00	+20.00	
Limit (minimum)*	285.60	12.40		2.00	36.48	121.32	74.34	0.51	846.00
Limit (maximum)*				2.42	54.72	161.76	99.12	0.77	
Kariega\$	369.00	13.00	12.40	2.40	50.40	132.00	94.30	0.75	954.00
BPT02/06	396.00	14.20	13.70	3.60	79.10	118.60	124.70	1.07	861.00
Tolerance (min)	-15.00	-1.00		-20.00	-20.00	-10.00	-10.00	-20.00	-10.00
Tolerance (max)				+10.00	+20.00	+20.00	+20.00	+20.00	
Limit (minimum)*	313.65	12.00		1.92	40.32	118.80	84.37	0.60	858.60
Limit (maximum)*				2.64	60.48	158.40	113.16	0.90	

* Minimum and maximum limits calculated according to set tolerances

= Kariega as biological standard for BPT01/07

\$ = Kariega as biological standard for BPT02/06

From Table 6.19 it can be seen that BPT01/07's baking characteristics as in the case of its milling characteristics is very similar to that of Kariega. BPT02/06 displays very strong gluten characteristics. Its Alveograph characteristics can be negatively influenced due to its very hard kernel characteristics. According to the above-discussed culling method, BPT01/07 can be considered for provisional release, while BPT02/06 will not be acceptable.

The individual as well as the total milling and baking worth's according to Howard's (2003) procedure for each of the test lines include in this study can be seen in Tables 6.20 and 6.21 respectively. Significant differences on the total milling and baking worth values could not be calculated because the quality analysis was carried out on only one replicate.

Table 6.20. Individual milling worth values based on average values from the test lines included in this study.

Cultivar	FLY	HLM	TKM	BFLY	FCL	FLN	TOTAL
KARIEGA#	27.33	11.55	15.00	7.64	7.98	9.86	79.36
BPT01/07	28.31	13.35	14.94	8.13	7.02	9.74	81.47
KARIEGA\$	33.93	14.85	14.93	9.68	11.81	9.53	94.73
BPT02/06	20.08	16.05	15.01	9.96	9.00	9.15	79.26

= Kariega as biological standard for BPT01/07

\$ = Kariega as biological standard for BPT02/06

From Table 6.20 the BPT01/07 displayed a higher milling worth value than Kariega. BPT02/06 milling worth value was 15.47% lower than that of Kariega. The total milling values does not however, give any information regarding the inferior or superior milling characteristics.

Table 6.21. Individual baking worth values based on average values from the test lines included in this study.

Cultivar	LFV	FPC	FABS	APL	AS	MDT	TOTAL
KARIEGA#	29.76	11.20	3.61	11.40	15.49	16.01	87.47
BPT01/07	24.73	12.80	12.93	10.79	14.24	15.80	91.29
KARIEGA\$	31.97	10.40	13.29	11.96	16.07	15.98	99.67
BPT02/06	19.91	13.87	13.07	10.60	16.73	13.93	88.11

= Kariega as biological standard for BPT01/07

\$ = Kariega as biological standard for BPT02/06

From Table 6.21 the BPT01/07 displayed a higher milling worth value than Kariega of 3.8%. BPT02/06 milling worth value was 11.56% lower than that of Kariega. The total baking and milling values, also do not, provide additional information regarding the inferior or superior baking characteristics. According to Howard's (2003) milling and baking procedure, BPT01/07 will be an improvement on Kariega.

Making use of the canonical variate analysis for the milling characteristics, the discriminative equations can be obtained for CVA₁ and CVA₂ by making use of the following formulas:

$$CVA_1 = -0.024(TKM) + 1.265(SKCS-G) - 26.366(SKCS-DIA) - 0.255(FABS) + 0.027(FCL-C76) + 0.497(BFLY) - 0.131(FLY) - (-37.75)$$

$$CVA_2 = -0.08(\text{TKM}) - 0.312(\text{SKCS-G}) + 5.761(\text{SKCS-DIA}) - 0.104(\text{FABS}) - 0.065(\text{FCL-C76}) - 0.204(\text{BFLY}) + 0.924(\text{FLY}) - (59.55)$$

Thus for the milling characteristics regarding BPT01/07 CVA_1 value = -0.63, and CVA_2 = 0.214; for BPT02/06 its CVA_1 = -5.758, and CVA_2 = 0.322

Making use again of the Canonical variate analysis for the baking characteristics, the discriminative equations can be obtained for CVA_1 and CVA_2 by making use of the following formulas:

$$CVA_1 = 1.7216(\text{MDT}) - 0.0627(\text{ASTAB}) - 0.0236(\text{AD}) + 0.073(\text{AS}) - 1.4479(\text{P/L}) - (-1.006)$$

$$CVA_2 = -0.0657(\text{MDT}) + 0.0464(\text{ASTAB}) - 0.0138(\text{AD}) + 0.0389(\text{AS}) + 0.4544(\text{P/L}) - (2.823)$$

Thus for the baking characteristics regarding BPT01/07 CVA_1 value = -1.142, and CVA_2 = -0.071; for BPT02/06 its CVA_1 = 0.811, and CVA_2 = 3.681

The latent vectors for CVA_1 and CVA_2 as seen in Table 6.14 and 6.16 can be kept the same for all the other cultivars namely Karioga, Marico, SST 822, SST825 and SST 876 regarding their milling and baking characteristics respectively. The latent vector values for the CVA_1 and CVA_2 axis's regarding BPR01/07 and BPT02/06 were calculated according to the abovementioned formulas for their milling and baking characteristics respectively. The grouping of all seven genotypes according to their CVA_1 and CVA_2 variates for the milling (Figure 6.4) and baking (Figure 6.5) characteristics are being illustrated in plots of the two canonical variates mean scores for each cultivar respectively.

Figure 6.4 illustrates that at the 90% confidence level SST 876 and Marico, Karioga and BPT01/07 were similar according to their milling characteristics. SST 825 and BPT02/06 differed from the rest of the cultivars regarding their harder kernel textures, larger kernel diameters, higher farinograph water absorption levels, and higher and whiter flour yields. SST 822 on the other hand was significantly different from the rest of the cultivars regarding its medium kernel texture, medium kernel diameter, medium farinograph water absorption level, medium flour yield and dark flour. According to the CVA analysis

BPT01/07 can be accepted regarding its milling characteristics while, BPT02/06 is too hard for the current South African wheat market.

From Figure 6.5 it is evident that only Kariega and SST 822 were significantly similar regarding their baking characteristics. Marico and BPT02/06 showed long mixograph mixing times, strong gluten characteristics, while BPT02/06 displayed a low dough distensibility and Marico on the other hand too high dough distensibility. SST 876 and BPT01/07 produced shorter mixing times with less stronger gluten strengths higher dough distensibilities. From the CVA analysis for the baking characteristics it is evident that BPT02/06 contain too strong dough characteristics for the South African wheat market while BPT01/07 produced dough with slightly weaker dough characteristics than the optimum.

6.5 Conclusions

Some shortages do exist currently in the South African wheat cultivar release system which operates on an independent culling method namely : (i) The system does not take the consistency regarding the new candidate in comparison to that of the biological standard (in this case Kariega) into consideration. (ii) The local system remained static for the past five years, without seriously looking at improving the system or incorporating new methods or equipment. (iii) In South Africa there is not a grade available for high yielding wheat with inferior bread making quality, intended for animal feed. According to Drynan (2001) discounted wheat with sprouting damage or low-test weight is often blended into higher quality wheat, essentially increasing the value of the discounted wheat. In a discriminating market, low quality wheat would probably have to move into a market category, which might be classified as feed wheat. This classification of feed wheat is most often open for abuse. A feed wheat class evolving out of a market need, could overcome most, if not the entire tendency toward abuse (Drynan, 2001). (iv) There is no room for different hardness classes, all the cultivars are being classified as hard wheat, while some researchers had proved that different hardness classes do exist within the bread wheat class (Van Deventer, 1999; Manley, 2000; Manley *et al.*, 2001). SST 825 is a textbook example of harder wheat that is not conditioned properly. (v) The fact that the South African processing industry wants superior multi-purpose wheats, makes it

extremely difficult for the breeders to obtain suitable cultivars, similar results has been shown by Finney *et al.* (1987). (vi) The lack of uniformity of kernel characteristics can be an important factor in milling economics. Narrow ranges in variation of diameter, hardness and weight among individual kernels in a wheat lot can have an impact on mill adjustment, and consequently flour yield (Drynan, 2001). The present South African marketing practice of blending disparate wheats to accomplish average acceptable quality or grade parameters, can cause a significant lack of uniformity in wheat kernel characteristics, with inferior flour yields. This latter statement is being clearly illustrated when looking at the milling and baking characteristics differences that do exist within the current commercial irrigation spring wheat cultivars (Tables 6.5 and 6.6). (vii) Each of the different wheat production areas have their own inherent risk factors and therefore the wheat release systems should be adapted in such a way that the risks of each are accommodated within separate release systems, specifically developed for an area. (viii) The system combines two diverse methods in order to evaluate new candidates which complicates interpretation of the data. (viii) The system puts too much emphasis on characteristics that are mainly under environmental influence.

Lukow's (1991) multiple regression analysis selected Marico as the cultivar with the best baking strength index value; it also identified SST 825 as the cultivar with the best overall score (Table 6.8). Therefore, it can be concluded that Lukow's method has the tendency to identify lines that has stronger gluten strength characteristics, which makes sense because it was developed for the Canadian wheat market. When this method is going to be used the possibility does exist to develop lines that has increased dough strength beyond the capability of the Chorleywood Breadmaking process, that needs flour with protein levels of approximately 10% and a dough mixing requirement of 8-11 Wh kg⁻¹ (Van Lill and Purchase, 1995). This method can therefore not be promoted.

Howard's milling and baking worth values is an option to rank cultivars according to the values that is being considered as ideal values set by the processing industry. There are however some deficiencies that have to be taken into consideration when using Howard's method. (i) The total percentages do not give detail information about the causes that is responsible for the differences between the total contributions, Both Marico and SST876 ranked last regarding their total milling worth value but SST 876 weak gluten strength, while Marico has strong gluten strength. (ii) The individual contributions of FCL and TKM to the total milling worth value are too high and should be

reduced, because their genetic contribution is very low, which indicates a huge environmental influence that will hamper the breeding progress. LFV and FLP contribution to the total milling worth value should also be drastically reduced, because their genetic contribution are almost insignificant. Hectolitre mass should also be increased due to its higher genotypic variance contribution. Falling number is also being given a contribution of 10% to the milling value, but it is not really a problem in the irrigation areas and the deviation from the mean is also larger than the current acceptable minimum limit (Table 6.7). (iii) In order to calculate the milling and baking worth values the cultivars should be evaluated in the same trials and seasons, this however, prevents the evaluation of lines in different sets of trials (iv) The efficiency of the total milling worth value decreased due to the severe penalization of hardness levels as represented by the BFLY value. The breeders can only accept this alteration, when different hardness classes are being implemented and if SAGL also alters its conditioning method before milling in order to have room for different hardness classes. (v) The milling and baking values should differ for each wheat production area in order to reflect the inherent needs or deficiencies of each area. (vi) In order to test the ingenuity of the milling and baking worth for different cultivars, more than one replicate is needed which will increase the expenditure drastically. Currently only one replication are tested and from Chapter 4 it is clear that only one replication is needed to keep the quality evaluation process effective.

The CVA analysis has certain advantages above the latter methods namely (i) If the quality data for a line or cultivars is available its CVA_1 and CVA_2 values can be calculated and the line can then be plotted in order to predict its quality performance against that of the biological quality standard and other well known commercial cultivars. (ii) A long term data basis can now be generated from data over years and localities from even different breeding programmes, this information will provide valuable data for decision making regarding the release of new lines as cultivars. (iii) The CVA analysis provides specific detail about the quality characteristics that discriminate cultivars or lines from each other. (iv) From the 11 milling characteristics only five explained the observed variation (in descending importance) efficiently namely, SKCS-DIA, FABS, BFY, FLY and FCL(C76). The characteristics that explain most of the observed variance in descending order of importance for baking quality are MDT, ASTAB, P/L, AS and AD. (v) Thus, the long term data suggests that a breeding programme can only incorporate the mixograph test, alveograph test, Buhler flour extraction, farinograph water absorption and SKCS test

in order to improve milling and baking characteristics efficiently. (vi) From Table 6.16 it also clear that the influence of the milling characteristics regarding discriminating among spring wheat cultivars under irrigation was 30.57% higher than in the case of baking characteristics. Therefore, if cultivars are to be classified according to their different hardness classes, the current observed variation for milling and even baking characteristics could be drastically lowered for South African wheat cultivars produced under irrigation. (vii) The evaluation costs at the SAGL can be drastically reduced if only the tests mentioned in section (v) are to be carried out. (viii) All the characteristics identified by the combined CVA analysis for the milling and baking worth's has high genotypic variation components (Tables 3.12 and 3.13 in Chapter 3), which means that the environment influence is low, resulting in more rapid progress in breeding for improved milling and baking quality characteristics. For BPT01/07 its dough characteristics was inferior when plotted against that of Kariega as seen Figure 6.5. This can be ascribed to the fact that Kariega's longterm quality included the biplot was more favourable as during the evaluation period when BPT01/07 was tested. Therefore, in order to rectify this problem a few suggestions can be made namely, a CVA should be carried out on a larger set (more years, than in this study) in order to get more accurate correlations for the milling and baking characteristics. Another option is to also plot the short term data from Kariega to determine how it differs form Kariega's original long term data in the CVA biplot. Only trials for which the milling and baking characteristics for Kariega equals or exceed the upper and lower limits set by the SAGL should be included for calculation and plotted in the biplot

The cluster analysis grouped Kariega and SST 822 together for milling characteristics, while it clustered SST822, Kariega and SST 825 together for baking characteristics. From the Cluster analysis it is not indicated clearly which of the milling or baking characteristics provide the dissimilarities between the observed clusters. The cluster analysis will also not provide a means of incorporating milling and baking data regarding new test lines against current cultivars on a long term basis from different breeding programmes such as in the case of the CVA analysis.

6.6 References

- AACC, 1983. Falling number determination method 56-81B; Experimental milling Buhler method 26-21A; Mixograph method 54-40A; Farinograph method 54-2A using 50g of flour; Alveogram method 54-30A; SDS-sedimentation the method used to determine gluten strength, method 56-70. In Approved methods; 8th ed. American Association of Cereal Chemists Inc.; St Paul, MN, USA.
- AACC; 1995. Dumas Leco-FP200 method for protein determination, method 46-30. In Approved methods; 8th edn. American Association of Cereal Chemists Inc.; St Paul, MN, USA.
- BAKER, S., HERRMAN, T.J. & LOUGHIN, T., 1999. Segregating hard red winter wheat into dough factor groups using the single kernel measurements and whole grain protein analysis. *Cereal Chem.* 76(6): 884-889.
- BRUCKNER, P.L. & FINNEY, P.L., 1992. Milling and baking quality attributes of soft red winter wheat bulk populations and derived lines. *Crop Sci.* 32: 1174-1179.
- BUSHUK, W., 1998. Wheat breeding for end-product use. *Euphytica* 100: 137-145.
- BUTT, M.S., ANJUM, F.M., VAN ZUILICHEM, D.J. & SHAHEEN, M., 2001. Development of predictive models for end-use quality of spring wheats through canonical analysis. *International Journal of Food Science and Technology* 36: 433-440.
- CLINE, M.N. & ESFELD, M.A., 1998. New horizons for the amber waves- Technologies boost the capabilities of wheat. *Cereal. Foods World* 43: 4-10.
- COX, T.S., SHOGREN, M.D., SEARS, R.G., MARTIN, T.J. & BOLTE, L.C., 1989. Genetic improvement in milling and baking quality of hard red winter wheat cultivars, 1919-1988. *Crop Sci.* 29: 626-631.
- CROSSA, J., 1990. Statistical analyses of multilocation trials. *Advances in Agronomy* 44: 55-85.
- DIGBY, P., GALWEY, N. & LOWE, P., 1989. Genstat 5: A second course. Oxford University Press, Oxford.
- DRYNAN, R., 2001. Wheat quality in the twenty-first century. <http://www.wheatworld.org/forum11.ht>.
- ESKRIDGE, K.M., 1990. Selection of stable cultivars using a safety-first rule. *Crop Sci.* 30: 369-374.
- ESKRIDGE, K.M., PETERSON, C.J. & GROMBACHER, A.W., 1994. Probability of wheat quality falling within acceptable limits. *Crop Sci.* 34: 866-869.
- FINNEY, K.F., 1984. An optimized straight-dough bread making method after 44 years. *Cereal. Chem.* 61: 20-27.
- FINNEY, K.F., GAINES, C.S. & ANDREWS, L.C., 1987. Wheat quality: A quality assessor's view. *Cereal Foods World* 32(4): 313-319.
- FOX, P.N. & ROSIELLE, A.A., 1982. Reducing the influence of environmental main-effects on pattern analysis of plant breeding environments. *Euphytica* 31: 645-665.
- GEDDES, W.F., 1941. Objectives in breeding for improved quality in hard wheat. *Journal of the American Society of Agronomy* 33(6), 490-503.
- GENSTAT 5 COMMITTEE OF STATISTICS, 1987. Committee of the Statistics Department, Rothamsted experimental station. Genstat 5 Reference Manual. Clarendon Press, Oxford.
- GHADERI, A., EVERSON, E.H. & CRESS, C.E., 1980. Classification of environments and genotypes in wheat. *Crop Sci.* 20: 707-710.

- GITTENS, R., 1985. Canonical Analysis. A Review with Applications in Ecology. New York: Springer-Verlag.
- GRAYBOSCH, R., PETERSON, C.J. & MOORE, K.J., 1993a. Comparative effects of wheat flour protein, lipid and pentosan composition in relation to baking and milling quality. *Cereal Chem.* 70: 95-101.
- GRAYBOSCH, R., PETERSON, C.J., MOORE, K.J., STREARNS, M. & GRANT, D.L., 1993b. Comparative effects of wheat flour protein, lipid, and pentosan composition in relation to baking and milling quality. *Cereal Chem.* 62: 350-355.
- GRAYBOCH, R.A., PETERSON, C.J., SHELTON, D.R. & BAENZIGER, P.S., 1996. Genotypic and Environmental modification of wheat flour protein composition in relation to end-use quality. *Crop. Sci.* 36: 296-300.
- HAZEL, L.N., 1943. The genetic basis for constructing selection indices. *Genetics* 28: 476-490.
- HENNING, J.A. & TEUBER, L.R., 1996. Review and interpretation. Modified convergent improvement: A breeding method for multiple traits. *Crop Sci.* 36: 1-8.
- HINTZE, J.L., 2000. NCSS 2000 Statistical System for Windows. Number Cruncher Statistical Systems. Kaysville, Utah.
- HOTELLING, H., 1936. Relation between two sets of variates. *Biometrika* 28: 2321-2377.
- HOWARD, N.L., 2003. Notes on milling and baking values and the rationale behind their determination. In: Final report on the milling and baking worth of South African bread wheat cultivars, Small Grain Institute, Agricultural Research Council, South Africa.
- JONES, H., JARMAN, R.J., AUATIN, L., WHITE, J. & COOKE, R.J., 2003. The management of variety reference collections in distinctness, uniformity and stability testing of wheat. *Euphytica* 132: 175-184.
- KADAR, R. & MALDOVAN, V., 2003. Achievement by breeding of winter wheat varieties with improved bread-making quality. *Cereal Research Communications* 31(1-2): 89-95.
- KEMPTHORNE, O. & NORDSKOG, A.W., 1969. Restricted selection indices. *Biometrics* 15: 10-19.
- KILBORN, R.H. & TIPPLES, K.H., 1981. Canadian test baking procedures. I. GRL remix method and variations. *Cereal Foods World* 26: 624.
- KOEKEMOER, F.P., 1997. Inheritance of protein related characteristics in spring wheat. MSc. Thesis, Orange Free State.
- LABUSCHAGNE, M.T., MAMUYA, I.N. & KOEKEMOER, F.P., 2002. Canonical variate analysis of bread making quality characteristics in irrigated spring wheat (*Triticum aestivum*). *Cereal Research Communications* 30(1-2): 195-201.
- LIN, C.S., BINNS, M.R & LEFKOVICH, L.P., 1986. Stability analysis: where do we stand?. *Crop Sci.* 26: 894-900.
- LUKOW, O.M., 1991. Screening of bread wheats for milling and baking quality – A Canadian perspective. *Cereal Foods World* 36(6): 497-501.
- LUKOW, O.M. & McVETTY, P.B.E., 1991. Effect of cultivar and environment on quality characteristics of spring wheat. *Cereal. Chem.* 68(6): 597-601.
- MANLEY, M., 2000. A comparative scanning electron microscopic study of a number of South African and Canadian wheat's of different hardnesses. Report to the Wheat Research Trust, University of Stellenbosch.

- MANLEY, M., VAN ZYL, L. & OSBORNE, B.G., 2001. Deriving grain hardness calibrations for whole ground wheat samples by means of particle size index (PSI) method and fourier transform near infrared (FT-NIR) spectroscopy. *S. Afr. J. Plant Soil* 18(2): 69-74.
- OSBORNE, B.G., SALMON, S. & CURTIS, P.S., 1993. Quality assessment of new wheat varieties, pp318-333. In: Taylor, Randall and Viljoen (eds.). Cereal science and technology impact on a changing Africa, selected papers from the ICC International symposium, CSIR, Pretoria, South Africa.
- PENA, R.J., TRETOWAN, R., PFEIFFER, W.H. & VAN GINKEL, M., 2002. Quality (end-use) improvement in wheat: compositional, genetic, and environmental factors. *J. of Crop Production* 5(1-2): 1-37.
- PETERSON, C.J., GRAYBOCH, R.A., SHELTON, D.R. & BAENZIGER, P.S., 1997. Baking quality of hard winter wheat: response of cultivars to environment in the Great Plains. Wheat: prospects for global improvement. Proceedings of the 5th International Wheat Conference, Ankara, Turkey, 10-14 June 1996. Kluwer Academic Publishers, Dordrecht, Netherlands: 223-228.
- PIEPHO, H.P., 1995. The use of multilocation trials to select cultivars that are better than a control. *Plant Breeding* 114: 337-340.
- SAGL, 2002. Analysis procedure and evaluation norms for the classification of wheat breeder's lines for the RSA. Revised by: Monsanto, Pannar, SGI, SA Chamber of Baking, National Chamber of Milling, September 2002.
- SALMON, S., 1998. Quality testing of new wheat varieties in trials: an overview of European methods. Review no. 10. Campden & Chorleywood Food Research Association, Chipping Campden, Gloucestershire, UK.
- SOUZA, E.J., GRAYBOSCH, R.A. & GUTTIERI, M.J., 2002. Breeding wheat for improved quality. *J. of Crop Production* 5(1-2): 39-74.
- TIPPLES, K.H. & KILBORN, R.H., 1974. "Baking strength index" and the relation of protein content to loaf volume. *Can. J. Plant Sci.* 54: 231.
- VAN DEVENTER, C.S., 1999. Classification of wheat according to end use. Research Report about the genetic quality parameters affecting the classification of wheat. Department of Plant Breeding. University of the Free State, Bloemfontein.
- VAN LILL, D., PURCHASE, J.L., SMITH, M., AGENBAG, G.A. & DE VILLIERS, O.T., 1995a. Multivariate assessment of environmental effects on hard red winter wheat. I. Principle component analysis of yield and bread-making quality characteristics. *S. Afr. Tydskr. Plant Grond* 12(4): 158-163.
- VAN LILL, D., PURCHASE, J.L., SMITH, M., AGENBAG, G.A. & DE VILLIERS, O.T., 1995b. Multivariate assessment of environmental effects on hard red winter wheat. I. Canonical correlation and canonical variate analysis of yield, biochemical and bread-making characteristics. *S. Afr. Tydskr. Plant Grond* 12(4): 164-169.
- VAN LILL, D. & SMITH, M.F., 1997. A quality strategy for wheat (*Triticum aestivum* L.) where growth environments predominates. *S. Afr. J. Plant Soil* 14(4): 183-191.
- VAN LILL, D. & PURCHASE, J.L., 1995. Directions in breeding for winter wheat yield and quality from 1930-1990. *Euphytica* 82: 79-87.
- WESTCOTT, B., 1986. Some methods of analysing genotype x environment interaction. *Heredity* 56: 243-253.

WILSON, W.W. & PRESZLER, T., 1992. End-use performance uncertainty and competition in international markets. *Am. J. Agric. Econ.* 74: 556-563.

High ← SKCS-DIA, FABS → Low

Low ← BFY → High

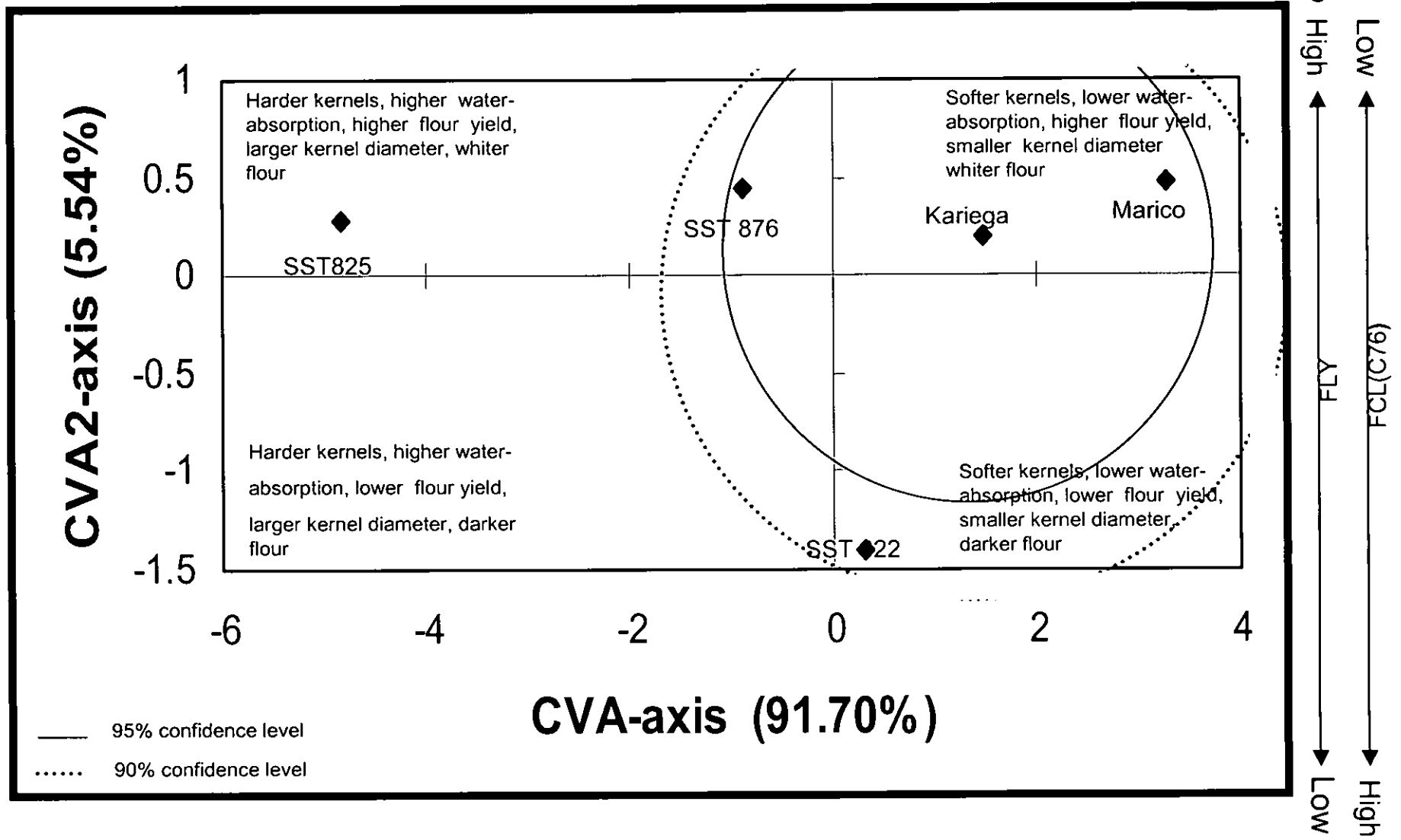


Figure 6.1. CVA analysis for the milling characteristics for five cultivars at five localities from 1997 until 1999.

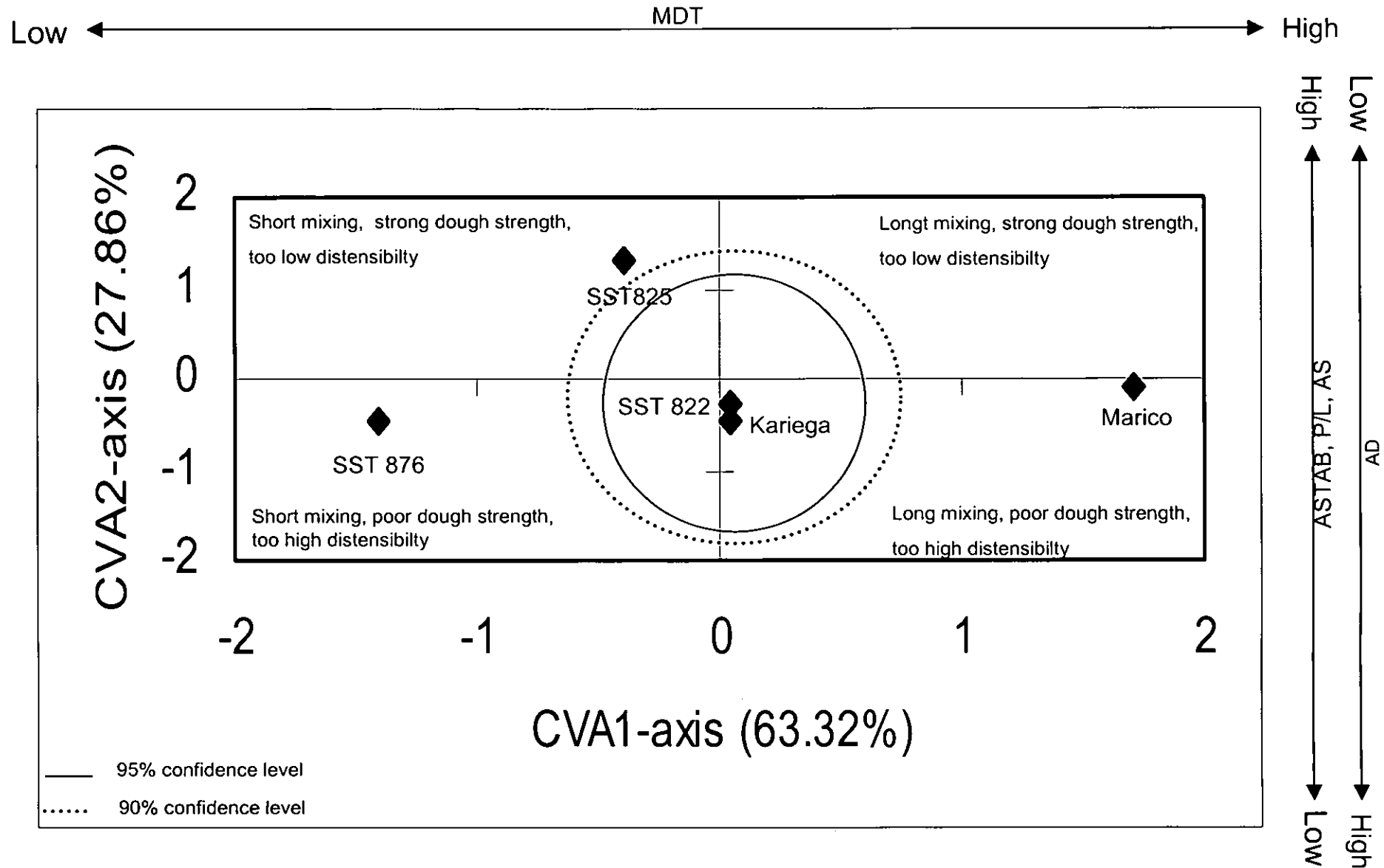


Figure 6.2. CVA analysis for the baking characteristics for five cultivars at five localities from 1997 until 1999.

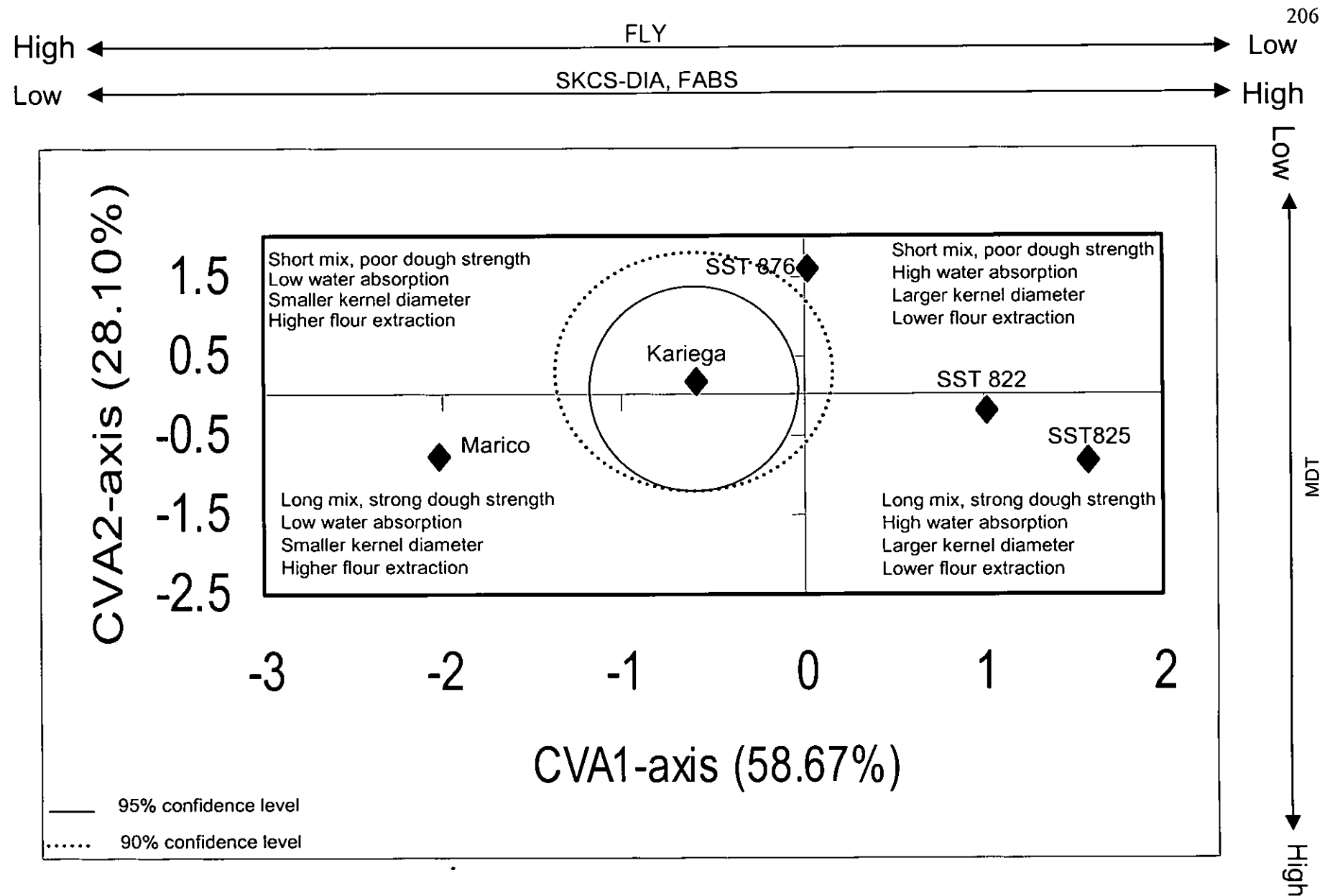


Figure 6.3. CVA analysis for the milling and baking characteristics combined for five cultivars at five localities from 1997 until 1999.

High ← SKCS-DIA, FABS → Low

Low ← BFY → High

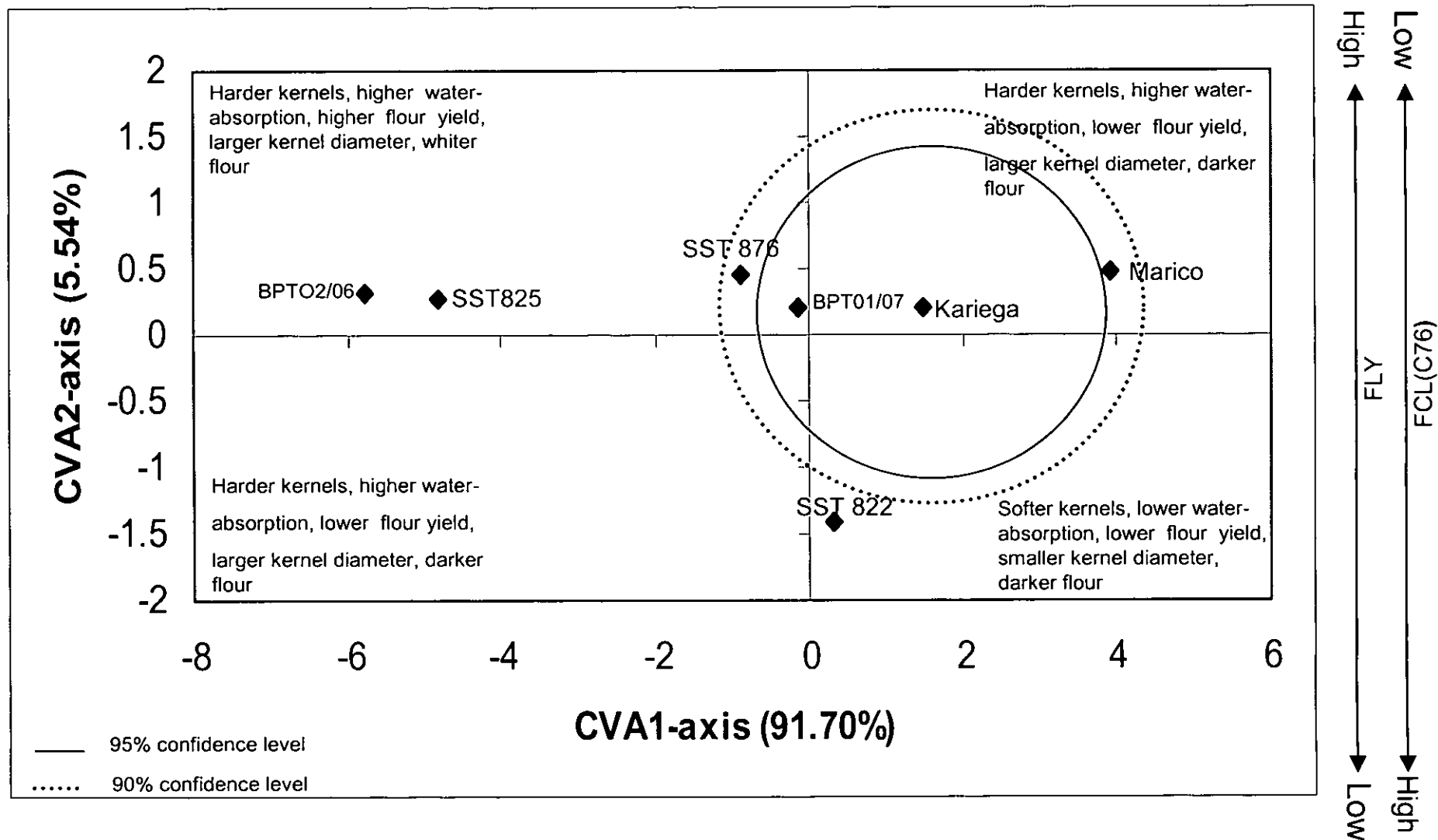


Figure 6.4. CVA analysis for the baking characteristics for five cultivars in comparison to two new test lines at five localities.

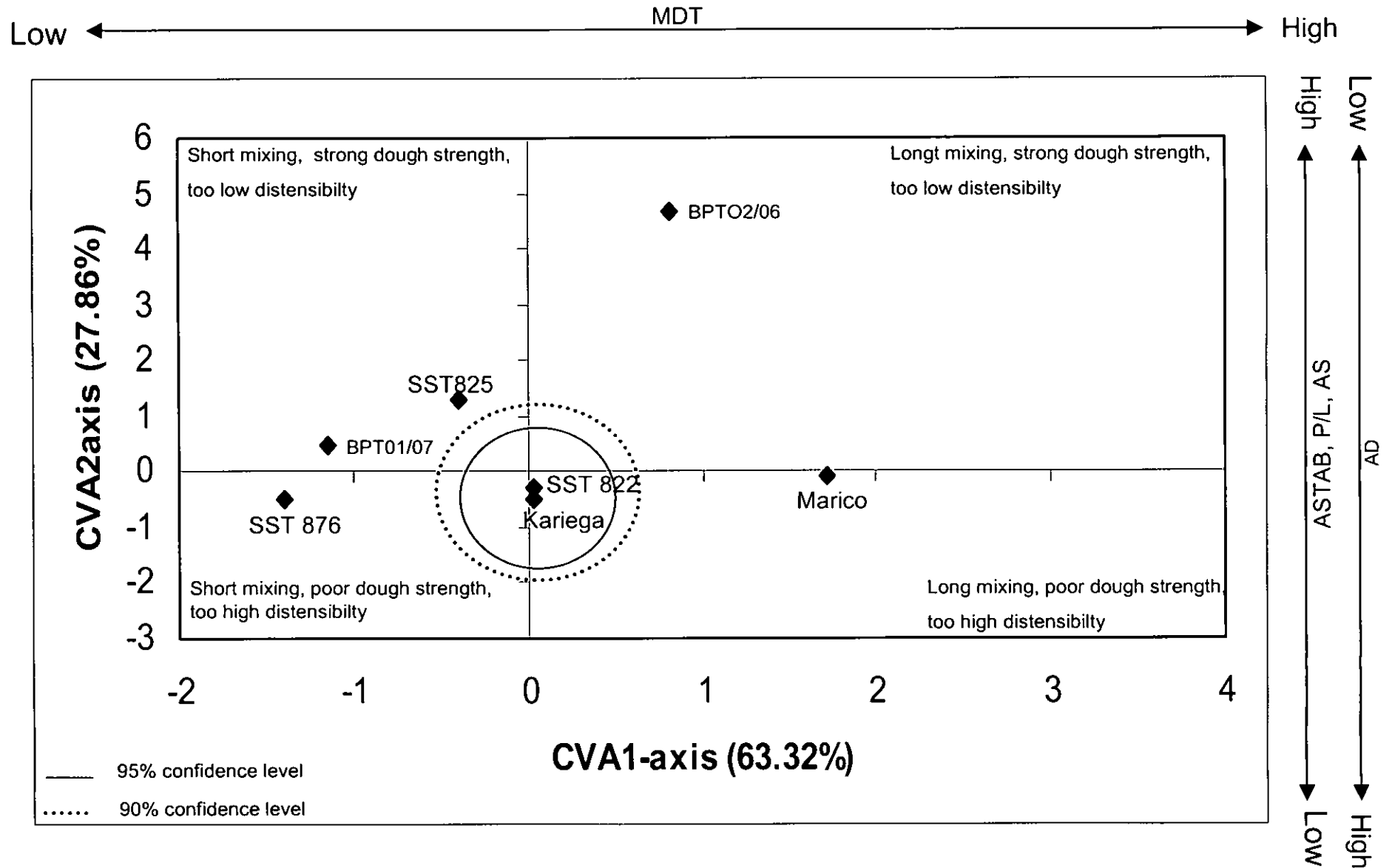


Figure 6.5. CVA analysis for the baking characteristics for five cultivars in comparison to two test lines at five localities.

CHAPTER 7

Summary/Opsomming

The main aim of this study was to use a data with regards to milling and baking quality characteristics generated under similar environmental locations and seasons, in order to determine the source, size and magnitude of genotype x environment interaction; the optimal locality, year, and replication combinations; to compare the various available statistical procedures in assessing performance stability and to evaluate the different existing methods available regarding their suitability for grouping different genotypes into homogeneous groups. In order to achieve this, five spring wheat cultivars (*Triticum aestivum* L.) were grown in five environments under irrigation from 1997 through 1999. The cultivars used in this study displayed a broad range in milling and baking quality.

1. The source, size and magnitude of genotype x environment interaction for spring wheat under irrigation were determined. From the results, the best and poorest cultivar in overall milling performance was Kariega and SST 822 respectively, while the best and poorest overall baking performance were displayed by Kariega and SST 876 respectively. All the characteristics related to gluten strength and the elastic properties namely SDS-sedimentation test, wet gluten content standardized at 12% protein, mixograph mixing time, alveograph strength, alveograph distensibility and alveograph P/L ratio displayed genotypic variance contributions above 30% and even as high as 57.65% for mixograph mixing time. Genotype x location and genotype x year interaction components for most of the milling and baking characteristics was insignificant. However, genotype x location x year interaction was significant for most milling and baking characteristics.

2. The optimal locality, year, and replication combinations regarding the screening of spring wheat genotypes for milling and baking quality under irrigation were also determined.

From the data it was clear that there is not a large improvement in relative efficiency when a second and third replicate is used in the determination of the optimal amount of localities in order to distinguish between genotypes. A similar pattern is also observed regarding the number of years needed and almost no differences were observed if either three, four or even five year's quality data are taken into account. It has been proven that for both the milling and baking characteristics five trials are needed over a two-year test period.

3. Various available statistical procedures were used in assessing performance stability regarding milling and baking characteristics in order to identify the most suitable method. The following statistical analysis were conducted and procedures followed in order to determine stability for the milling and baking characteristics: (i) Wricke's - W_i (1962) ecovalence, (ii) Eberhart and Russell's - S^2d_i (1966) deviation parameter, (iii) Shukla's - σ^2_i (1972) stability variance, (iv) Linn and Binn's - P_i (1988a) cultivar superiority performance and (v) AMMI stability value - ASV (Purchase, 1997). Lower significant rank correlation coefficients were found in the pairwise comparisons of both Eberhart and Russell's as well as that of Lin and Binn, but in the latter to a lesser extent. From this study, it would appear that all three the following appropriate methods namely Wricke's ecovalence, Shukla's stability variance as well as the AMMI Stability Value can be used to describe the stability of a genotype.

Looking at the stability of the cultivars per se it can be concluded that Marico is very unstable for its hectolitre mass (HLM) values. Marico is however very stable for the expression of its inherent kernel hardness values (VK, SKCS-HI and BFLY). Kariega is however very unstable regarding the expression of its inherent kernel hardness value. SST 825 displays unstable hectolitre mass and hardness values. SST 825 has very stable characteristics that influence kernel size. SST 822 expressed very stable flour yield as well as hardness values. SST 876 produced very stable values for hectolitre mass as well as the traits that influence kernel size but it produced an unstable flour yield.

Marico is very unstable regarding its rheological as well as baking properties. Kariega on the other hand displays remarkable stable rheological as well as baking performance properties.

SST 825 is unstable in the expression of its grain (GPC-Leco) and flour protein (FPC-Leco) levels. SST 825 produced stable alveograph strength (AS) and alveograph distensibility (AD) values. SST 822 however has very stable GPC-Leco as well as FPC-Leco values. Although SST 876 showed very stable GPC-Leco as well as FPC-Leco values, its rheological properties is weak.

4. Different selection methods were used to group different genotypes into homogeneous groups according to their milling and baking characteristics respectively. How effective these methods identify superior genotypes according to their milling and baking characteristics was also determined. The suitability of these methods were evaluated, in order to determine which is the appropriate method for evaluating the milling and baking quality characteristics from multilocation field trials for new testing lines to be considered for release. Therefore, two test lines were also used in order to verify the accuracy of the evaluation methods, which were the combination of the independent culling with absolute limits of acceptability relative to a check method from the SAGL, Lukow's (1991) multiple linear regression analysis method, Howard's (2003) milling and baking worth procedure, canonical variate analysis (CVA) and cluster analysis. It can be concluded that Lukow's method has the tendency to identify lines that has stronger gluten strength characteristics, which makes sense because it was developed for the Canadian wheat market. Howard's milling and baking worth procedure has relative value for ranking cultivars, but the weighted contributions should be changed according to environmental influence on milling and baking characteristics. It was found that the CVA analysis is an objective and efficient procedure to evaluate new breeding lines regarding their milling and baking potential in comparison to a biological quality standard. The cluster analysis gave similar clusters when compared with the groupings of the CVA for baking results but not for the milling characteristics.

Die hoofdoel van die studie was om 'n data stel te gebruik ten opsigte van maal en bakeienskappe wat verkry is onder dieselfde lokaliteite en jare om sodoende die bron, omvang van die genotipe x omgewinginteraksie te bepaal; die optimale aantal lokaliteite, jare en replikasie kombinasies te bepaal; om tussen verskillende beskikbare statistiese metodes wat stabiliteit bepaal te vergelyk; om 'n geskikte metode te identifiseer wat genotipes in

homogene groepe kan opdeel op grond van hul maal- en bakeienskappe. Om die doelwitte te bereik is vyf lentekoring cultivars (*Triticum aestivum* L.) afkomstig van vyf omgewings in die besproeiingsgebiede vanaf 1997 tot 1999 gebruik. Die cultivars gebruik in die studie toon 'n wye reeks variasie ten opsigte van hul maal- en bakeienskappe.

1. Die bron, grootte en omvang van die genotipe x omgewinginteraksie vir lente koring onder besproeiing is bepaal. Vanuit die resultate is die beste en swakste presteerders rakende hulle maaleienskappe Kariega en SST 822 respektiewelik, terwyl die beste en swakste presteerder ten opsigte van hul bakeienskappe, Kariega en SST 876 onderskeidelik was. Al die eienskappe verbonde aan glutensterkte en elasticiteit naamlik SDS – sedimentasie, nat gluteninhoud gestandardiseer by 12% proteïeninhoud, miksogrammentyd, alveograafsterkte, alveograafrekbaarheid, en alveograaf P/L verhouding het genotipiese variasie bydraes bo 30% en selfs so hoog as 57.65% vir miksogrammentyd getoon. Komponente vir genotipe x lokaliteitinteraksie asook vir genotipe x jaarinteraksie was nie betekenisvol vir meeste van die maaleienskappe sowel as die bakeienskappe nie. Die genotipe x lokaliteit x jaarinteraksie vir meeste maal- en bakeienskappe was betekenisvol.

2. Optimale lokaliteit, jaar en herhaling kombinasie is ook bereken, ten opsigte van die toetsing van lente koringgenotipes onder besproeiing vir beide die maal- en bakeienskappe. Uit die data is dit duidelik dat die effektiwiteit nie verbeter wanneer twee of meer herhalings ingesluit word nie, om sodoende die optimale aantal lokaliteite te bereken. 'n Soortgelyke tendens is ook waarneembaar vir die aantal jare ingesluit, omtrent geen betekenisvolle verbetering in effektiwiteit kon verkry word wanneer drie, vier of selfs vyf jaar se kwaliteitsdata in berekening geneem word nie. Vir beide maal-en bakeienskappe is vyf lokaliteite oor 'n twee jaar toetsperiode voldoende.

3. Verskeie statistiese tegnieke is gebruik om die stabiliteit ten opsigte van die maal- en bakeienskappe te beraam, die mees effektiewe tegnieke is ook bepaal. Die volgende statistiese tegnieke is uitgevoer op die data (i) Wricke se - W_i (1962) "ekovalens", (ii) Eberhart en Russell se - S^2d_i (1966) afwykingsparameter, (iii) Shukla se - σ^2_i (1972) stabiliteitsvariansie, (iv) Linn en Binn se - P_i (1988a) cultivar superioriteitsprestasie (v) AMMI

se stabiliteitswaarde – ASV (Purchase, 1997). Laer betekenisvolle rangordekorrelasies is gevind vir Eberhart en Russel sowel as Lin en Binns se tegnieke, alhoewel tot 'n mindere mate vir die laasgenoemde tegniek. Uit die studie is dit duidelik dat al die die ander tegnieke naamlik Wricke se ekovalens, Shukla se stabiliteitsvariansie en die AMMI stabiliteitswaarde gebruik kan word om die stabiliteit van 'n cultivar te kan beskryf.

Indien die stabiliteit van die cultivars apart bestudeer word kan daar afgelei word dat Marico baie onstabiel is ten opsigte van hektolitermassawaardes (HLM). Marico is egter baie stabiel ten opsigte van die uitdrukking van korrelhardheidseienskappe (VK, SKSC-HI en BFLY). Kariega aan die ander kant is weer baie onstabiel ten opsigte van die uitdrukking van sy hardheidseienskappe. SST 825 is baie onstabiel ten opsigte van hektolitermassa sowel as hardheidswaardes. SST 825 is egter baie stabiel in die uitdrukking van eienskappe verantwoordelik vir korrelgrootte. SST 822 is baie stabiel ten opsigte van meelopbrengs asook hardheidswaardes. SST 876 toon baie stabiele hektolitermassawaardes asook stabiele waardes ten opsigte van eienskappe betrokke by korrelgrootte.

Marico is baie onstabiel ten opsigte van die reologiese-eienskappe sowel as bakeienskappe. Kariega is egter baie stabiel ten opsigte van die bogenoemde eienskappe. SST 825 is baie onstabiel in die uitdrukking van graan- (GPC-Leco) asook meelproteïeninhoud (FPC-Leco) vlakke. SST 825 produseer egter baie stabiele alveograafsterktes (AS) en alveograafrekbaarheidswaardes (AD). SST 822 toon egter baie stabiele GPC-Leco asook FPC-Leco waardes. SST 876 vertoon baie stabiele GPC-Leco asook FPC-Leco waardes.

4. Verskeie seleksiemetodes is gebruik om die cultivars in homogene groepe te groepeer op grond van hul maal- en bakeienskappe. Die metodes is ook beoordeel op grond van hul effektiwiteit om uitstaande cultivars te identifiseer ten opsigte van hul maal- en bakeienskappe. Die geskiktheid van die metodes om nuwe potensiële cultivars te identifiseer afkomstig uit kwaliteitsdata uit meervoudige lokaliteite, is ook ondersoek. Dus is twee nuwe toetslyne se kwaliteitsdata ingeluit om die effektiwiteits van die metodes te evalueer. Die volgende seleksiemetodes is ondersoek, naamlik 'n kombinasie van onafhanklike eliminering gekoppel aan voorafbepaalde absolute limiete in verhouding tot 'n

standard metode van die SAGL, Lukow se (1991) meervoudige liniêreregressie-analise, Howard se (2003) maal- en bakwaardemethode, kanoniese veranderlike-analise (CVA) en trosanalise. Dit is gevind dat Lukow se metode nie geskik is nie, omrede dit genotypes identifiseer met sterk gluteneienskappe. Howard se metode kan gebruik word om cultivars te orden volgens hul prestasie, maar die gewigte toegeken aan eienskappe wat meestal beïnvloedbaar is deur die omgewing is nog te hoog. Die CVA metode is 'n objektiewe en effektiewe metode om nuwe genotypes te beoordeel op grond van hul maal- en bakeienskappe teenoor die biologiese standard. Die trosanalise verskaf ooreenstemende groepe met die CVA ten opsigte van maaleienskappe maar nie vir die bakeienskappe nie.

CHAPTER 8

Recommendations

It has been proven that for both the milling and baking characteristics five trials are needed over a two-year test period with one replication, because adding more years or replications do not improve the statistical accuracy significantly. The first, second and third year advanced lines are also planted in the same trial and therefore it will be difficult to vary the amount localities, years and replications for the different testing levels. The recommendation will shorten the current testing period with one year, in order to release new spring wheat cultivars under irrigation. This will reduce expenditure significantly regarding the amount of trials to be planted in the breeding programmes as well the amount of test samples to be tested in the quality laboratory of the SAGL.

Kariega as the biological standard is very unstable regarding the expression of its inherent kernel hardness value. Breeding lines that are more stable for kernel hardness is therefore critical. Releasing cultivars that display similar stability values when compared to Kariega is also needed for the rheological characteristics. This will reduce the effect of genotype x environment interaction on the milling and baking characteristics drastically and will result in an improvement in consistency. Normally the consistency varies between batches of either flour or dough, which is mostly problematic for the processing industry.

From this study, it would appear that all three the following methods namely Wricke's ecovalence, Shukla's stability variance as well as the AMMI Stability Value can be used with similar results to describe the stability of a genotype.

The CVA analysis can be used to address most of the problems that are currently being experienced with the South African evaluation system in order to release new cultivars for the

commercial market. In order to improve the accuracy of the CVA analysis only trials for which the milling and baking characteristics for Kariëga equals or exceed the upper and lower limits as set by the SAGL should be included for calculation and plotted in the biplot. From the 11 milling characteristics only five explained the observed variation (in descending importance) efficiently namely, SKCS-DIA, FABS, BFY, FLY and FCL(C76). The characteristics that explain most of the observed variance in descending order of importance for baking quality are MDT, ASTAB, P/L, AS and AD. Thus, the long term data suggests that a breeding programme can only incorporate the mixograph test, alveograph test, Buhler flour extraction, farinograph water absorption and SKCS test in order to improve milling and baking characteristics efficiently.

From the study it is also clear that the influence of the milling characteristics regarding discriminating among spring wheat cultivars under irrigation was 30.57% higher than in the case of baking characteristics. Significant variation regarding hardness levels among the cultivars was observed, which implies that such cultivars should be treated differently in order to obtain proper conditioning. Therefore, if cultivars are to be classified according to their different hardness classes, the current observed variation for milling and even baking characteristics could be drastically lowered for South African wheat cultivars produced under irrigation.

