School of Public Health

Boundaries for use in wheat variety classification in Australia

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made

This thesis contains no material that has been accepted for the award of any other degree or diploma in any university.

Signature -
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Publications and presentations

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You cannot open a book without learning something new

Abstract

Suppliers of wheat must ensure that their products have the required quality profile demanded by customers and consistently deliver that quality in order to be competitive. Australia's wheat industry is highly exposed to such competitive threats because it relies heavily on exports. An integral component in maintaining Australia's competitiveness has been its classification system. The first step involves the complex process of determining a genotypic quality profile of each variety – a variety classification. At harvest, subsequent steps are the use of a statutory declaration and testing of physical quality traits. Together these steps determine how deliveries of wheat are segregated. A single variety can have different classifications across the 7 classification regions of Australia. Most classification regions are divided along state borders and these are not reflective of potential environmental influences.

The manner in which Australia wheat breeding programs now tackle their task has changed since 1999. The commercially focused companies of the current era have national targets to remain viable, and are focused on costs. Other evolutions associated with the change, are the introduction of different sources of parental material, and moving to more economic composite quality testing regimes instead of the individual site by site testing used in the past. Together, these factors, particularly variety adaptability and stability of performance, have the capacity to increase variability. The likelihood of variation is further increased given that the current classification regions upon which classification decisions are made do not adequately reflect environmental effects on the expression of quality.

To determine whether better divisions of the Australian wheat-belt could be identified for variety classification purposes, a substantial spatial and temporal database of historical quality results was assembled. The creation of this relational database was unique, because never before had expansive sets of independent, state-based, quality sub-sets been joined together. However, the data were unbalanced and required alternative statistical tools to be analysed. The relational database was the platform from which three phases of research were conducted.

The first research phase investigated the extent of cross over, or re-ranking of results, statistically referred to as genotype × environment interaction. The approach was to assess balanced data sets, in a manner reminiscent of the most common method identified from the literature. The results of those analyses showed that the size of genotype and environment interaction was small compared with the main effects of genotype and environment.

The second phase of research focused on identifying alternative boundaries for classification purposes. Test divisions were compared with the current set of 7 classification regions for the capacity to minimise environmental variance while maintaining differences between the zones of a set. Test divisions were based on fourteen published divisions of the Australian wheat-belt. Analyses were conducting using residual maximum likelihood because of the unbalanced structure of the data. Estimates of variance components, quality trait means and standard errors were calculated. Consideration of such estimates resulted in the identification of 4 different divisions of the wheat-belt that had low environmental variance levels for important quality traits such as maximum resistance, dough development time, and water absorption. In addition, these 4 divisions of the wheat-belt had fewer number of zones compared with the existing set of classification regions because they linked separate parts of the wheat-belt together. In order of decreasing merit, the 4 divisions of the wheat-belt represented average October maximum temperatures; agro-ecological zones reported by Williams et al. (2002); average annual rainfall; and Departments of Agriculture recommendation zones.

A final phase of crosschecking was performed to assess the veracity of the 4 identified divisions. A cluster analysis supported the orientation of their boundaries and it was also observed that the use of fixed boundaries for classification purposes would not be negatively affected by seasonal variation.

The 4 divisions of the wheat-belt identified in this research support the use of environmentally focused classification boundaries. In addition to improving the capacity to segregate consistent quality, the linking of geographically separate production areas of the wheat-belt reduced the number of zones and this offers process efficiencies.

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Chapter 1 Introduction

The gross value of the Australian wheat industry is around AUS$5 billion per annum (ABARE, 2005, Australian Bureau of Statistics, 2006). Australia is ranked as the third largest exporter in the world (US Department of Agriculture, 2005) and consequently a significant component of that value, estimated to be over 60%, comes from the sale of export wheat. International competitive factors, and an increasing use of mechanisation in food processing, mean there is a greater demand for consistency – in terms of both wheat quality and supply. The ability to provide a consistent quality product meeting customer's requirements is paramount if a high sale price is to be achieved (Dexter and Worden, 2005).

In Australia, maintaining a consistent quality and remaining competitive relies on the grade classification system. Three steps are critical to the effectiveness of that system. The first is the classification of all new varieties to a marketing grade based on their processing performance. Such performance parameters are intrinsically linked to a variety's genetic composition. The second step is the measurement, at the point where a parcel of wheat is to be segregated, of physical quality traits associated with environmental influences. The final step of the grade classification system is a variety statutory declaration. Together these steps ensure that wheat is effectively stored as parcels of consistent quality that meet customer requirements.

For convenience, the term 'variety' has been used in Chapters 1, 2, 3 and 8. It is acknowledged that 'cultivar' would have being a more appropriate term (Brickell et al., 2004) but the use of 'variety' persists in Australia and is the commonly used term. However, in Chapters 4 to 7, the term 'line' has been used to describe both advanced breeding lines and released varieties.

The first step of the grade classification system aims to group individual varieties of similar quality to produce a grade or class recognised in the market place for certain processing attributes (Cracknell and Williams, 2004). Classification decisions focus on a variety's inherent quality traits, but that process is complicated by the fact that few quality traits can be regarded as solely genotypically or environmentally controlled (AWB Limited, 2005b). Further challenges in determining the profile of a

variety are encountered because within the broad grouping of genotype and environment influence, there are intra- and inter-trait relationships. Thirty years ago, heritability studies guided breeders as to which quality traits they might have success in targeting (Baker et al., 1971, Bhatt and Derera, 1975, Fowler and de la Roche, 1975). Today, molecular markers for important traits such as grain hardness, protein and starch quality mean breeders can be selective in how they pursue quality. Despite the improvements in understanding which genes control quality, the influence on the expression of genes by environmental conditions ultimately determines the quality segregated at harvest each year and that can vary across the Australian wheat-belt.

It is internationally recognised that making a classification decision is a time consuming and expensive exercise (Lukow and McVetty, 1991). In Australia, for a new variety to be given a grade classification it must have been grown, harvested and analysed in at least 1 of current 7 classification regions. A final classification decision is only made after reviewing quality results for an expansive range of laboratory based quality tests from at least 3 years and is applicable only to that region. For other, out-of-region classification decisions to be made, that testing process must be, in part, repeated (AWB Limited, 2005b).

The current Australian classification regions reflect the traditional development of wheat varieties by state government departments and regional universities, and boundaries essentially run along state borders. Unfortunately, this means the regions ignore environmental influences on wheat quality. In Australia, the breeding sector has undergone recent change from being publicly funded to a more competitive, profit focused sector. The result has lead to breeding companies with expanded target production regions, the use of a greater diversity of parental material and business models that demand containment of operating costs across the full range of activities. The latter inevitably has an impact on quality testing strategies including the types of tests and the numbers of locations evaluated per target region. If future variety classification decisions are made on regions not truly representing environmental influences and the changes in the breeding sector result in reduced quality testing, then there is potential for an increase in the quality variability of the Australian wheat crop.

Consequently, the opportunity to determine more appropriate boundaries for classification purposes, based on environmental factors, was taken. The timeliness of this research is important because it occurred before the changes described above might impact on quality consistency, and it also made use of appropriate single site quality results rather than composite samples which are increasingly being used in quality evaluation.

1.1 Hypothesis

To determine that better boundaries, compared with those currently in use, could be identified for wheat variety classification purposes.

1.2 Study aims

The aim of this research was to identify a set of zones (holistically referred to as a division) that had low levels of environmental variance for quality traits important in variety classification and in total, numbered less than 7. A reduction in environmental variance would improve quality consistency, due to a more uniform expression of genotypic quality traits associated with variety classification. A lower number of zones used in the classification process would offer industry participants improved efficiencies due to the requirement for less testing.

To investigate that aim the following research steps were taken:

1. Create a relational database that could be used as the data transfer platform for all subsequent statistical analyses.
2. Determine whether significant genotype and environment interaction effects were observed on 8 wheat quality traits (the absence of a significant effect making analysis of the data assembled less complicated).
3. Identify a set of zones of the Australian wheat-belt that when holistically grouped together as a division had lower environmental variance compared with the existing set of classification zones. At the same time, it was important to also ensure that any set of zones making up a division were different to each other.

4. Valid the divisions identified using alternative data sets and assessment methods. In addition, the independence of fixed boundaries from seasonal variation was assessed. The analyses performed was an important validation process, however, since an independent data set was not available, this part of the research was referred to as crosschecking rather than validation per se.

Chapter 2 Literature review

As an applied piece of research, the literature review has focused on the five most important themes, viz., the criteria of quality, quality trait heritability, wheat variety classification, environmental division of the Australian wheat-belt and understanding genotype, environment and interaction effects on quality.

2.1 The criteria of quality

Wheat quality is a vague term because it does not identify which aspects of quality are important. These vary depending upon who is using the wheat (Nelson et al., 2006, Wrigley et al., 2006). A farmer, for instance, is interested in aspects that control the amount they will be paid. Australian farmers are paid on the basis of wheat protein, moisture, screening levels and soundness measurements. A high priority for a flour miller would be potential flour yield, although this would be balanced by their ability to meet their customer's quality specifications. Another perspective comes from different food manufacturers who each require specific flour functionality. The quality requirements of a noodle manufacturer are different to that of a baker and a biscuit maker. Therefore, wheat quality is more than just physical measurements. It incorporates the quality of wheat's secondary, tertiary and processed forms – flour, dough and end-products.

Understanding wheat quality is further complicated because of its complex inter-relationships. Moss (1983) discussed how one quality trait can influence other traits. Strong relationships, for example, have been reported between flour protein and bake volume, grain hardness and water absorption, Pelshenke time and maximum resistance (Bhatt and Derera, 1975, O'Brien and Ronalds, 1984, Eagles et al., 2002a). Variations in the strength of such relationships can be attributed to the combinations of varieties and environments studied.

Adding to the complexity of understanding wheat quality is the influence growing conditions have on the complex inter-relationships described by Moss (1983). Traits like protein level and grain size are largely determined by environmental factors (Simmonds, 1989). Other quality attributes like flour yield, dough strength and noodle texture are more genetically controlled (Morris, 1998), but their quality as

measured by empirical tests is a result of environmental influences on gene expression (Blumenthal et al., 1993, Wrigley, 2003). Consequently, care needs to be taken when using the term quality inter-relations as it can refer to different aspects of wheat quality.

Fortunately, the table of contents in wheat quality monographs provide an insight to how the discussion of quality has been structured (for example, Pomeranz, 1988a, b, Simmonds, 1989, Henry and Kettlewell, 1996, Cornell and Hoveling, 1998). It is divided into distinct areas, aligned to the orderly fashion in which quality measurements are made. Sequential measurements commence on wheat, as an unprocessed product, then the act of milling, and the subsequent tests on the processed mediums of flour, dough and end-products. The partition of tests into such categories has allowed for sensible reporting. When considered together, these 5 categories have been used in Australia to characterise an over all quality profile, from an individual variety to a grade of wheat.

The subsequent five sub-sections (Section 2.1.1 *Physical wheat measurements* through to Section 2.1.5 *End-product performance*) have focused on the quality tests commonly used in Australia to profile wheat quality.

2.1.1 Physical wheat measurements

Test weight, along with grain size, screenings and visual appearance, are all characteristics that are determined on unprocessed wheat. The tests are simple and quick (compared with flour, dough and end-product quality measurements) and are non-destructive in the sense that the wheat can be re-used after assessment. In Australia, these tests are key components of the testing regime performed at harvest to determine how a parcel of wheat will be segregated and stored.

Test weight is a measurement of bulk density. It reflects the weight of kernels relative to their size and grain packing capacity (AACC, 2006). It is a test that is globally used because despite being a simple and quick test, it provides a guide to flour milling yield potential. In Australia, the 74 kg/hl target has been used to

separate good and poor milling wheats for over 30 years (Whitwell and Sydenham, 1991, Cracknell and Williams, 2004).

Grain, or kernel weight, as the name suggests, is simply a measurement of weight – reflective of grain size and the potential amount of flour within the kernel. Several techniques have been developed, all relying on measuring the weight of a known number of individual grains to provide an estimated weight of a single kernel. The common technique used in Australia has involved the counting of 1,000 grains, weighing the total mass and then calculating an average grain weight; referred to as the thousand-kernel weight. The Single Kernel Characterisation System has also gained acceptance because, in addition to measuring grain weight, estimates of hardness, kernel length and width, and softness equivalent can be calculated (Gaines et al., 1996a). A limitation, though, of the Single Kernel Characterisation System is that it crushes the sample, not allowing re-use of the sample.

Screenings refers to the material unlikely to produce any meaningful amount of flour, whether that be small or broken grains, chaff or other material like weed seeds. The standard Australian sieve used to determine screenings has rectangular slots 2mm in width. Varying maximum levels of screenings apply to the various grades used for segregation (AWB Limited, 2006a). Historically, the method of determination involved the manual movement of the screen for a designated number of forwards and backwards motions, measuring the weight of the material having passed through the slots. The mechanical action of the Agtator is now today's objective method of determination (AWB Limited, 2000). Other sieve sizes and tolerances are used in other countries, such as the United States (US Department of Agriculture, 2004). High spring temperatures are most often associated with screenings due to 'crop haying off', but the susceptibility of certain varieties to screenings has been linked to genetic composition (Sharma and Anderson, 2004).

Frosts during the spring grain-filling period of wheat can cause both physical and visual damage. The timing of low temperatures during the reproductive phase and their severity causes shrivelling due to an imbalance in the way starch and proteins are deposited into the grain. The damage from a frost not only results in the production of small grains and high screenings, but also has an adverse effect on

protein quality and a negative visual impact. Severely frosted grains can appear blue-grey in appearance (Halverson and Zeleny, 1988).

The most common and also economically significant discolouration defect in Australia is that of black point. Black point is the presence of dark markings on the outer layers of the kernel, and such discolouration is perceived as unhygienic and any wheat having such a defect considered in some markets as not fit for human consumption. In many Middle Eastern countries, household consumers purchase their wheat from local markets and arrange for their own milling. To successfully sell wheat in such a market dynamic has meant that grain must be plump and bright in appearance, devoid of any visual defects like black point. Severe cases of black point have also been shown to penetrate into the endosperm, causing flour and resultant end-products to be of inferior quality (Lehmensiek et al., 2004). Managing market perception has been difficult since the actual mechanism for black point expression has only recently been clarified (Williamson, 2004). There was debate as to whether it was a caused by biological or metabolic events, with the latter now the favoured cause. There was always agreement, though, that moist, humid conditions during crop ripening were important in the development of black point and that varieties differed in their susceptibility to the defect (Williamson, 1997, Anderson et al., 2000).

Sound wheat is required for most food processes. Sprouting is the germination of grains prior to harvesting and results in unsound wheat. Sprouting occurs due to the occurrence of rain during ripening and harvest. Such rain leads to the development of the enzyme α-amylase that breaks down starch into sugars and this has negative impacts on parameters such as milling performance and end-products (Canadian International Grains Institute, 1982). Morris (1998) wrote that such is the "severity and frequency of sprouting" that considerable research has been devoted to the subject. Sprouting can be detected visually, but due to price differentials between milling and feed quality wheats, objective assessments are the preferred method to segregate grain (Dexter and Edwards, 1997). Objective harvest testing in Australia has been based on the Falling Number test that measures the consistency of a flour-

water slurry as it goes through a heating cycle. It is a viscosity measurement, which is then correlated with assays of the amount of α-amylase .

2.1.2 Flour milling

The milling performance of wheat is a critical assessment step because there are only a few wheat based food products not requiring the use of flour (Moss, 1971, Bayram, 2000, Celik et al., 2004). Flour millers have two goals. They want to extract as much flour as possible whilst being mindful of their customer's quality specifications (Meers, 1987, Dines and Armstrong, 2003). The straight, or full run, extraction rate is when all millstreams (breaks and rolls) are combined together. In contrast, patent flours are created when millstreams are selected, in order to achieve specific quality requirements, such as low ash or particular dough properties (Crosbie et al., 1998). Straight run extraction flours are associated with higher levels of contaminants like bran and ash relative to a patent flour (Southan et al., 2000). Therefore, milling performance is an assessment of the how much flour can be readily extracted from wheat and the quality of the flour produced.

To produce flour for quality evaluation, laboratory equipment and methods have been developed that utilise small quantities (<10kg). Such equipment and methods aim to replicate commercial milling practices (Table 1). A widely used piece of equipment is the Buhler laboratory mill due to its size and ability to produce high quality straight and patent flour (Cracknell and Watts, 2005). Smaller mills (for example, Quadrumat) have less capacity to separate bran and germ from flour, and cannot sieve the flour into different streams, restricting their use. Such smaller mills have been used to provide gross distinctions in potential milling performance, good versus bad, of early generation breeding material.

The milling methodology used influences the resultant quality of flour. Consequently, care needs to be taken in the manner in which wheat is milled irrespective of the equipment used. Conditioning is a preparation stage of milling. It is aimed at toughening the bran layer so it is less brittle and less likely to shatter during the milling process, reducing contamination due to bran particles. It also serves to make the endosperm more friable. Varying the amount of water added, and

or the time elapsed before milling, can change the quality of flour produced. Roll settings also change the quality of flour produced. Narrow settings produce excessive grinding force and increase the level of starch damage and consequently the flour water absorption level.

Table 1 Laboratory scale milling methods

Method Description	AACC Method
Experimental Milling: Temper Table	26-95
Experimental Milling: Batch Method for Durum Wheat	26-42
Experimental Milling: Batch Method for Soft Wheat	26-32
Experimental Milling: Bühler Method for Soft Wheat Straight-Grade Flour	26-31
Experimental Milling: Batch Method for Hard Wheat	26-22
Experimental Milling: Bühler Method for Durum Wheat	26-41
Experimental Milling: Bühler Method for Soft Wheat Short-Extraction Flour	26-30A
Experimental Milling: Bühler Method for Hard Wheat	26-21A
Brabender Quadrumat Jr. (Quadruplex) Method	26-50

Source (AACC, 2006)

2.1.3 Flour appearance tests

Internationally recognised tests and instruments are utilised in the measurement of flour appearance such as flour ash, Kent Jones colour grade, and colorimeters (Black and Panozzo, 2004) based on the definitions of colour by the Commission Internationale de l'Eclairage (CIE). However, agreement on what aspects of appearance should be tested, and how that be should done, has been problematical (Oliver et al., 1992). Despite diverging opinions, flour appearance can be acceptably divided into 2 components - the first is purity of the flour and the second is flour colour.

Contamination of flour from ash and bran particles has gained attention since they dull the flour's appearance. Ash is the term used to describe the mineral content of grain or flour and is concentrated in the outer layers of the kernel. The ash levels of wheat and flour ash do not generally exceed 1.6% and 0.5% by weight, respectively (Simmonds, 1989). The determination of ash involves incinerating a sample and weighing the resultant mass. In addition to dulling flour appearance, excessive levels of ash, and also bran particles, can lead to end-product speckiness and discolouration (Miskelly, 1998). The acceptability of such contamination varies by end-product.

Another assessment of flour purity, widely used in Australia, has been the Kent Jones test. The Kent Jones method is a reflectance measurement of flour-water slurry and is indicative of flour brightness and bran contamination. Some cereal chemists believe that such methods are outdated and outclassed (Oliver et al., 1992) but since many flour millers and processors still use flour ash as a specification, such tests will continue to be mainstream tests (Cracknell and Watts, 2005).

More recent approaches to measuring flour purity have been with the use of such instruments as Tristimulus colorimeters and Branscan®. Tristimulus colorimeter instruments use the CIE system that describes L* as a measure of black to white (0-100), a* as a measure of redness and greenness (+ve to -ve), and b* a measure of green-blue differences that is translated as yellowness and blueness (+ve to -ve) (Oliver et al., 1992). The L* measurement has been associated with flour purity, however its small range of readings suggest that it might not be discriminating, and that care needs be made in any determination of good and bad flour purity based on L* measurements alone. The Branscan® instrument was developed to discriminate between good and bad milling performance (Branscan, 2006). The calculation of a Milling Quality Index from Branscan® measurements allows for ranking estimates to be made between samples on the level of flour contamination (Southan et al., 2000) but this approach has yet to gain widespread industry adoption.

It might be questionable that Tristimulus colorimeters instruments can effectively discriminate flour purity, but such instruments have gained widespread usage for their measurement of flour and end-product colour (Mares and Campbell, 2001, Barber et al., 2002). Adoption has been driven by the easy access to instruments such as the Minolta Tri-Colour meter, and a better understanding of end-product colour requirements. Industry use of Minolta Tri-Colour meters now mean that for quality discerning processors, they can specify flour to be white, yellow or creamy along a graduated scale. Flour whiteness or yellowness is a key point of differentiation between good and bad quality flour. It results from a combination of genotype, environmental and testing method influences (Barber et al., 2002, Takata et al., 2002). The general preference is for white and bright flour because it is more

versatile across a range of end-products, however certain products, for example Japanese udon noodles, are best made from creamy coloured flour.

2.1.4 Dough properties

Wheat flour is unique because it can form a visco-elastic dough when mixed with water (Wrigley et al., 2006). The manner in which that dough is formed and its function is described as rheological behaviour. Hibberd and Parker (1975) described dough rheology as a deviation from the ideal elastic solid and viscous liquid properties, concluding that dough was a nonlinear viscoelastic material. To measure a nonlinear viscoelastic material, instruments need to provide information on the relationships between stress, strain, time taken for deformation to occur, and stress history. The key instruments used in Australia to characterise rheological behaviour have been the farinograph and extensograph. The former instrument is focused on mixing attributes, while the latter instrument focuses on dough handling properties. In other countries there is a preference for alternative instruments such as the alveograph in France and parts of Africa, and the mixograph in North America. Common to these different instruments is that tests are conducted on a 'dough piece' unlike chemical tests that have been used as alternatives in predicting dough properties.

A common feature of rheological tests has been that they are used to predict the functionality of the bread making process – without actually making a loaf of bread (Morris and Rose, 1996). The farinograph instrument measures the resistance of a dough piece against a constant mechanical shear force at a constant temperature. The characteristic curve represents a visual record of the flour's mixing behaviour profile such as strong or weak flour (Figure 1). The measurements of water absorption, dough development time, dough stability and softening are universally associated with the Farinograph (Shuey, 1975, AACC, 2006). For example, hard-grained wheats are associated with high water absorption levels and longer dough development times, attributes favoured for example in baking bread. In contrast, soft-grained wheats generally have low water absorption levels and short development times making them more suited to biscuit making. The actual capacity of flour to absorb water is influenced by the combined effects of grain hardness,

milling, damaged starch granules, pentosans and protein level (Simmonds, 1989). The farinograph has been the dominant piece of equipment used in Australia to determine water absorption. Newer enzymic tests of starch damage are gaining popularity as supplementary tests to water absorption measurements (T.Watts pers. comm., 2005).

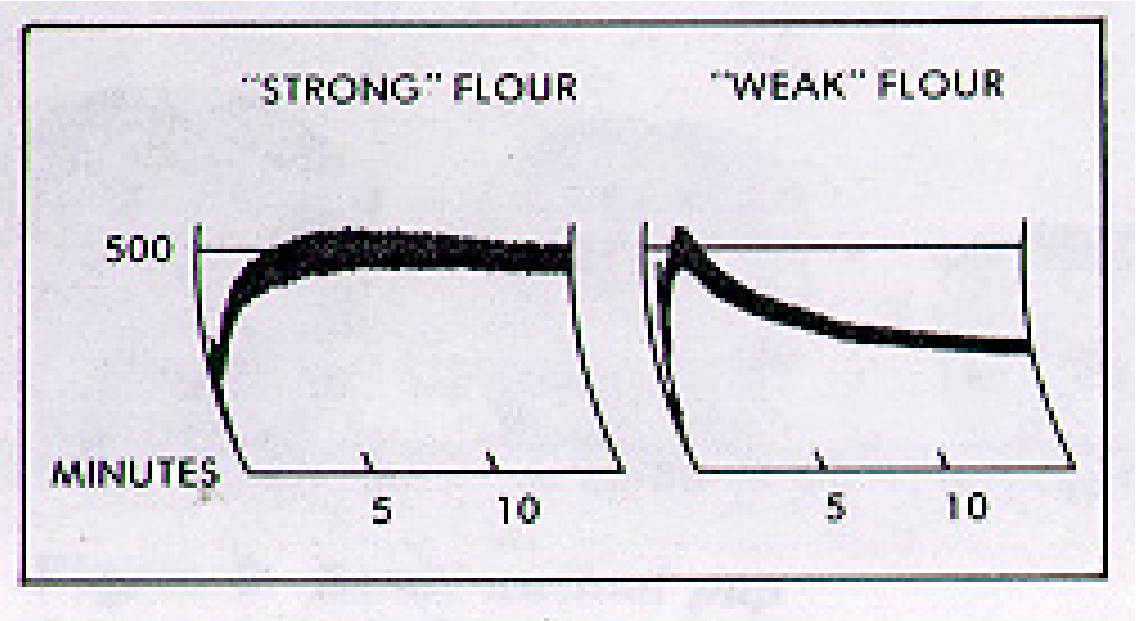


Figure 1 Farinograph traces showing the mixing profile of strong and weak flours
Source (Food Resource, 2007)

The extensograph instrument measures the stretching properties of a dough piece. Characteristic curves produce visual records of dough handling properties (Figure 2) and these can be easily used to distinguish between weak, strong and over-strong doughs. The terms extensibility, maximum resistance and energy or total force (measured as area under the curve) are the universally recognised measurements produced by the Extensograph (AACC, 2006). Considered together, measurements such as extensibility and maximum resistance provide an insight into whether a dough has 'balanced' properties – a key parameter for most end products (Cracknell and Williams, 2001) .

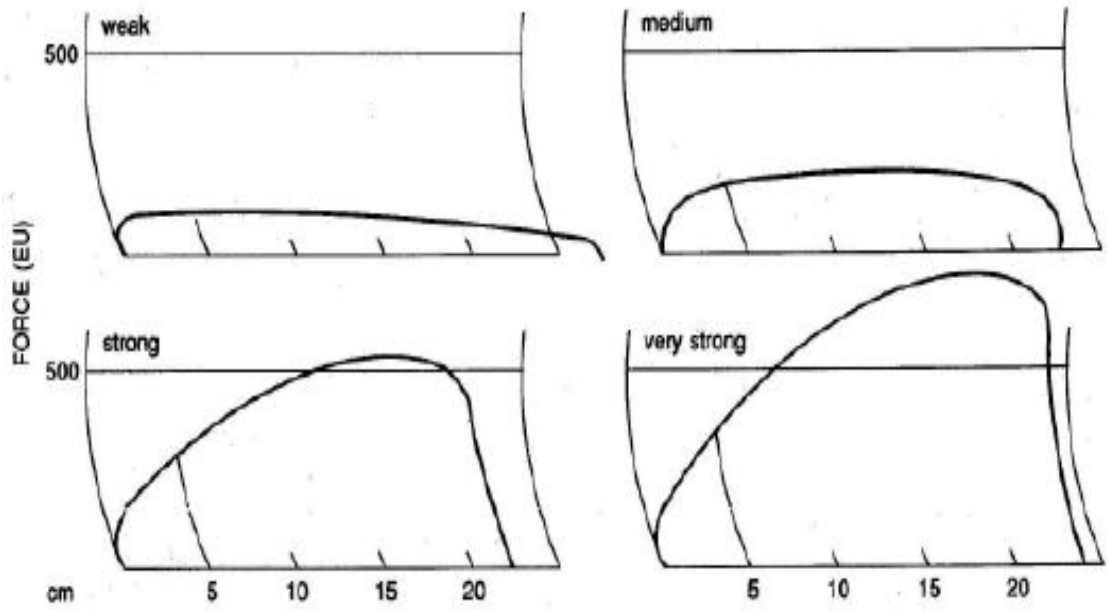


Figure 2 Extensograph traces illustrating different dough handling properties
Source US Department of Agriculture (2000)

Chemical tests have also been used to predict dough functionality based on their assessment of protein quality. Acidic sedimentation tests are popular in assessing protein functionality in Europe and the United Kingdom. The Zeleny sedimentation test is used as a rapid means of estimating baking quality. It relies on the relationship between flour baking strength and gluten hydration capacity, assumed as a function of gluten quantity and quality. It involves the suspension of flour in the weak acidic solution such as lactic acid, or sometimes isopropanol, in a graduated cylinder with the height of sediment measured after 5 minutes (Gooding and Davies, 1997, AWB Limited, 2005a, AACC, 2006). The sodium dodecyl sulphate (SDS) sedimentation volume test is used in the United Kingdom since it is considered to be a better predictor of baking quality compared with the Zeleny test (Gooding and Davies, 1997). The main difference between the two tests are the use of the SDS solution, rather than lactic acid or isopropanol, and a longer settling time for the SDS test.

The Pelshenke wheatmeal fermentation test is another method that has been used to estimate protein functionality (equating to dough properties). It involves making

dough balls from a wholemeal grist and yeast mixture then immersing the dough balls in water and measuring the time it takes for them to disintegrate. Generally, weak doughs disintegrate quickly, within 30 minutes, while over strong doughs may remain intact for over 400 minutes (Gooding and Davies, 1997).

2.1.5 End-product performance

MacRitchie et al. (1990) made the observation that the "proof is in the pudding". Despite that description the majority of quality measurements are predictive rather than end product test per se. Establishing links between quality measurements and end-product traits is challenging because there are many different end-products produced around the world from wheat flour, as distinct to pasta and couscous products made from durum (*Triticum turgidum* L.*)*. Considerable research, however, has focused on predicting end product performance since sufficient quantities of grain are only available late in the breeding cycle, when a breeding line is already homozygous (Crosbie, 1991). Simplistically, Germaine et al. (2004) grouped human consumption of wheat based foods into 6 broad groups (Table 2).

Table 2 Major wheat flour end-product groups

Product Groups	Biscuits	Breads *	Cakes*	Flat Breads	Noodles	Steamed Products
Style/Types	Cracker	Bulk fermentation	High ratio	Arabic	Yellow alkaline	Bread
	Sweet	Mechanical dough development	Low ratio	Baladi	Instant	Buns
		Rapid dough		Tanoor	White salted	
		Roller dough		Lavash		
		Sponge and Dough		Tortilla		

Breads and cakes* have been differentiated by process rather than end-product style
Adapted from Germaine et al. (2004)

Across the 6 broad groups there are sub-categories (Table 2), and these can in turn be further divided upon differences in appearance, texture, type of wheat, ingredients and or ethnic background. For example yellow alkaline noodles can be further divided into hokkien and ramen, while white salted noodle can be broken into udon and Chinese styles. These differences reflect varying protein level, grain hardness, flour colour, starch quality, dough strength and extensibility requirements specific to

each style that together form unique ethnic products of specific visual and eating quality (Miskelly, 1998).

In Australia, end-product assessments were traditionally restricted to Western pan style breads, biscuits and cakes (O'Brien and Blakeney, 1985). The use of varying methods by different laboratories though made the comparisons of results amongst laboratories problematic. In the case of pan style bread, as recently as 2005 and 2006, collaborative work has shown that changes are required to improve the consistency of baking results between laboratories in Australia (Cracknell and Watts, 2005, Watts et al., 2006).

The assessment of other end-products, such as noodles, steamed products and flat breads, have only been widely adopted in Australia over the last 10-15 years and has been driven by quality demands from major international markets using Australian wheat. Unfortunately, the prediction and rankings of such end products between laboratories has also been poor. An additional feature contributing to variation amongst laboratories for these newer end-products has been which aspects of quality to report, and how they should be measured. Additional challenges are that such end-products have local subtleties (even within a single country) and that subjective assessment of eating and appearance qualities are difficult to replicate.

2.1.6 Sources of testing error

With the exception of end-product tests, all other quality tests are trying to predict some subsequent processing trait. For example, test weight has been used to estimate flour yield potential, the farinograph used to predict dough mixing times in a bakery or starch viscosity to predict noodle eating quality. Irrespective of the prediction, the interpretation is only effective when the test results are accurate and precise. Some cereal chemists have suggested that quality measurements are plagued by unexplained error. Allen et al. (2000) discussed laboratory error, and its effect on the interpretation of extensograph measurements. The difficulty in separating sources of error, whether that be field or other effects, was noted by Pumpa et al (2002). Others have simply accepted that variability exists and must be accommodated in any final determination of quality (BRI Australia Limited, 1995).

Meanwhile, there is increasing reference to the use of experimental designs that aim to reduce sources of error (Smith et al., 2001, Mann et al., 2005, Kuchel et al., 2006).

Experimental design, in particular replication, would normally limit 'nuisance' effects (Stern et al., 2004). However, due to the large number of time consuming and expensive tests required for variety quality evaluation, process management has been used in laboratories instead of testing replicated samples. Quality control procedures have focused on ensuring consistent results have been generated for any given instrument. In terms of individual varieties, since testing is performed on composites instead of individual replicates, a substitute for replication has been the testing of that variety across multiple years. The combining of replicates into a single sample has been necessary, in order to make an adequately sized sample for milling and subsequent testing. A consequence has been that if variability was within expected guidelines, results were deemed satisfactory for use (BRI Australia Limited, 1995). Industry acquiescence to such protocols has resulted in limited publications on quality instrument error (Allen et al., 2000). The lack of publications on such an issue is probably related to laboratories not wanting to expose deficiencies though it is likely most laboratories maintain confidential performance records.

Another source of potential error comes from sampling (Williams, 2001). Such error can be attributed to the endemic variability of wheat as a natural product. Protein differences have been recorded across a single paddock, and even within a single spikelet of wheat (Parish, 1963, Bremmer and Rawson, 1978, Crosbie et al., 1995). A further example of natural variation is evident from the research undertaken by Wrigley and Baxter (1974) who determined the number of grains required to make a varietal identification of high probability. Another viewpoint in managing error was proposed by Smith et al. (2001) whereby statistical design could improve accuracy with respect to milling yield results. Regardless of the test in question, or solution proposed, there is common agreement that variability exists - it is just how best to manage that within the confines of each specific situation.

An excellent example of trying to manage variation comes from the classification of varieties in Australia. Watts and Cracknell (2004) described an accreditation program designed to provide surety of quality results for classification purposes. Their aim was to ensure that if results were being used for classification purposes then variety rankings would be the same, irrespective of the laboratory or specific test methods being reviewed. When they reported on the progress of their accreditation program, Cracknell and Watts (2005) found that when given specific guidelines, laboratories could produce results of equivalence, thus allowing results from different laboratories to used in the determining variety classifications. An alternative viewpoint has been to limit variation by restricting testing to a single laboratory (Robert, 1997). However, that can give the illusion of reducing error while increasing bias if the laboratory in question was an outlier in its prediction of quality traits relative to other laboratories. Since quality testing is not static due to adoption of evolving methods and new instruments, even laboratories reporting the quality of the same sample might not be in agreement. Therefore, an underlining consideration, when assessing results from different laboratories, is that they must be treated with caution, particularly if making direct comparisons on empirical values rather than relative rankings.

In other recent Australian collaborative studies, Mugford and Southan (2003) found that different laboratories could discriminate between good and bad quality milling wheats, but considerable variability existed in the level of flour extracted and its characteristics. That prompted the suggestion by Mugford and Southan (2003) that greater standardisation in milling procedures was required. Examination of farinograph and extensograph equipment and the reporting of water absorption, dough development time, extensibility, and maximum resistance were reported by Shepherd et al. (2000). They found that there was general agreement between different laboratories for these tests, but noted some laboratories were consistent outliers. Quail and Walker (1998) reported on bake tests and while equipment and methods were variable, Friedman rank tests indicated general agreement between the participating laboratories for loaf volume and loaf score, though they did comment on inconsistencies in some rank ordering and high standard deviations.

2.2 Quality trait heritability

When developing new varieties, breeders aim to target traits that have high heritability since these are more likely to deliver the desired outcomes as opposed to those with low heritability (Nyquist, 1991). Mayo (1987) defined heritability as "the proportion of the total variance of a character attributable to genetic as opposed to environmental factors". Falconer (1989) noted that 2 meanings of heritability existed and these have been referred to as broad and narrow sense heritability. The extent to which phenotypes are determined by the genotypes is referred to as the broad sense heritability. Narrow sense heritability reflects the extent to which phenotypes have been determined by genes transmitted from the parent. These estimates of heritability can be written in the following forms.

Broad sense heritability is $h^2 = \frac{V_G}{V_P}$ and Narrow sense heritability is $h^2 = \frac{V_A}{V_P}$

Where V_G = genotypic variance; V_P = phenotypic variance and V_A = additive genetic variance.

Since heritability can be estimated in different ways care needs to be taken when appraising results, particularly when different studies are compared. Mazumder et al. (2000) reviewed heritability estimates of milling yield and reported a divergence of findings. These were associated with differing heritability calculations and also the wheat variety populations studied. Studies of heterozygous variety populations generally had the same trends as homozygous populations, although the heritability estimates of the former were lower (Bhatt and Derera, 1975, O'Brien and Ronalds, 1987). Consideration of other quality traits examined by Australian researchers provides further examples of divergence, but importantly also the range of heritability estimated that can be found for a single quality trait (Table 3). Despite variations, the salient trends from those studies listed in Table 3 were that the heritability of grain hardness was higher than that of protein quality measurements and that in turn protein quality measurements were higher than protein level. These traits consequently became targets for breeders trying to improve quality. The variation of estimates seen in Table 3 also support the notion that results should be restricted to the material assessed (Fowler and de la Roche, 1975, Baenziger et al.,

1985, Peltonen-Sainio and Peltonen, 1993, van Lill et al., 1995a, Morris et al., 1997, Zhang et al., 2004).

Table 3 Australian estimates of quality trait heritability

Study	Quality traits studied and their heritability estimates	Method of estimation	Population studied
Bhatt and Derera (1975)	Test weight = 0.44 - 0.83 Flour yield = 0.67 – 0.87 Grain protein = 0.42 – 0.88 Flour protein =0.55 – 0.91 Baking score =0.46 – 0.65 Baking volume =0.46 – 0.65 Flour colour =0.54 – 0.87 Hardness =0.83 – 0.93	Reported a range of broad sense heritability estimates based on 6 trials of differing composition	Released varieties and relatively homozygous F_4 to F_8 lines
Pearson et al. (1981)	1000-kernel weight = 20-88[a] and 72[b] Pearling resistance= 79-90 [a] and 80[b] Grain protein = -ve to 42 [a] and 19 [b] Flour yield = -ve to 89 [a] and 57 [b] Pelshenke = 82-92 [a] and 80 [b]	Reported ranges of variance components and single narrow sense heritability estimates	F3 and their F4 progenies
Fischer et al. (1989)	Hardness = 77 Grain protein = 24 Flour yield = 18 Flour protein =- 21 SDS volume = 44 Pelshenke = 47	Reported single narrow sense heritability estimates	F1 derived progeny grown in F3 generation
O'Brien and Ronalds (1987)	Hardness = 68[c] and 71[d] Flour yield = 38[c] and 46[d] Water absorption = 70[c] and 81[d] Dough development time = 15[c] and 25[d] Dough breakdown = 30[c] and 32[d] Extensibility = 21[c] and 28[d] Maximum resistance = 65[c] and 65[d]	Reported single narrow sense heritability estimates for a pooled data sets of 7 crosses and 6 crosses	F3 and their F4 progenies
O'Brien et al. (1993)	Flour yield = 11 - 94 Flour ex bran = 7 - 83 TP mill yield = 15 - 92 Colour Grade = 20 - 93 Yellow Pigment = 64 - 88 Flour protein =27 - 72	Reported ranges of narrow sense heritability estimates	F2 and their F3 progenies
Eagles et al. (2002a)	Hardness =0.73 Flour yield = 0.66 Flour protein = 0.36 Water absorption = 0.71 Dough development time = 0.76 Extensibility = 0.52 Maximum resistance = 0.67	Reported single intra-class correlations estimates that are equivalent to broad sense heritabilities	F5 or subsequent inbred generations

[a] = variance component estimates
[b] = single narrow sense heritability estimates
[c] = pooled data sets of 7 crosses
[d] = pooled data sets of 6 crosses

Successful wheat breeders will release varieties that have a range of attributes, attractive to farmers and end users. While plausible, releasing a variety with a full complement of ideal agronomic and quality attributes has been difficult because such traits seem diametrically opposed (Brennan and O'Brien, 1991). Numerous

examples can be used to illustrate such a nexus. Herring et al. (2000) reported a detrimental linkage between flour yield and water absorption. They showed that while Australian milling yields had improved over time it was associated with an unfavourable lowering of water absorption levels. The incorporation of cereal cyst nematode resistance genes into new varieties is another example of a detrimental linkage. In some varieties, this agronomical beneficial gene has been associated with problematic small grain size and high screenings (R. Eastwood pers. comm., 2004). Achieving the many quality targets required of a udon noodle variety has meant there has been a lag in assembling a competitive package of quality attributes and agronomic performance compared with other varieties with less discriminating targets (G.B. Crosbie pers. comm., 2006). Recently, Kuchel et al. (2006) discussed the negative relationship between water absorption and dough strength. Therefore, breeders might focus on traits with high heritability but improvement is not always realised because of negative relationships with other traits, be that quality or agronomic.

2.2.1 Key genetic components defining quality interrelations

The results from quality trait heritability studies were important to breeders before the wide spread availability of molecular markers. Today, knowledge about which genes influence grain hardness, protein quality and starch mean that breeders and cereal chemist have a greater chance in successfully targeting a certain quality trait. That improved success is linked to the objective measurement of genes (Table 4) unlike heritability, which is determined from a calculation of estimates of genotypic and environmental factors. However, it is still recognised that the observed quality of such traits is a result of the influence of environmental conditions on the expression of those genes. A good, practical example has been the documentation of the link between protein quality and high spring temperatures (Blumenthal et al., 1993, Wrigley, 2003).

Table 4 Genes linked to the expression of grain hardness, protein and starch quality

Trait	Genes and their products	Gene products
Grain hardness	*Pina-D1* and *Pinb-D1*	Puroindoline a and b proteins
Protein quality	*Glu-A1*, *Glu-B1*, *Glu-D1*, *Glu-A3*, *Glu-B3*, and *Glu-D3*	High and low molecular weight glutenins
Starch quality	*Wx-A1*, *Wx-D1*, *Wx-B1*	Granule-bound-starch synthase and the production of amylose

Morris (1998) listed a table of quality related genes based on the Catalogue of Gene Symbols for Wheat as published by McIntosh *et al.* (1993). The catalogue has been updated (McIntosh et al., 2003) with supplements available from the Annual Wheat Newsletter (http://wheat.pw.usda.gov/ggpages/awn/) volumes 50 and 51

2.2.1.1 Grain hardness

Grain hardness continues to be used as a primary tool to segregate wheat (Canadian Grain Commission, 2003, US Wheat Associates, 2004, AWB Limited, 2005c). In addition, grain hardness attracts the attention of cereal chemists because of its influence on other quality traits (Simmonds, 1989). At a molecular level, it is unequivocal that hardness is linked to the *Pina-D1* and *Pinb-D1* genes, and varying allelic composition conferring different milling performance (Morris, 2002, Cane et al., 2004). Wheats that are hard-grained are considered free flowing due to the manner in which the endosperm fractures during the milling process (Simmonds, 1989). Conversely, wheats that are soft-grained produce particles of irregular shape that can choke the through-put of a flour mill due to their fluffiness (Ford and Kingswood, 1981, Simmonds, 1989). The differing fracturing patterns are related to the degree that starch granules are embedded in the protein matrix.

In addition to its effect on milling, grain hardness indirectly influences the amount of water that can be ultimately absorbed by the flour during processing. During milling, starch granules are damaged and this increases their water absorption capacity (Pomeranz, 1988b). Harder grained wheats have relatively more starch damage than softer grained wheats, and consequently hard-grained wheats generally have higher water absorption levels. The intertwined nature of wheat quality also means that protein level, in addition to grain hardness and starch damage, influences the realised water absorption level (Simmonds, 1989, Cornell and Hoveling, 1998).

The interest in the capacity of flour to absorb water relates to economics since water is cheaper than flour. For example, a baker wishes to use the minimal amount of flour to make a loaf of bread so bakers usually have a high, minimum flour water absorption specification. In contrast, biscuits are sold as dry products and considerable energy is required to evaporate the water during cooking. Therefore the biscuit manufacturer, from a cost perspective, wants flour with a low water absorption level. The final level of moisture in an end product (whether it be bread or a biscuit) influencing its shelf-life.

Measurement of grain hardness in Australia has focused on the Particle Size Index (PSI) concept developed by Symes (1965). The reference PSI measurement is obtained by grinding and sieving and converting the resultant data into a relative hardness index (AACC, 2006). Another test, the Single Kernel Characterisation System involves mechanical crushing, but in this instance it is assessing wheat hardness (sometime referred to as texture) by the force required to crush the wheat kernel. NIR calibrations (destructive and non-destructive) have also been developed that can quickly predict grain hardness, and for this reason they have been used as tools in breeding selection and segregation. The PSI value, and that of other hardness tests, is based on a linear scale. A single variety can have a range of PSI measurements but in relative terms a hard variety will always have PSI values that reflect harder measurements compared with those of a soft-grained variety.

2.2.1.2 Protein

Protein is a fundamental quality test of wheat, especially in Australia, since it forms the basis for payment to farmers. The term protein, however, is confusing because it does not distinguish between whether it is the level or quality that is of interest. Protein level is an estimation based on the amount of nitrogen present in the grain. The amount of nitrogen measured converted into protein by the equation %N x 5.7 (Tkachuk, 1969). The level of protein is strongly influenced by environmental and farmer management factors. The quality of protein, in contrast, is linked to genetic composition (Eagles et al., 2002a) and the how environment influences gene expression (Wrigley, 2003). Therefore, it is always important to recognise whether protein level or protein quality is being discussed.

The level of protein can be accurately measured by chemical and NIR methods. The chemical reference method for determining protein level is the measurement of nitrogen (AACC, 2006). Typically the Kjeldahl method was the reference method of choice, but recently alternative methods such as the Dumas process have gained international acceptance due to their accuracy and safety (Mugford and Fox, 1999, Oak and Dexter, 2006). NIR instruments have been calibrated against chemical reference determinations to allow for quick and accurate prediction of protein level (Williams, 2000).

A consequence of the ability to readily measure its level, protein is the most widely reported quality trait. Wheat protein is more often reported than flour protein, simply because a flour protein result requires the wheat to be milled. However, flour protein can be estimated from a wheat protein level, based on the fact that approximately 1% of the total protein of the grain will be lost in the bran and offal during milling (Baker et al., 1971, Fischer et al., 1989, van Lill et al., 1995b).

The protein level measured is dependant upon a range of environment factors including, but not restricted to, soil fertility and rainfall (Crosbie and Fisher, 1987). Other factors that stress the wheat plant, such as disease, competition from weeds and spring temperatures, plus root uptake efficiencies, can also affect the final protein level (Mason, 1987). The protein level of wheat varies from year to year, and within individual paddocks (Gartrell, 1990, Skerritt et al., 2002, Strong et al., 2003).

The quality of wheat protein is more difficult to assess than its level (Veraverbeke and Delcour, 2002). The complexity arises because, to assess protein quality, one needs to examine the amount and quality of gluten. A range of measurements are available from determination of the actual amount of gluten (AACC, 2006) through to the assessment of viscoelastic dough properties (see Section 2.1.4 *Dough properties*) and molecular measurement of amino acids groups. Irrespective of what is measured, inevitably protein quality is related to its functionality and end-product processing potential.

The task of assessing gluten quality is challenging since it is composed of 2 major storage protein fractions; glutenins and gliadins (Shuey, 1975, Shewry and Halford, 2003). Glutenins are associated with dough strength and have been estimated to account for 47% to 60% of variation in breadmaking qualities (Halverson and Zeleny, 1988). Gliadins are associated with dough extensibility and decreases in dough strength (Daniel and Triboi, 2000). Glutenins are considered to be more independent of environmental influences, since gliadins have been shown to have good correlations with protein level on which environmental factors have a major impact (Gras et al., 2001).

Advancements in the understanding and identification of high molecular weight and low molecular weight glutenin fractions have allowed today's breeders to use Mendelian genetics in selecting for specific dough properties. In genetic terms there are 3 chromosome sets for each molecular weight glutenin type. The high molecular weight glutenins are referred to as *Glu-A1, Glu-B1*, and *Glu-D1* loci and are located on the long arms of chromosomes 1A, 1B, and 1D, respectively. Genes coding for the low molecular weight glutenins, *Glu-A3, Glu-B3*, and *Glu-D3* loci, are on the short arms of the same chromosomes. Each locus has many different alleles that code for protein subunits (Gras et al., 2001, Eagles et al., 2002a). Gliadins have a heterogeneous composition and can be divided into 4 subgroups α-, β-, γ-, and ω-gliadins. The ratio of gliadins in wheat is reflective of environmental conditions on gene expression of the subgroups (Daniel and Triboi, 2000). The availability of nitrogen has been demonstrated to influence ultimate gluten properties (Johansson et al., 2004). Temperature during the grain-filling period is also known to affect dough functionality (Blumenthal et al., 1993) and more recently the identification of over expression of certain genes (Darlington et al., 2003, Vawser and Cornish, 2004).

The research examining the effect of elevated temperatures during the grain filling period on dough properties is expansive. Skylas et al (2002) described the elevated temperatures either as a few days with a maximum over 32^{o}C or a lengthy period in the range of 20-32^{o}C. Those specific temperature profiles have arisen from extensive research performed in Australia (Blumenthal et al., 1990, Randall and Moss, 1990, Blumenthal et al., 1991a, Blumenthal et al., 1991b, Blumenthal et al.,

1994, Stone and Nicolas, 1994, Blumenthal et al., 1995a, Blumenthal et al., 1995b, Stone and Nicolas, 1995, Stone et al., 1997, Stone and Nicolas, 1998a, b, Panozzo et al., 2001, Wardlaw et al., 2002) as well as in other growing environments around the world (Ciaffi et al., 1996, Corbellini et al., 1997, Corbellini et al., 1998, Daniel and Triboi, 2000, Altenbach et al., 2003, Rharrabti et al., 2003b, Zahedi et al., 2003).

2.2.1.3 Starch

Starch is the major component of wheat and has 2 forms, either as amylose or amylopectin, both of varying molecule size (Rahman et al., 2000). The ratio of these components influences a range of functional properties, including starch gelatinisation, pasting properties and end-product textural properties (Crosbie, 1991, Panozzo and Eagles, 1998). The biosynthesis of amylose is strongly influenced by granule-bound starch synthase, and this enzyme has been recognised as of critical importance to certain end-products like noodles (Crosbie et al., 1998).

Several tests have been used to assess starch quality. All have the common feature that they all employ heating and measurement of the gelatinisation process, but differ in the time taken to perform and relative cost, plus the location where the test is best performed. The Falling Number instrument has been successfully used in the assessment of sprouted wheat. Importantly in Australia, it has been used at country grain harvest facilities for a timely and objective verification of rainfall damage. The Rapid Visco Analyser (RVA), an Australian invention, was developed as a robust alternative to the Falling Number instrument for the conditions encountered during the hot summers of the wheat-belt (Elliott et al., 2000). However, the ability to alter the heating profile of the RVA has seen it gain greatest use as a quick and easy laboratory measurement of viscosity properties, instead of use at grain harvest facilities (Wrigley, 2000).

Large scale laboratory tests to determine starch quality are also available (such as the Amylograph or Viscogram), while the flour swelling volume (FSV) method has gained use in breeding evaluation (Crosbie, 1991). Some large scale tests require at least ¾ hour running time, while the FSV was developed to be an accurate predictor of inherent pasting performance using only a small sized sample, that could be performed quickly and on a wholemeal grist instead of flour. The FSV test has been

used in laboratories focusing on the development of wheats for udon noodles, such as at the Department of Agriculture and Food Western Australia and Western Wheat Quality Laboratory in Pullman Washington, United States of America (Crosbie et al., 1992, Morris et al., 1997).

Despite functional starch characteristics being recognised as important (Crosbie, 1991, Morris et al., 1997, Zhang and He, 2002, Graybosch et al., 2003) they have not been the subject of enduring examination such as grain hardness and protein parameters (Morell et al., 2006). The difference, possibly related to the fact that testing of starch quality beyond simple assessment of α-amylase to profile gelatinisation has only recently occurred. In addition, discriminating end-product tests (particularly noodles) have only recently emerged. Putting those aspects together, has allowed an understanding of starch functionality to develop. For example, Zhang et al. (2005) found RVA breakdown to be significantly correlated with viscoelasticity and smoothness of Chinese fresh white noodles. He et al. (2004) found that RVA Peak Viscosity was the only measurement to be significantly correlated with all the dry white Chinese noodle quality parameters they assessed. The correlations reported in these recent studies confirming earlier research on udon and ramen noodles (Crosbie, 1991, Crosbie et al., 1999).

2.2.2 Expression of genetically controlled traits

As discussed, certain gene combinations control grain hardness, protein, and starch quality, but the observed quality profile is the result of how those genes are expressed in the presence of certain environmental influences. High maximum temperatures during the grain filling period have been well documented in changing dough properties. Importantly, variations in quality profiles have been noted by the AWB National Pool Wheat Variety Classification Panel from year to year, but varieties have been consistently ranked for traits more genetically controlled (AWB National Pool Wheat Variety Classification Panel pers. comm., 2004-2006). The implication is that despite genetically controlled traits being influenced by environmental factors, they are still relatively independent of the environment when compared with protein level or grain size. Consequently, genetically controlled traits

have been used to determine a variety's quality performance, with those more linked to the environment used to categorise wheat for segregation purposes.

2.3 Wheat variety classification

Classification has been defined as the categorisation of varieties into a commercial type or style, recognisable for their milling performance, dough properties and end use capabilities (Williams and Cracknell, 2001). Major exporting countries of wheat around the world share a similar definition (Cracknell and Williams, 2004). The primary reason international wheat marketers classify varieties is to produce parcels of consistent quality, and this has become more important in an increasingly competitive global market (Martinez, 1997, Canadian Wheat Board and Canadian Grain Commission, 2005, Fritz, 2005). Classification can also serve as a price market signal where a hierarchical grade structure exists, as it does in Australia, and as an adjunct it can determine quality targets for wheat breeders (Lambe et al., 2003).

2.3.1 General philosophy of classification processes

Classification procedures are primarily focused on genetically inherited quality traits. They also accommodate the fact that quality attributes are influenced by environmental factors such as soil fertility, ambient temperature, solar radiation and rainfall. Collectively, these make the classification process complicated and time consuming. Consequently, decisions require the professional judgement of those able to balance the factors causing quality variability, something that could not be achieved via a formula-based approach. The message of Cauvain (2005) was that cereal chemists required intuition to understand the complex quality of wheat since no results truly predicted ultimate processing performance.

The use of control varieties is a common practise by those making classification decisions. The process involves the comparison of the potential variety with an existing variety(s) of known quality to determine what grade the new variety should be given (Cracknell and Williams, 2004). Fowler and de la Roche (1975) made a similar observation when they commented that "quality classes should be defined in terms of representative control varieties". The advantage of control varieties has been that their known quality performance could be used to measure the relative

performance of potential material, regardless of year to year differences; for example environmental influences causing variation in protein levels. The actual specifics of classification process vary from the formal but pragmatic and market-driven approach taken in Australia, to the free-market appraisal system in the United States, to the formal process in Canada governed by both the Canada Grain Act and Seeds Act and Regulations (Canadian Food Inspection Agency, 2000).

2.3.1.1 Variety classification in Australia

The major buyers, and hence classifiers of wheat in Australia, AWB Limited and the domestic flour milling industry have strict protocols with respect to obtaining a classification. The requirements focus on the provision of multiple years of quality data for an extensive set of tests (AWB Limited, 2005a). The classification process involves the comparison of a new variety's quality profile against control varieties. The comparison against control varieties grown at the same location recognises the possible environmental influences on wheat quality and that empirical values will not be the same from year to year. Those making the classification decision also acknowledge a distinction between quality measurements, with some parameters considered essential and which cannot be compromised (Cracknell and Williams, 2004). Deficiencies for less important attributes can be accommodated, provided that they do not have a negative influence on the final quality profile and this may be because they are compensated for by other beneficial attributes. The classification process establishes for which quality grades a new variety is eligible. AWB Limited has 7 major grades, all of which have different quality profiles to each other, and in some cases there are differences within a grade such as AWB Noodle wheat (AWB Limited, 2004, 2005c)

The classification decision has become critical in the pursuit of consistent quality since current technology does not allow for quick and accurate assessment at harvest of genetically controlled quality traits like milling performance, flour and dough properties, and end-product suitability. Instead, a statutory variety declaration system is used to link the inherent processing quality of the variety (the classification decision) with its allocation to a specific quality grade. Farmers make their statutory declaration when grain is delivered, establishing the grade for which the delivery

might be eligible. Actual grade is determined by assessment of a sample taken at receival versus sets of receival standards for each grade.

The grades of Australian wheat are valued according to their quality profile, with Prime Hard having the highest dollar value of the hard grain wheat grades. The actually differential between grades though varies upon prevailing local and international supply and demand (Table 5). To complete appropriate segregation, and payment of wheat in Australia, the final step involves measurements of physical quality traits. Such measurements determine how a delivery is segregated, and in addition to ensuring the delivery is stored with deliveries of similar quality farmers are paid directly upon protein level, screenings, and moisture content. It is the combination of variety classification, statutory declaration and harvest testing of physical quality traits that underpin Australia's capacity to delivery parcels of wheat to customers according to their quality expectations.

Table 5 Example of pricing differentials of some Australian wheat grades

Australian wheat grades	Price differential ($/tonne)	Quality comments about wheat grades
Prime Hard (13% protein minimum for segregation purposes)	+28	The top quality Australian milling wheat, used to produce premium quality Chinese style yellow alkaline noodles and Japanese Ramen noodles, as well as being suitable for the production of high protein, high volume breads
Hard (11.5% protein minimum for segregation purposes)	+9	Specific hard-grained white wheat varieties selected for superior milling performance and excellent dough quality, ideally suited to the production of a wide range of baked products including European style pan and hearth breads, Middle Eastern flat breads and Chinese steamed products such as Mantou and Pao, as well as Chinese style yellow alkaline noodles
Premium White (10% protein minimum for segregation purposes)	Base	A unique, multi-purpose mid-protein blend of hard-grained white varieties that can be used to produce a range of Asian noodles, including Hokkien, instant and fresh noodles, Middle Eastern and Indian style breads and Chinese steamed bread
Standard White	-14	Versatile medium to low protein mixed hardness white wheat representing excellent value for straight milling or blending purposes
General Purpose	-19	Non-specific hardness and protein wheat blend with physical defects. Depending upon quality will be used in either human or animal processes
Feed	-53	Primarily weather damage segregation, also covering the maximum limits for other defects. Used mainly in animal or industrial processes.

Source (AWB Limited, 2006b)

The dependence of the current system on statutory variety declarations seems entrenched. Predictive NIR technology has been used to develop whole grain calibrations for traits such as flour yield, water absorption and dough rheology features and these have been used in early breeding generation selection (Crosbie, 2005). The application of such technology is limited to assessment of breeding lines since calibrations are unlikely to be adaptable for geographically widespread use during harvest (G.B. Crosbie and W. Lambe pers. comm., 2005). Consequently, segregation of Australian wheat at harvest into distinct quality grades is likely to remain reliant on variety classification decisions and statutory declarations to determine potential processing profiles.

2.3.1.2 Variety classification procedures in other wheat producing countries

In contrast to the Australian situation, the system of classification in the United States has been conducted in a less formal way. Wheat Quality Councils are funded by the various State Wheat Commissions to consider potential varieties. Four main regional laboratories of the US Department of Agriculture, 1 located in each of the main production class areas, generate results. In addition, flour millers perform their own testing as a basis for their subsequent buying strategies, as do private breeding companies (Cracknell and Williams, 2004). While this may appear similar to the Australian process, the final decision as to whether a variety is released is much more in the hands of its institutional owner. An important distinction to the Australian system is that US recommendations committees are institutional not statutory. The result is that there have been 2 distinct release procedures in the United States and these have been related to whether breeding was publicly funded, or conducted via closed loop private arrangements (Lin and Vocke, 2004).

The Canadian variety registration system, by comparison, has been a formal, fee-based process, coordinated by the Variety Registration Office. Potential varieties are registered before evaluation is undertaken by separate recommending committees examining morphological, pathologic, agronomic, physiological, biochemical characteristics and kernel information. The significant difference to the process employed in Australia is that all nominated quality parameters must be at least matched by a potential variety. In addition, the Canadians have required each of their wheat classes to look different, referred to as ‘kernel visual distinguishability’.

Until recently this was another requirement to which any new variety must adhere, but this has now been restricted to the Canadian Western Red Spring and Canadian Amber Durum classes (Canadian Grain Commission, 2005). While the tight release requirements were aimed at delivering consistent quality, speculation abounds as to whether the combination of unwavering quality specifications and 'kernel visual distinguishability' has held back advancements in agronomic and quality performance of the Canadian wheat varieties (D.B. Fowler pers.comm., 2002).

2.3.2 Variety classification boundaries in Australia

Australia currently has 7 classification regions (Figure 3). The regions are divided along state boundaries with the exception of New South Wales. In New South Wales, 3 regions (the northern, central and southern regions) are recognised reflecting divisions of least cost freight pathways and environmental effects. The focus of classification regions on individual states is a consequence of the manner in which wheat varieties were traditionally bred by state Departments of Agriculture and universities (O'Brien, 2004) and reinforced when AWB Limited, through a consolidation process in 1999, removed within state divisions (Table 6).

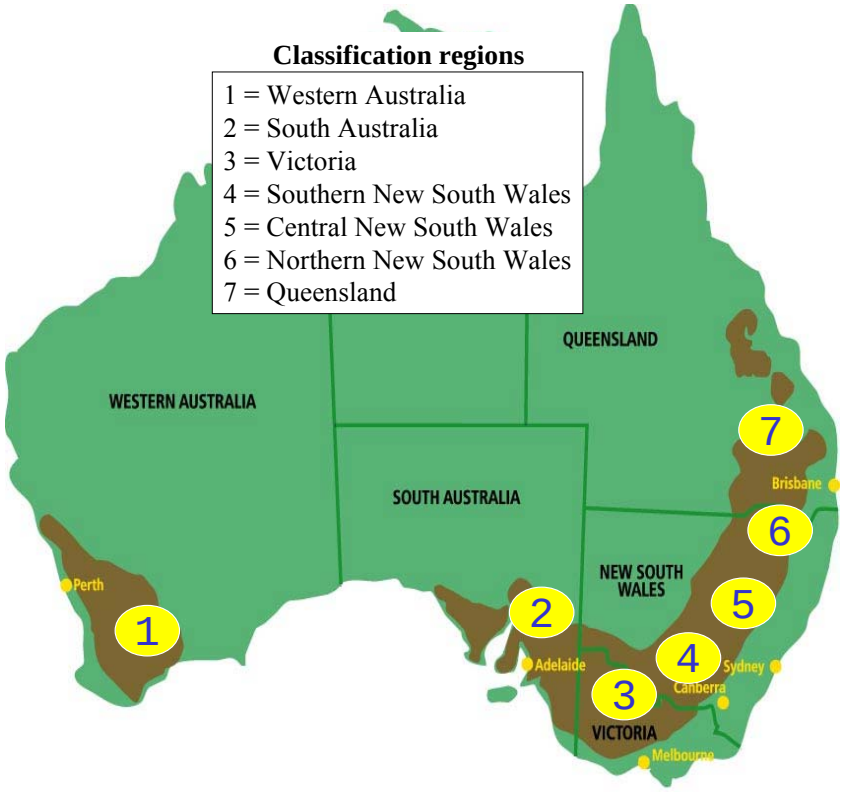


Figure 3 Current Australian wheat variety classification regions

From a historical perspective, the number of zones used by industry participants to divide the wheat-belt has been considerably more than today. Different terminologies have also been used to describe such divisions. In 1946, the NSW Department of Agriculture divided NSW into 22 wheat zones for recommendation purposes (NSW Department of Agriculture, 1946). Today, the same style of information is presented to farmers for 3 silo groups (McRae et al., 2004). Other state Departments of Agriculture around Australia publish similar information on a recommendation zone basis, or an equivalent term, that is used by farmers in management of wheat production on their farms.

Table 6 Silo groups or zones used by AWB Limited for variety classification purposes

Harvest	States				
	Queensland	New South Wales	Victoria	South Australia	Western Australia
1990/91	1	1, 2, 3, 4, 5, 6	A, B, C, D, E	1,2 3,4, 6	A, B, C
1991/92	1	1, 2, 3, 4, 5, 6	A, B, C, D, E	1,2 3,4, 6	A, B, C
1992/93	1	1, 2, 3, 4, 5, 6	A, B, C, D, E	1,2 3,4, 6	A, B, C
1993/94	1	1, 2, 3, 4, 5, 6	A, B, C, D, E	1,2 3,4, 6, 7	A, B, C
1994/95	1	1, 2, 3, 4, 5, 6	A, B, C, D, E	1,2,3,4, 7	A, B, C
1995/96	1	1, 2, 3, 4, 5, 6	A, B, C, D, E	1,2,3,4, 7	A, B, C
1996/97	1	N.NSW and S.NSW	A, B, C, D, E	1,2,3,4, 7	A, B, C
1997/98	1	N.NSW and S.NSW	A, B, C, D, E	1,2,3,4, 7	A, B, C
1998/99	1	N.NSW and S.NSW	A, B, C, D, E	1,2,3,4, 7	A, B, C
1999/00	Queensland	N.NSW and S.NSW	Victoria	South Australia	Western Australia
2000/01	Queensland	N.NSW and S.NSW	Victoria	South Australia	Western Australia
2001/02	Queensland	N.NSW and S.NSW	Victoria	South Australia	Western Australia
2002/03	Queensland	N.NSW and S.NSW	Victoria	South Australia	Western Australia
2003/04	Queensland	N.NSW, C.NSW and S.NSW	Victoria	South Australia	Western Australia

Source: AWB Limited Wheat Receival Standards 1990-2003

Division of the wheat-belt has also been used for variety classification purposes. Initially, Australia's major quality classifier of wheat varieties, AWB Limited (then the Australian Wheat Board) used the Department of Agriculture recommendation zones when variety classification was introduced in 1980 (Whitwell and Sydenham,

1991). That situation continued until AWB Limited consolidated the variety classification regions used in 1999 (Table 6). Examples have been presented to illustrate that variety classification regions mimicked departmental recommendation zones.

In 1995, the then NSW Standing Advisory Committee on Wheat recommended to the NSW Minister for Agriculture that 2 silo groups be created, replacing the existing 6 groups (NSW Department of Agriculture, 1995). The rationale reported by Gammie (1995) included:

- Deregulation of the domestic wheat market
- Grain handling system privatisations
- List of approved varieties (in 1983 Banks was the most popular state wide variety at 26% of sowings [and this had decreased by each silo group to a range from 0.15% to a high of 3.63% in 1993)
- Grain proteins, and some large declines
- On farm agronomy practices – rotations
- Willingness of producers to respond to market signals

Having identified various change impetus, coupled with a desire to ensure that future NSW wheat production was of a quality demanded by customers, the 'North' and 'South' silo groups were introduced for the 1996/97 harvest. While the recommendation was intended for the Minister of Agriculture in NSW, the same zones were concurrently adopted by AWB Limited for its classification of varieties (Table 6).

An overriding consideration on where the division between 'North' and 'South' was placed, as outlined by Gammie (1995), were storage and segregation issues. The boundary was located along the division between wheat moving into an exportable position at the ports of Newcastle and Port Kembla. In retrospect, the division ignored genotype and environment effects on quality, and was a move away from the Department's traditional recommendation zone philosophy. More recently, representatives from NSW Agriculture, farmer lobby groups and AWB Limited have reassessed the divisions of New South Wales and are recommending that all industry

participants adopt 3 regions for variety classification purposes in that state (McRae et al., 2004). The boundaries of the new zone reflect what is thought to be appropriate from a production perspective, rather than solely a logistical one. For other wheat production regions in Australia, similar industry advisory committees in the past have made decisions on where recommendation boundaries should be placed (Parish, 1965, McCann and Mullaly, 1971, Parish and Jones, 1971).

In Victoria, the recommendation given by McCann and Mullaly (1971) to the state's Wheat Advisory Committee was based on a review of protein levels balanced by a desire to take into consideration agronomic performance and market requirements. Seven zones were consequently adopted for wheat variety recommendations purposes. The same number are still in use today for agronomic and disease recommendations (Eastwood, 2003). From a classification perspective however, Victoria is now considered a single region, ignoring the various sub-environments previously identified, irrespective of any changes that may have occurred over the ensuing 30-year period.

In Western Australia, a similar story has evolved to that in Victoria. Protein level performance was the focus of a number of reviews (Parish, 1965, Parish and Jones, 1971, Toms and Parish, 1971, Crosbie and Fisher, 1987). The consensus of those reviews was that Western Australian wheat production could be divided into zones based on average protein levels. Parish (1965) made the observation that these protein zones were closely matched to both rainfall and soil distributions. Incorporation of multiple factors were used when the latest iteration, the Agzones, were created for recommendation purposes. These Agzones reflect differences in rainfall, length of growing season, and crop performance (Department of Agriculture Western Australia, 2004). Needless to say, the boundaries identified in protein reviews conducted 20-30 years ago bear striking similarities to the current Agzone boundaries (Figure 4). Despite what appear to be very appropriate divisions in the way they account for environment influences, like in Victoria, the Agzones have been ignored from a variety classification perspective with Western Australia considered a single classification region.

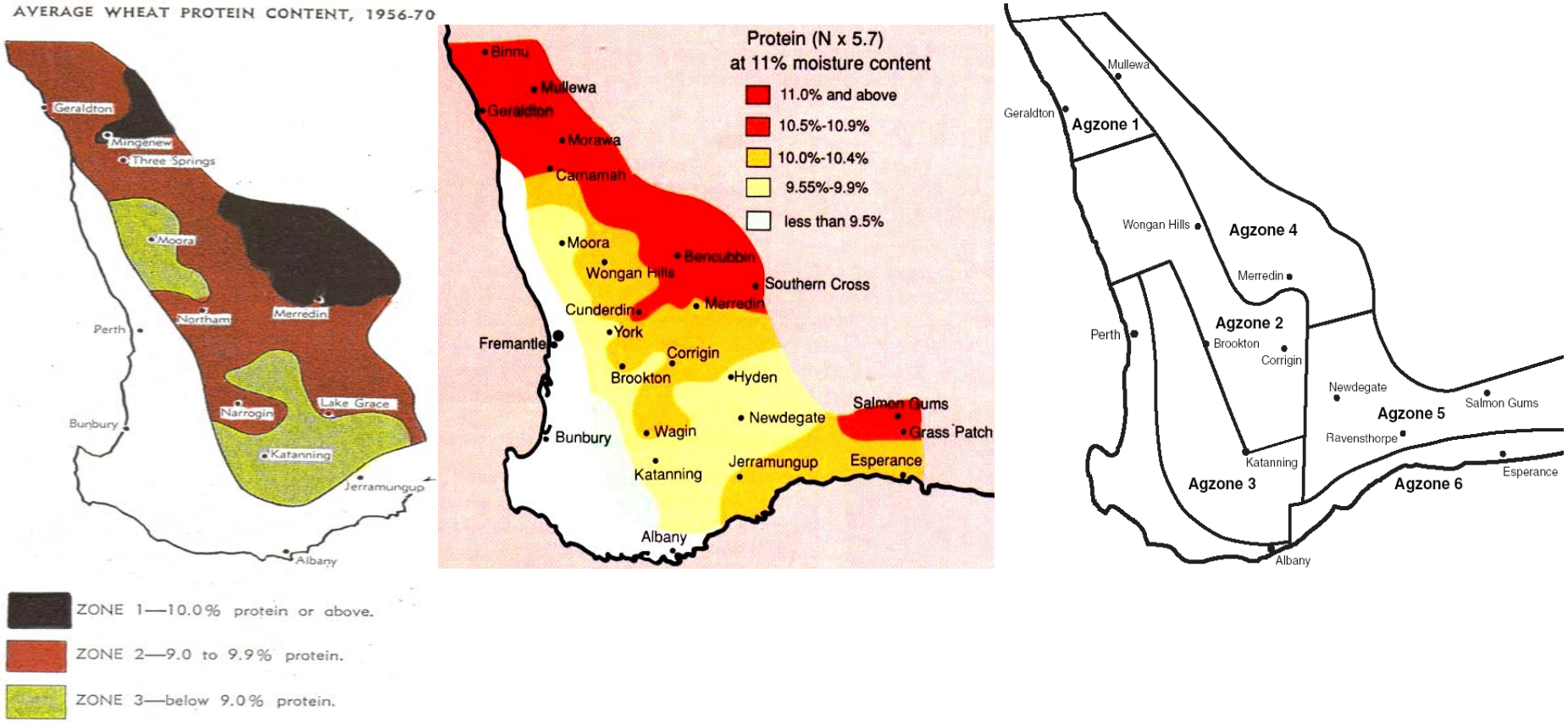


Figure 4 Division of the wheat-growing region of Western Australia

Left Toms and Parish (1971); Middle Crosbie and Fisher (1987); Right Department of Agriculture (2004)

2.3.3 Brief history of Australian wheat breeding

Historically, wheat breeding in Australia was a non-commercial endeavour, largely conducted by the public sector (O'Brien, 2004). Activity was centred around 8 regional Departments of Agriculture and University programs that focused on their immediate geographical region (O'Brien and Blakeney, 1985). The programs were essentially independent, but maintained strong but informal collaborative arrangements.

The structure of the sector changed when the Grains Research and Development Corporation (GRDC) commenced investment rationalisation late in the 1990's. GRDC considered change was required because there were too many programs, with general inefficiencies and state borders hindering cooperation and progress. In April 2001 GRDC announced completion of their first stage of restructure with a statement about the creation by GRDC and its partners of Australian Grain Technologies Pty Ltd, Enterprise Grains Australia, and SunPrime Seeds Pty Ltd (GRDC, 2002). Private companies such as LongReach Plant Breeders and Grain Biotechnology Australia had been created prior to this time (Lindner, 2004). The new commercial focus of the breeding sector was hoped to result in greater responsiveness, with participants having a national outlook, efficient cultures and strong linkages to international programs, and critically an ability to release varieties faster. Importantly, GRDC considered they would get 'better bang for their buck' through investments in fewer programs (Williams, 2005).

The impetus created by GRDC has seen continued fluidity in the breeding sector. For example, SunPrime Seeds Pty Ltd is now a wholly owned subsidiary of Australian Grain Technologies. The Department of Agriculture and Food Western Australia withdrew from Enterprise Grains Australia, while Grain Biotechnology Australia has dissolved. It is expected that change in the sector will continue until a balance is struck between the number of participants and their economic viability.

2.4 Environmental divisions of the wheat-belt

Given the growing conditions endured, the harvest of grain suitable for food processing is an impressive accomplishment. From germination through to grain

ripening and maturity, there is exposure to various environmental factors. Not enough rain early in the season could result in the seed struggling to germinate. If the seed was sown too deep, irrespective of available moisture, the seedling might not be able to reach and breakthrough the soil surface before its stored energy reserves expire. For a seedling to grow into a plant it requires further rain, more nutrients and protection from a host of diseases and competition with weeds. The occurrence of frost during the transition from vegetative to reproductive phase can be devastating. Similarly, rainfall at maturity can activate α-amylase, rendering the harvested wheat not suitable for most human food uses. The focus of this section in the literature review is on environmental factors that have been categorised for the entire Australian wheat-belt and have potential influence on wheat quality. The discussion will be limited to rainfall, temperature, soil type and agro-ecological regions.

Before discussing those environmental factors, the following description of Australia taken from the National Land and Water Resources Audit (2001) provides useful background regarding the environment where wheat is grown.

> "The continent is broad and flat with few hills and basins. Its low average elevation and relief (rarely greater than 1600 metres and the lowest of any continent) is partly due to the absence of volcanic and tectonic activity in recent geological time and to prolonged wind and water erosion. The Great Dividing Range, located inland from the eastern seaboard provides the main upland topographic relief and alpine areas. Australia has few major rivers or fresh water bodies. Most rivers flow irregularly (due to rainfall variability) and slowly (because of low topographic relief). Some drain inland and eventually evaporate, while coastal rivers in steeper terrain can drain rapidly to marine environments. Water yields from run-off are usually very low… enormous stores of salt characterise Australian landscapes… It has extreme variations in climatic conditions covering tropical, subtropical, desert, temperate, Mediterranean and subalpine climates".

Despite these apparent challenges, wheat is grown in a continuous coastal oriented arc from Western Australia through to Queensland (Figure 5).

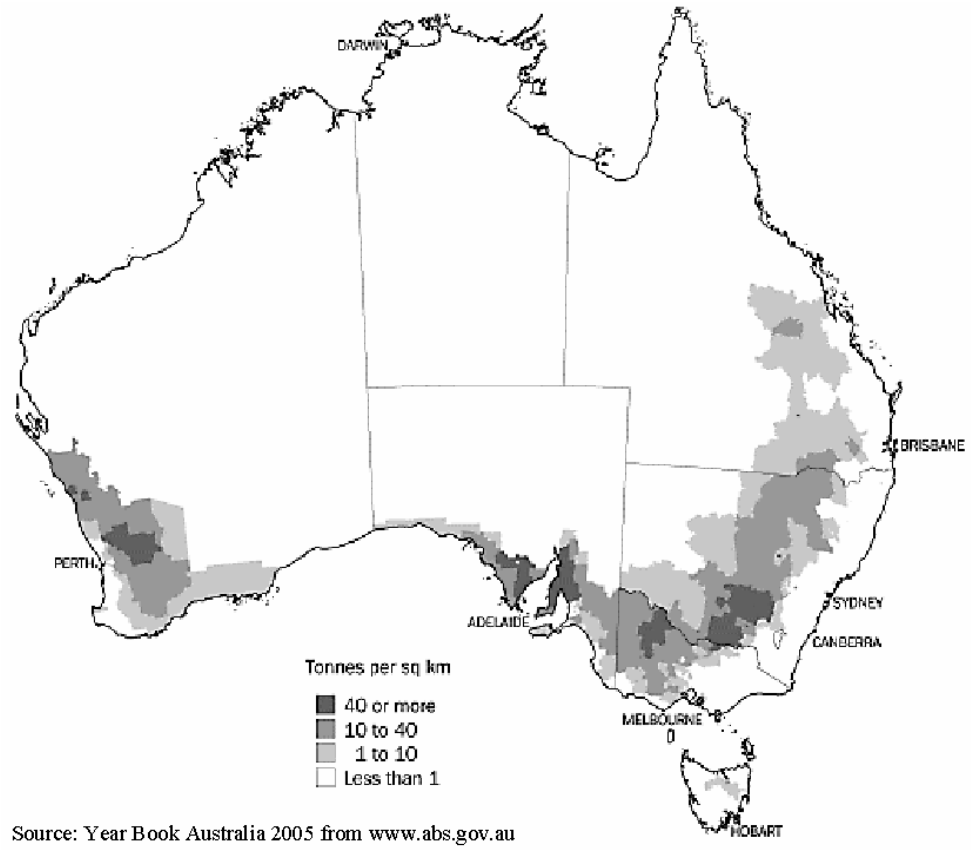


Figure 5 The Australian wheat-belt

Throughout the wheat-belt different sub-environments exist, as does variety adaptation to those environments. For example, farmers manage the effect of frost through the choice of variety and its associated maturity (P. Martin pers. comm., 2005). The maturity of the variety determining at what growth stage the plant will be when possible frost events might occur. From a quality perspective a critical period in the growth cycle of the plant has been referred to as the 'flowering window' (Setter and Carlton, 2000). The 'flowering window' of wheat in Australia commonly occurs during the spring of each year, though actual timing differs for each variety and sub-region. Following the 'flowering window', grain filling occurs and this period has also been shown to have a major effect on wheat quality (Randall and Moss, 1990, Wrigley et al., 1994, Panozzo and Eagles, 1999).

2.4.1 Rainfall

Water is considered one of the major limiting factors on the production of wheat in Australia since it is rated as the driest continent (National Land and Water Resources

Audit, 2001). The amount of rainfall across the wheat-belt varies considerably, with a range from <300 to >600mm, and this influences the proximity of the wheat-belt to the coast. The amount of water may be restrictive but of significance is when rain falls during the 'growing season' and its timeliness. Based on the seasonal rainfall zones published by the Bureau of Meteorology (2005) the wheat-belt can be divided into dominant patterns of either winter dominant, winter, uniform or summer rainfall (Figure 6).

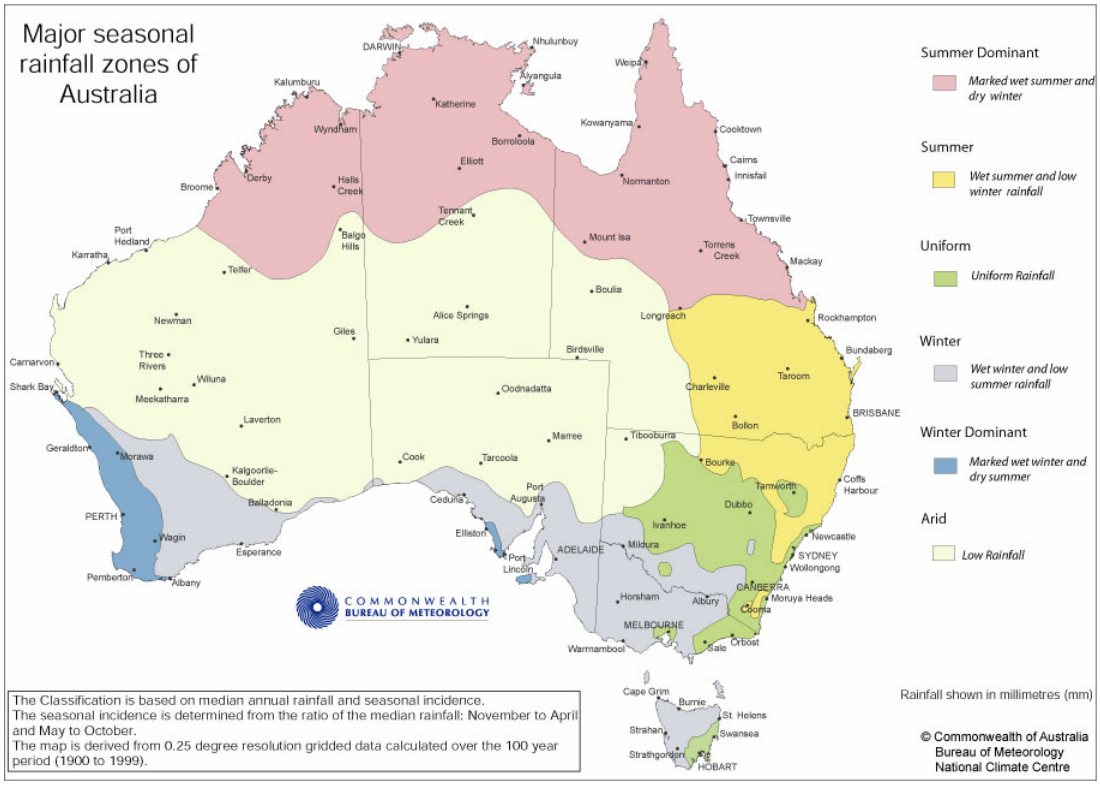


Figure 6 Major seasonal rainfall zones of Australia

The amount and timing of rainfall have a direct impact on the growing plant (French and Schultz, 1984). For example, the moisture retention capacity of soils in Queensland and northern New South Wales has meant that wheat crops can be successfully harvested with the plants surviving on moisture from the previous summer. In contrast, water stress has been shown to have a negative impact on quality by increasing screening levels (Sharma and Anderson, 2004). Winter and summer rainfall patterns also impose different disease pressures. O'Brien et al. (2001) discussed the relationship between disease burden and rainfall patterns. *Septoria tritici* blotch does not develop in the relatively dry and warm winters of the northern wheat-belt, however, it can thrive in the colder and wetter conditions of the

southern wheat-belt. Conversely, high spring temperatures and an increased likelihood of rainfall in the northern wheat-belt are ideal conditions for wheat stem rust.

Compounding Australia's limited water availability is its rating for high year to year rainfall variability (National Land and Water Resources Audit, 2001). Opportunely, while rainfall is variable, the capacity to predict it has improved with greater understanding of currents and water temperatures of the Pacific, Indian and Southern oceans. The most recognised relationship is that of El Nino, measured by the Southern Oscillation index of the Pacific Ocean (National Land and Water Resources Audit, 2001).

Actual and predicted rainfall data on a daily, monthly and yearly basis are available for locations through-out Australia from several sources such as the Bureau of Meteorology, SILO (SILO, 2006) and trial providers. In addition, long-term average rainfall pattern maps are also published covering time periods, spanning 30 to 100 years (Bureau of Meteorology, 2005).

2.4.2 Temperature

Temperature during the growth cycle of wheat has a critical effect on grain yield and quality. Specifically, elevated temperatures have been related to changes in dough properties (Blumenthal et al., 1993, Skylas et al., 2002) and the production of grains with reduced weight (Wardlaw et al., 2002) and the likelihood of higher screening levels. Nix (1975) also discussed the importance of solar radiation, since the wheat crop was regarded as a conversion system of solar energy. Temperature has been a basic recording at all Bureau of Meteorology stations, but unfortunately solar radiation has not been routinely recorded either at these locations or at wheat trial sites. However, the Bureau of Meteorology has produced maps of the average hours of daily sunshine, based upon approximately 90 stations for which they had at least 15 years of records. Such maps of maximum temperature and hours of sunshine (Bureau of Meteorology, 2005) show the same trends and that is for Australia to be divided along east-west gradients with cooler zones in the south and hotter zones in the north (Figure 7).

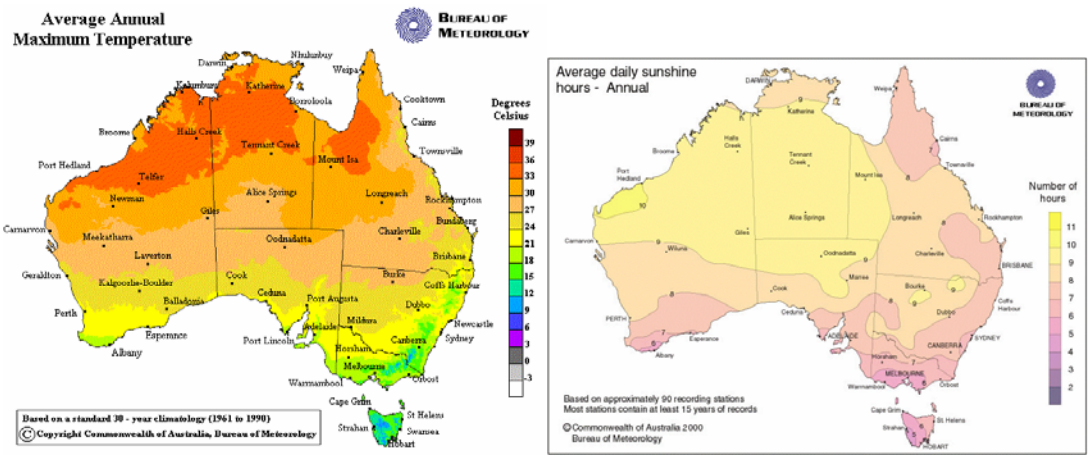


Figure 7 Annual average maximum temperature (left) and daily hours of sunshine (right)

Like rainfall, actual and predicted temperature records are available for locations across the wheat-belt. Alternatively, the Bureau of Meteorology (2005) has published maps of long-term averages and monthly temperature profiles.

2.4.3 Soil

The soils across the Australian wheat-belt vary considerably. The significance of that is that soil type influences the quality and quantity of wheat produced. However, best farm management practises can equalise most inherent soil differences and such a perspective is not new. McGarity (1975) considered it was possible to grow wheat on soils with any deficiencies since they could be offset by agronomic management, provided that water and solar radiation were not limiting. The capacity of management to neutralise the influence of soil suggests that it might not be an effective environmental basis upon which to consider wheat quality. An added inefficiency is that management practices differ from farm to farm, and for this reason have not been mapped across the scale of the wheat-belt. Before discounting soil, it is important though, to appreciate the definition of soil type.

Several soil classification approaches have been taken in Australia and most notable were the great soil group classification system used by Stace et al (1968) and the factual key of Northcote (1979). Isbell (1996) reviewed both these approaches, in addition to the workings of Hubble et al (1983), to redefine Australian soils into 14 orders. The science of soil classification has focused on describing a 'soil profile' to

a depth of at least a metre. Surface mapping appears to have been a secondary output. Isbell et al (1997) clearly stated that the Australian Soil Classification referred to profiles and was not intended to provide delineations on a map. Nevertheless a national soil map has been published (Figure 8). Unfortunately, it is difficult to distinguish between regions of soils since one type is a continuum of the adjoining type (Figure 8). That difficulty is exacerbated since single paddocks can potentially contain multiple soil types. Consequently, given that management can neutralise differences and mapping by soil order is problematic, a simplified perspective is required if soil was to be considered as an environmental basis for a classification boundary. Few such broad soil categories were found in the literature. A simplified version (Figure 9) was included in Callaghan and Millington (1956) and showed five broad soil groups covering the wheat-belt – podzols and coastal marshes, mallee soils and other brown soils of light texture, red brown earths and red earths, grey and brown soils of heavy texture, and black earths. Another simplified map was discussed with an industry colleague (L. O'Brien pers. comm., 2004).

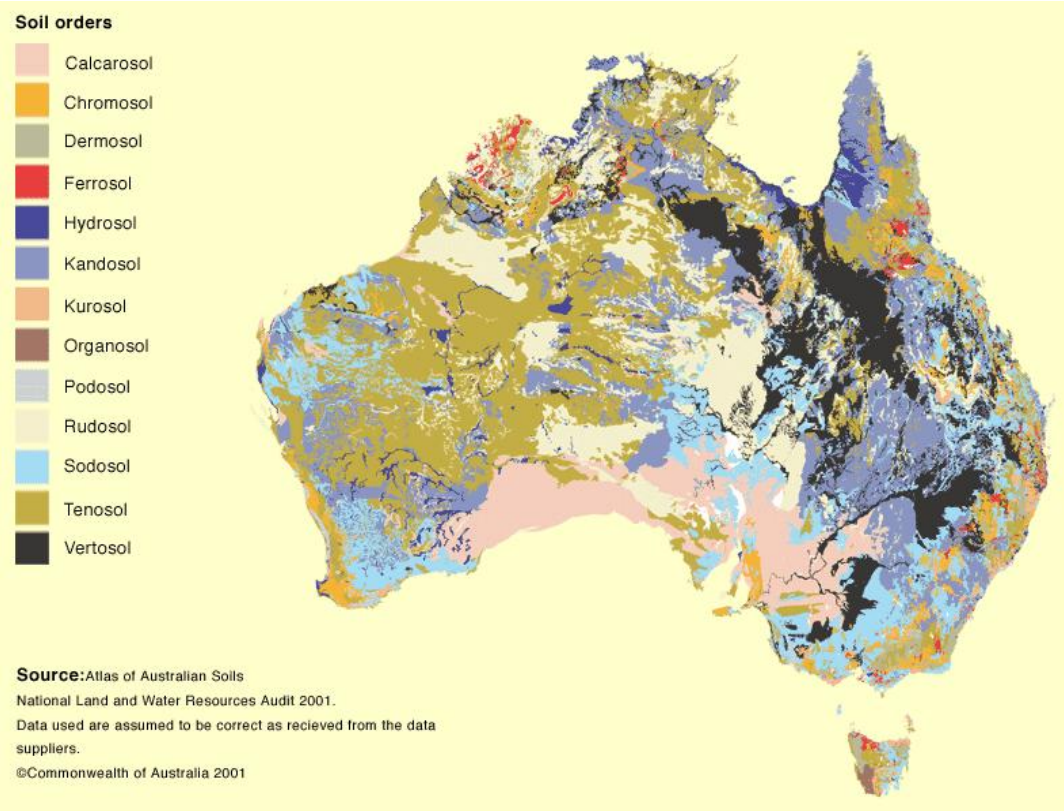


Figure 8 Distribution of major soil types in Australia

Source National Land and Water Resources Audit (2001)

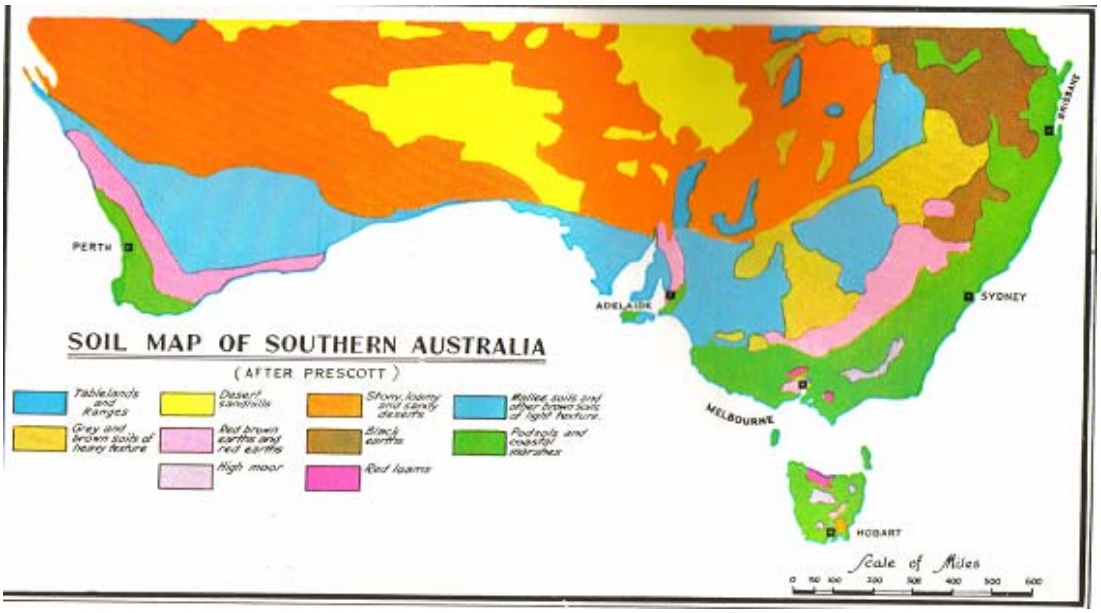


Figure 9 Soil map of southern Australia taken from Callaghan and Millington (1956)

2.4.4 Agro-ecological zones

Advancements in statistical software, computer simulation and mapping technologies have made it easier to amalgamate rainfall, temperature, and soil into agro-ecological or agro-climatic zones. Leslie et al. (1997), as part of their review on the crop evaluation processes in Australia, produced such an integrated map (Figure 10). They estimated which groups of environments were likely to influence grain variety trials in the same way, based on rainfall, temperature and evaporation (Leslie et al., 1997).

The GRDC uses 18 agro-ecological zones to identify research priorities and distribution of financial support (Figure 11). It seems that GRDC modelled their agro-ecological zones on the workings of Leslie et al (1997) given their similarities, and this was despite the limitations described Leslie et al (1997) regarding how their agro-ecological zones had been assembled. Regardless, a benefit associated with such agro-ecological zones has been the capacity to consolidate them and GRDC has done this by amalgamating sub-zones to create 3 macro-regions to simplify their investment management (Figure 12).

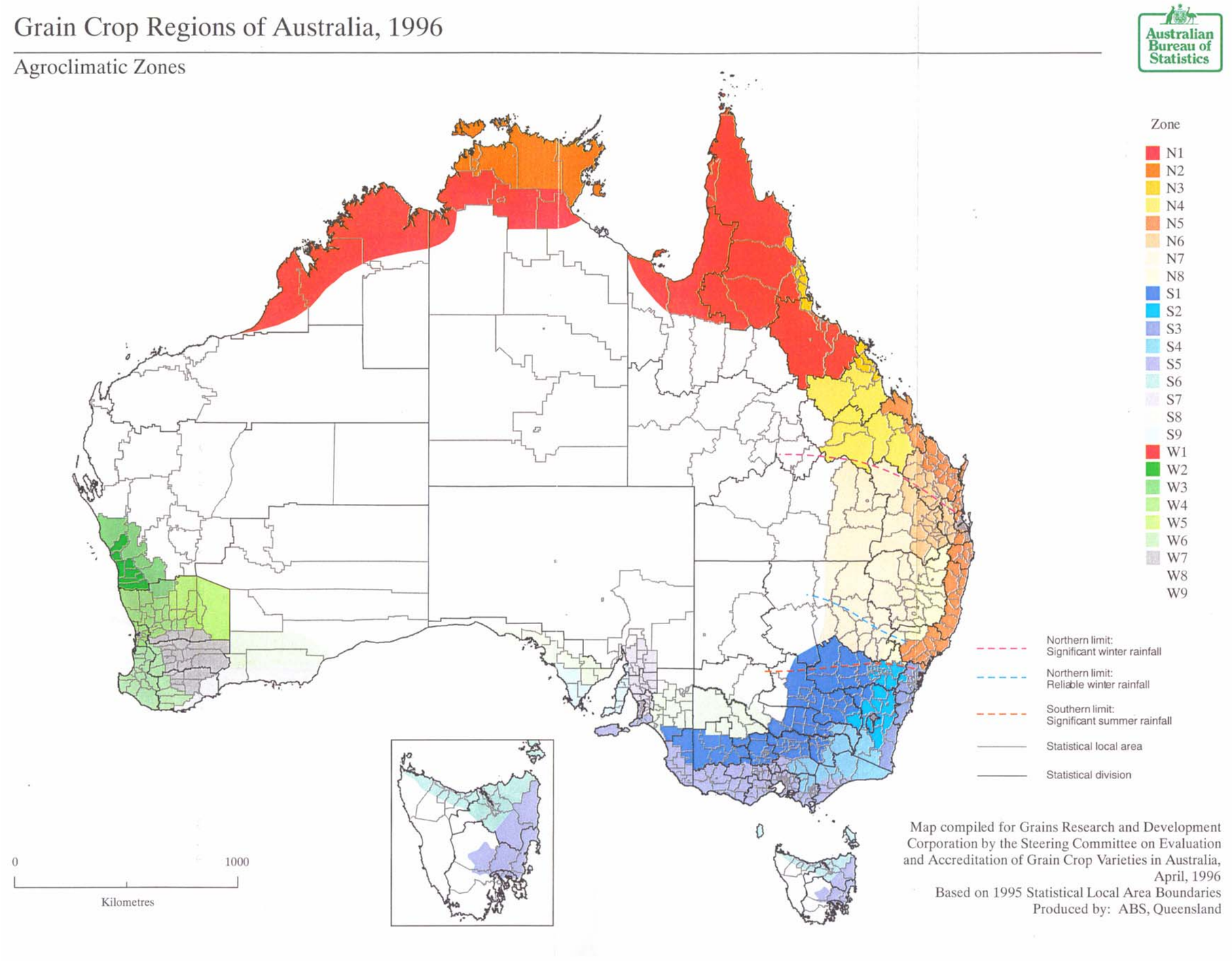


Figure 10 Agroclimatic zones of Australia taken from Leslie et al (1997)

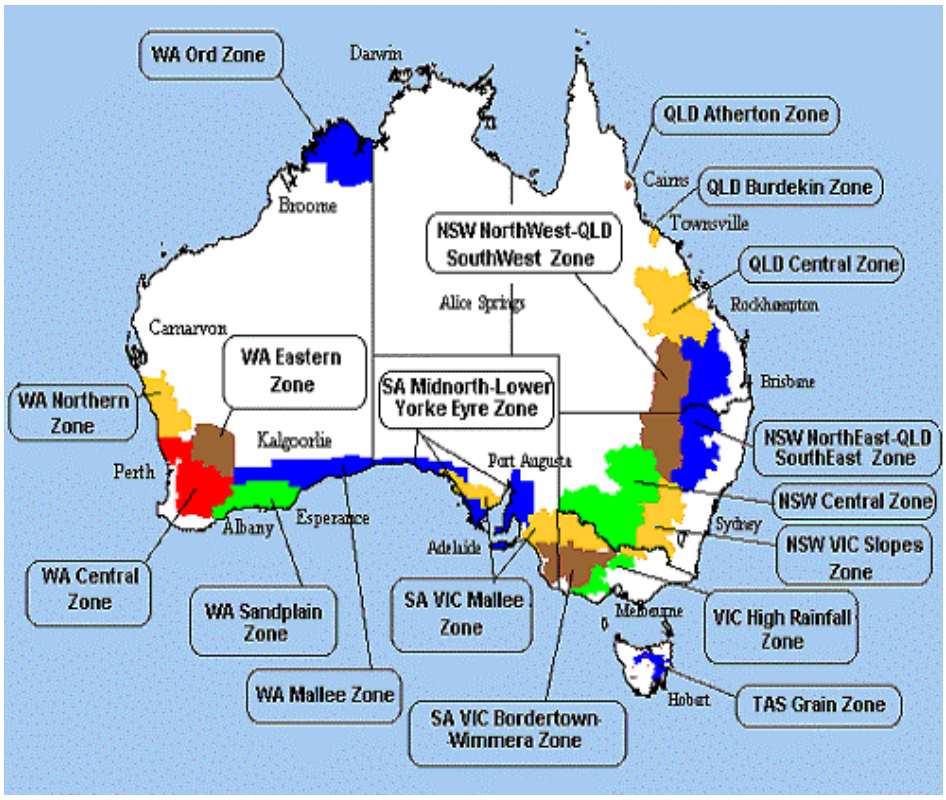


Figure 11 GRDC agro-ecological zones taken from www.grdc.com.au

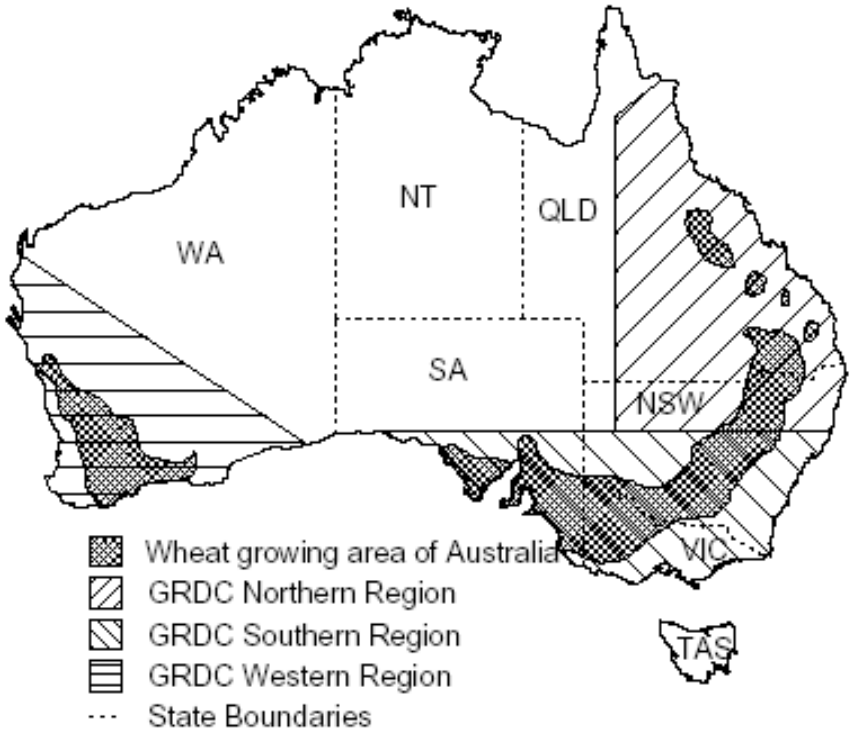


Figure 12 GRDC management regions taken from Basford and Cooper (1998)

A more thorough review of agro-ecological regions was performed by Williams et al (2002). They analysed the "inter-relationship between agronomy/farming system and various environmental features, not just climate". The result was the identification of 46 agro-ecological regions that for simplicity reasons could be amalgamated into 11 macro-regions. The macro-regions reported by Williams et al (2002) are similar to the agro-ecological zones published in the 'Sustainable Agriculture - Assessing Australia's Recent Performance' by SCARM (1998).

Another set of zones had earlier been described by Nix (1975). Based on data from 150 locations, the wheat-belt was classified into similar sectors based on the simulated phasic development pattern of the insensitive photoperiod and vernalisation variety Gabo. Simplistically, these could be grouped on the basis of rainfall, or radiation and temperature regimes. For example, rainfall separated a "wetter, south-eastern Australian sector from the remainder of the wheat-belt". Radiation and temperature regimes split the wheat-belt into 4 major groups. These were the high temperature areas of Queensland and Western Australia; sections of Queensland, northern New South Wales, South Australia and Western Australia; the major part of the south-eastern wheat-belt; and lower temperature of south-eastern wheat-belt aligned with higher rainfall.

The various state Departments of Agriculture have also identified zones based on a combination of influences. These have generally reflected variety sowing recommendation zones, rather than agro-ecological zones per se, as was discussed in Section 2.3.2 *Variety classification boundaries in Australia*. Intuitively, these recommendation zones represent different agro-ecological influences since their intended purpose is for farmers to use them in selecting the best variety(s) for their local environment, irrespective of the manner in which they may have been constructed.

For example, in Western Australia various zone systems have been used to provide recommendations to farmers. The latest iteration of 6 'Agzones' is based on the analysis of yield performance. Previously, the regional cells were separated along a North-South axis representing length of growing season, and West-East by annual average rainfall (Department of Agriculture Western Australia, 2004). The

recommendation zones used in other states have been listed in Table 7. Recommendations in Queensland are provided on the basis of planting time and yield performance. The boundaries for the latter trait identified from numerous yield studies (Brennan and Byth, 1979, Brennan et al., 1981, Sheppard et al., 1996, Sheppard et al., 1999).

Table 7 The nomenclature used for wheat variety sowing recommendations

State	Recommendation zones/regions/silo groups	Source
South Australia	Lower Eyre, Upper Eyre, Murray-Mallee, Mid North, Yorke Peninsula, South Eastern	Wheeler (2004)
Victoria	Mallee, South Mallee/North Wimmera, Wimmera, North Central, North East, Irrigated and South West	Eastwood (2003)
NSW	North, Central and South	McRae et al. (2004)
Queensland	Planting time – Central highlands (low frost risk and higher slopes), Central highlands (high frost risk and river flats), Western Downs and South West, Darling Downs (Northern Uplands), Darling Downs (Central Southern with high frost risk) and the Central Burnett, South Burnett and West Moreton areas	Queensland Department of Primary Industries (2004)
	Yield comparisons – Central and Southern	

2.4.5 The mechanism for creating a boundary

It can be contended that whenever a boundary is created, and it represents a monetary demarcation, problems occur. The wheat industry has encountered this problem with classification boundaries. Farmers have transported their wheat across boundaries in order to achieve a higher price for a grade not offered at their closest receival site. Recognising such potential difficulties Williams et al (2002) concluded that Local Government Areas (LGAs) were the best mechanism to base their agro-ecological regions because the Australian Bureau of Statistics used them as their basic classificatory unit. In addition, Williams et al (2002) considered LGAs advantageous because they have a defined legal status. Leslie et al (1997) had based the boundaries of their agro-climatic zones on Statistical Local Areas because they were the official statistical unit at the time. Given the availability of statistical data based on Statistical Local Areas they considered this an advantage. While the legal status of LGAs might avoid debate with respect to monetary differences on either side of their boundary, by nature they are administrative boundaries (straight lines) and ignore possible environmental variation. That negative aspect was recognised by Williams et al. (2002) and was mitigated by using aggregated LGAs rather than

analysing individual LGAs. Another advantage of either classificatory unit is that they have remained relatively consistent over time.

In contrast, climatic measurements vary considerably even for a single location, let alone for an aggregated region. Such variation would be considered advantageous from a modelling perspective. However, an assumption of classification boundaries is that their application across a geographical area does not regularly change, allowing farmers to make informed management decisions about the varieties they plant. Therefore, boundaries need to be consistent over time, and this makes the use of year-to-year climatic records problematic. The importance of rainfall and temperature on wheat production, though, cannot be ignored, and an alternative would be average long-term climatic measurements.

Alternatives to LGAs exist within the classification structure used by the Australian Bureau of Statistics (2001). In non-census years, the lowest structure is the Statistical Local Areas (SLAs), with 3 levels above it. The SLAs aggregate to form Statistical Subdivions and this aggregation principle continues up the remaining hierarchical levels of Statistical Districts and State/Territory. There is a linkage between LGAs and SLAs described by the Australian Bureau of Statistics (2001) as:

> "The LGA Structure shows the relationship between LGAs and SLAs. This relationship can be one LGA to one SLA or one LGA to many SLAs. The LGA Structure is maintained as a separate structure from the Main Structure because:
>
> - unlike spatial units in the Main Structure, LGAs do not cover the whole of Australia; and
> - unlike SLAs which aggregate to form SSDs and SDs, some LGAs do not wholly fit within an SSD and an SD (e.g. Gold Coast City in Queensland)."

2.5 Genotype, environment and interaction effects on quality

The terms variety and genotype will be used throughout this section of the literature review. The former is reference to individual varieties, while the latter is a group of varieties.

The study of genotype, environment and genotype×environment interaction (G×E) on the production of agricultural crops continues to be an area of research interest. The primary focus of such research has been G×E because its presence can slow advancements in breeding (Allard and Bradshaw, 1964). The G×E expression, and range of statistical methods now available to assess it, arose from breeders and biometricians wanting tools to unscramble G×E in order to identify the highest and most consistent yielding varieties across target regions. The interest in yield is purely economic since farmer's income is based on a 'per tonne equation' and the most successful varieties are those having high yield potential. Basford and Cooper (1998) reviewed Australian G×E research on wheat yield, and widespread throughout the literature are examples of studies examining the influence of G×E on the yield of other crops and in other countries. Less has been published on the importance of G×E on wheat quality and therefore such reviews and work on yield are essential background on the definition of G×E. Alongside the development of statistical methods was a desire for more efficient trial designs to identify superior varieties (Kang and Gauch, 1996). Consequently, it is accepted that if G×E exists in whichever form, then multi-location-year trials are needed to properly identify the best performing varieties across environments.

The simplest case of conceptualising G×E has been the comparison of 2 varieties, in 2 environments (Figure 13). Allard and Bradshaw (1964) used that platform to write that:

> "significant differences are obtained such that the 4 genotype-environment combinations can be placed in rank order 1 to 4. Twenty-four interaction types are possible among which 4 are shown in Figure 13 [please note that 6 graphs were originally referred to in their paper]. Some of the points to note about these particular interaction types is whether genotype A does better than B in 1 environment (as in type 1), whether A is superior to B in 1 environment and inferior to the other (as in type 4), and whether the change

in environment affects the 2 genotypes in opposite directions (as in type 3). Each of these interactions represents a type well known to plant breeders. For example, in types 1 and 3, genotype A can be taken as the universal variety; in type 6, A and X can be taken as specialized variety and matching favourable environment and B and Y as a less specialized variety and less favourable environment; with type 4, both A and B are specialized varieties and X and Y are specialized environments."

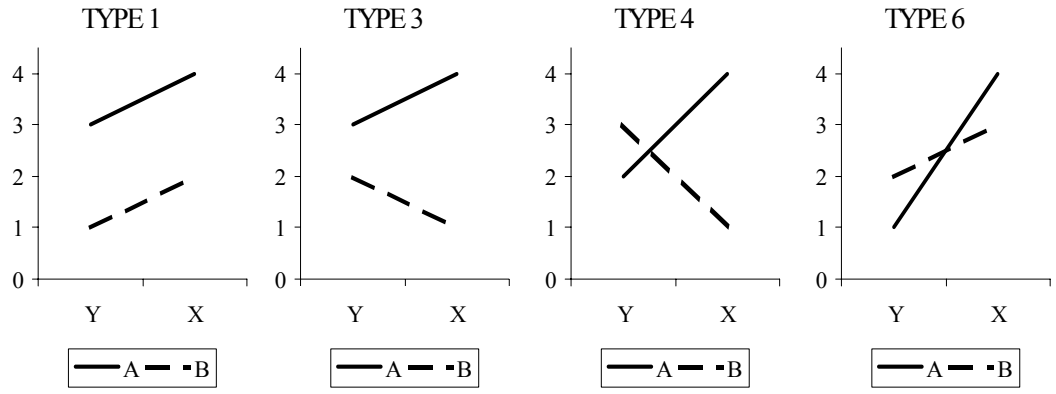


Figure 13 The graphical representation of some G×E situations taken from Allard and Bradshaw (1964)

G×E also hinders breeding selection based on quality parameters, but the situation is more complicated for wheat quality given its multi-faceted nature compared with the measurement of yield. For example, ideal dough strength differs between end-products and specifications can reflect a prescribed band rather than a single high or low value. Another tailored product is the noodle wheat segregated in Western Australia for Japan and South Korea. In this situation, to achieve the desired quality, the protein level is required to be within a 2% range. Therefore, rank order of genotypes can be consistent across environments, but quality bands can move up or down, placing limitations on the intended use of wheat.

A further complication, or rather confusion, has been the usage by cereal chemists of the G×E expression to explain environmental effects on the expression of genetically controlled quality traits. The G×E expression has commonly been used to describe the trait-by-trait inter relations such as described by Moss (1983), Simmonds (1989) and Cauvain (2005). These are not close to the statistical definition of G×E as described by Allard and Bradshaw (1964). Therefore, when quality studies are

considered, one needs to be careful in identifying whether a reference to G×E refers to potential cross over of results for example, or the interrelated nature of quality due to trait-by-trait relationships.

An excellent example of appropriate use of the G×E expression in its application to wheat quality traits was written by Matus-Cadiz et al. (2003). They wrote:

> "Selection for grain colour in a Hard White wheat breeding program requires knowledge of the magnitude of the G×E interaction. If interactions between G×E exist, then genotypes selected as superior in 1 environment may not be superior in other environments (Baker and Kosmolak, 1977). A significant G×E interaction may be either (i) a noncrossover G×E interaction where the rankings of genotypes remains constant across environments and the interaction is significant because of the changes in the magnitude of the response, or (ii) a crossover G×E interaction where a significant change in the rank occurs from one environment to another. When selecting genotypes for wide adaptation, plant breeders look for a noncrossover G×E interaction or preferably the absence of a G×E interaction."

Despite any terminology differences, the focus of quality studies assessing genotype and environmental factors have focused on trying to understand the relative influences of those factors on the expression of a particular trait, or traits. That overarching objective can be further divided into 3 parts.

Firstly, studies were conducted to understand the heritability of quality traits (Bhatt and Derera, 1975, Fowler and de la Roche, 1975). Knowledge as to the likelihood of inheriting a certain quality from one generation to the next is invaluable information for breeders attempting to improve the quality of wheat varieties. Such knowledge, though not redundant, is fast being replaced by a molecular understanding of quality and the ability to select certain gene combinations in the pursuit of quality (Snape et al., 2005, Kuchel et al., 2006). The second aspect has implications for breeders who wish to select genotype mean values approaching desired quality trait levels coupled with stable performance across different environments (Robert, 1997). The third, and a sub-group of the second aspect, has focused on identifying possible parental

material by examining the relative quality performance stability of varieties. Such knowledge is used to identify the best parents for crosses to enhance the likelihood of subsequent releases having the quality profile demanded by customers (Baenziger et al., 1985, Peterson et al., 1992).

2.5.1 Knowledge arising from genotype and environment studies on quality

The literature focused on understanding the effects of genotype and environment on wheat quality is diverse. A selection of published research that has focused on 'bread wheats' (*Triticum aestivum* L.) is shown by country in Table 8. Research undertaken in the United States (US) dominates the literature, followed by equal contributions from an amalgamated European Union (EU), Australia and Canada. China currently has to date only contributed 4% of those identified, but this does not reflect the larger volume of research that has only been published in Chinese. Considerable research has also been undertaken on durum (*Triticum turgidum* L.) and these have focused on environments surrounding the Mediterranean basin and Canada (Mariani et al., 1995, Koc et al., 2000, Marchylo et al., 2001, Rharrabti et al., 2003a, Lacaze and Roumet, 2004). Discussion henceforth has focused on the 100 'bread wheats' studies (Table 8).

Table 8 Some global genotype and environment studies focused on bread wheat quality

Where research was conducted	Papers meeting selection criteria	Where research was conducted	Papers meeting selection criteria	Where research was conducted	Papers meeting selection criteria
US	38	Egypt	2	India	1
EU	11	Norway	2	Jordan	1
Australia	11	South Korea	2	Pakistan	1
Canada	10	Yugoslavia	2	Romania	1
South Africa	6	Zimbabwe	2	Syria	1
China	4			Tanzania	1
International*	4				

International* equates to studies assessing trials grown in different countries
Research papers were counted if they had tested either multiple genotypes in multiple environments (the sum of location x year) and or had analysed the data with the intent of identifying the relative influences of genotype and environment effects on the quality traits assessed (eg quality trait correlation studies, individual analyses and or compositing of genotypes or locations) were utilised. An additional parameter was that the complete article was published in English

2.5.1.1 The influence of materials on observed results

The diversity of materials used in quality genotype and environment studies have had an important influence on the outcomes observed. Globally, experiments can be divided into those that tested varieties of uniform grain hardness, or when varieties of different grain-hardness were tested. North American studies have used additional

differentiation factors of red or white coloured grain (Dintzis et al., 1992, Hazen et al., 1997, Hazen and Ward, 1997, Graybosch et al., 2004) while many have combined differences for grain hardness and grain colour (Morris et al., 1997, Mikhaylenko et al., 2000, Davies and Berzonsky, 2003, Matus-Cadiz et al., 2003, Souza et al., 2004). Limited studies have assessed varieties of different maturity groups (Fowler and de la Roche, 1975, Johansson and Svensson, 1999, Johansson et al., 2000, Johansson et al., 2003). Gaines et al. (1996b) purposely examined varieties outside of their originally bred environment.

Use of a uniform grain hardness type limits possible variation and this has been shown for milling yield, farinograph water absorption, dough extensibility and other traits (Martin et al., 2001, Cane et al., 2004, Eagles et al., 2006b). Conversely, use of a diverse set of genotypes promotes the relative influence of genotype on the quality traits measured (Fowler and de la Roche, 1975, Morris et al., 1997, Fowler et al., 1998). An interpretation of the literature was that a wide range of genotypes was justified when the objective was to understand the maximum possible extent of genotype and environment effects on quality. For other purposes, a greater diversity of genotypes (for example grain hardness) merely confused the interpretation of results, and this was especially true for those experiments wanting to identify homogenous zones/regions of wheat production.

The other key influence on quality is the growing environment. The term environment has been used to conveniently describe unique location and year combinations. Widespread use of an environment factor in analyses is linked to Peterson et al. (1992) who considered each location-year as a separate environment for statistical purposes. That is not to say ‘environments’ had not been used earlier as Baker and Kosmolak (1977) had assessed the quality of 2 different growing environments in Western Canada. It seems that environments have been convenient, because it made the explanation of variance simpler since G×E and residual error were often incorporated together – often required in quality focused studies due to a lack of replication. The analysis of statistical ‘environments’ has continued to be a common practice (Graybosch et al., 1995, Graybosch et al., 1996, Hazen and Ward, 1997, Hucl et al., 1998, Grausgruber et al., 2000, Eagles et al., 2002a, Park et al., 2002)

In efforts to increase environmental differences some researchers have conducted their experiments in different countries (Pomeranz et al., 1985, Peterson et al., 1986, Mugala, 1989, Robert, 1997). In a study of European bread wheats Robert (1997) analysed 2 trial sets; the first grown in France, representative of a northern wheat production area, and a second set grown at locations in France, Spain and Italy to represent a southern wheat production area. Peterson et al. (1986) analysed results from 5 US locations and a single location in Germany. Mugala (1989) used a similar approach, with a core data set compiled from 3 Zambian wheat trials that were compared with results from Saskatchewan, Canada. Pomeranz et al. (1985) conducted the most diverse geographic experiment by analyzing samples from 11 trials grown in 8 different countries (France, Hungary, Italy, Switzerland, US – 4 different states, USSR, West Germany and Yugoslavia). Despite the varied environments in which these experiment were grown a common feature was that they assessed only a limited number of years. Robert (1997) had the most, using 3 years of results, while the others had assessed only a single year of results.

The issue of how many years, or locations, should be used in experiments remains one for each researcher to decide as no obvious trend emerged from the literature. To illustrate the experimental diversity a few examples have been chosen. Johansson et al. (2000) used only 1 test location to examine influences on bread-making quality, but their 5 experiments represented a range in years of 2 to 16. Other studies have also chosen to restrict their analysis to a single test location across varying numbers of years (Fowler et al., 1998, Uhlen et al., 1998, Guttieri et al., 2000, Khalil et al., 2002). In contrast, studies have generated samples for testing from more than 15 trial locations (Busch et al., 1969, Bassett et al., 1989, Collaku et al., 2002) but used fewer years. Such differences raise the question of which is better, more years or more locations, though the relative importance of each can is waived when environments are used. What is better depends on the aims of the study. Designing a breeding program for example, the breeder needs to know for the evaluation of both grain yield and quality, whether G×Y is greater than G×L, as this will determine the optimum selection strategy. If G×Y is greater, then evaluation of genotypes over years, rather locations will be more informative. An impression gleaned from the literature was that researchers might have been restricted by budget

constraints. Quality testing of complex traits is expensive and time consuming. Therefore, the final decision on whether to have more years or more locations in a factorial experiment were used possibly linked to available funding.

An alternative approach in the quest for greater representation has been the examination of a collection of independent trials. The rationale based on the assumption that a greater number of data points provide a higher confidence that the sub-sample analysed is representative of the true population. Morris et al. (1997) wrote that "each data set provided additional, unique information and provided substantiation, validation, and increased confidence in any conclusion that might be drawn." Some selected papers analysing data in that manner have been listed in Table 9. A feature common of these studies was that individual comparisons were often only grown for a single year.

Table 9 The experimental design of studies using multiple data comparisons

Author(s)	Experimental design	Author(s)	Experimental design
Fleming et al. (1960)	3 comparisons – 4Gx9Lx1Y; 1Gx3Lx1Y; 3Gx2Lx1Y	Park et al. (1997)	2 comparisons – 40Gx2Lx1Y; 10Gx3Lx1Y
Fowler and de la Roche (1975)	6 comparisons – 11Gx9Lx2Y; 8Gx8Lx2Y; 7Gx12Lx3Y; 4Gx5Lx2Y; 8Gx4Lx2Y; 5Gx3Lx2Y	Hucl et al. (1998)	2 comparisons – 16Gx31 environments; 11Gx 32 environments
Baker and Kosmolak (1977)	4 comparisons – 20Gx2Ex1Y; 20Gx2Ex1Y; 30Gx2Ex1Y; 29Gx2Ex1Y	Oury et al. (1999)	15 comparisons – 23Gx6Lx1Y; 27Gx6Lx1Y; 27Gx6Lx1Y; 31Gx7Lx1Y; 29Gx6Lx1Y; 26Gx7Lx1Y; 19Gx7Lx1Y; 22Gx7Lx1Y; 31Gx4Lx1Y; 47Gx4Lx1Y; 40Gx4Lx1Y; 39Gx4Lx1Y; 40Gx4Lx1Y; 34Gx4Lx1Y; 47Gx4Lx1Y
Tianu et al. (1996)	2 comparisons – 7Gx11E;9Gx8E	Johansson et al. (2000)	5 comparisons – 2Gx1Lx16Y; 9Gx1Lx7Y; 14Gx1Lx5Y; 8Gx1Lx2Y; $3Gx1^{t}x3Y$ ^{t} = 4 fertiliser treatments
Robert (1997)	2 comparisons – 6Gx32E (E=LxYxfungicide treatment [10L; 3Y; 2 treatments]) 7Gx27E (E=LxYxfertiliser treatment [7L; 3Y; 2 treatments])	Johansson et al. (2003)	4 comparisons - $4Gx1L^{t}x3Y$; $7Gx1L^{t}x3Y$; $2Gx1L^{t}$ x5Y; $2Gx4L^{t}x2Y$ ^{t} = 4 varying fertiliser treatments
Morris et al. (1997)	8 comparisons - 2Gx22Lx3Y; 3Gx16Lx3Y; 4Gx8Lx1Y; 2Gx8Lx1Y; 2Gx8Lx2Y; 4Gx1Lx4Y; 3Gx11Lx1Y; 5Gx7Lx1Y; 10Gx3Lx2Y		

G=genotype; L=location; Y=year; E=Environment

2.5.1.2 The effects of genotype, environment and G×E on quality

Since the materials used in global studies have been diverse, the ensuing observations have been equally varied. The interpretation of such variability is symptomatic of the fact that wheat quality is a result of many interacting factors and consequently each genotype and environment study is unique. However, it was found that quality parameters generally fell in line with the accepted thinking on heritability of traits as previously discussed (see Section 2.2 *Quality trait heritability*). Despite the variability, a commonality was that while regularly significant, interactions had relatively small influence compared with the main effects of genotype and environment.

Consideration of Australian studies in isolation reveals a slightly different perspective with respect to what factors affect quality (Table 10). From the perspective of breeding selection and identifying homogeneous quality parcels, it was observed that the most geographically diverse studies overall showed a lack of G×E. For numerous quality traits, genotype and environment rankings have been reported as similar across the Australian wheat-belt (Allen and Pumpa, 1999, Pumpa et al., 2002). In an earlier study involving samples from New South Wales, Victoria and Western Australia, Moss and Miskelly (1984) had found genotype and environment to have significant influence on starch quality parameters, but detected no genotype by trial location or year variation. At that time, differences between the varieties with highest paste viscosity (Halberd and Gamenya) and the lowest (Egret and Oxley) were associated with variations in amylose content. In a more recent study, genetic knowledge of waxy genes coding for granule bound starch synthesis was used by Panozzo and Eagles (1998) in the selection of varieties. In this study restricted to environments in Victoria, differences in varieties contributed most to the variation in peak viscosity (Panozzo and Eagles, 1998). In another Victorian focused study, O'Brien and Orth (1977) found rankings to be similar for variables associated with protein quality, but showed greater variability for milling yield, water absorption and protein level across test locations in Victoria.

Table 10 Summary of Australian genotype and environment studies focused on milling wheat quality attributes

Author(s)	Reported materials	Reported quality tests	Method of analysis	Major quality conclusions
Bhatt and Derera, 1975	Set 1 - 27Gs x 2Es Set 2 – 17Gs x 1E Set 3 – 28Gs x 3Es (all Gs hard-grained types) Trials grown in north-west NSW	TWT, GP, FY, FP, GP-FP, PSI, Kent Jones flour colour, BV, BS	ANOVA, broad sense heritability and correlations	Identified significant GxE for the quality traits assessed and recommended that to identify the best lines quality testing should be conducted at more sites over fewer years rather than fewer sites over many years. They also suggested that the likelihood of improvement for some quality traits was greater than others due to different heritability estimates and that selection could be made on the basis of correlations between tests.
O'Brien and Orth, 1977	Gs=18-26 (mixed hardness types) Yrs=1 Locs=6 (VIC)	FY, FP, WA, DDT, DB, RP	Correlation coefficient, step-wise regression coefficients	Quality traits largely dependent on protein quality showed no GxE, while rankings were different between Locs for FY, FP and WA.
Panozzo *et al.*, 1983	Gs=13 (soft-grained types) Yrs=2 Locs=3 (VIC)	FP, SDS, Zeleny and Pelshenke tests, RP, DB, RMAX	Regression analyses	Location changed test results, but the effect was not statistically significant, and consequently relative rankings of test values did not change.
Moss and Miskelly, 1984	4Gs=4 (mixed hardness types) Yrs=3 Locs=5 (NSW, VIC and WA)	FP, FFN, starch peak viscosity, starch paste stability, amylose content of starch	ANOVA and correlation	Found that genotype and environment contributed independently to the variance of peak viscosity, with Yr and Loc showing a meaningful interaction, but no interaction between either Yr or Loc and genotype.
Fabrizius *et al.*, 1997	Gs=2 random F5 populations (hard grained types) Yrs=1 and Locs=3 (QLD) Es=9 (varying management regimes)	GP	REML and pattern analysis	Concluded that selective crosses could produce progeny with both high protein achievement and high grain yield potential, despite a negative correlation between grain yield and protein level, and mixed effects.
Panozzo and Eagles, 1998	Gs=7 (mixture of different hardness and WxB1 GBSS types) Yrs=2 and Locs=9 (VIC) Es=15 (varying management regimes)	TKW, GP, PSI, starch granule size distribution, amylose, RVA peak viscosity, granule bound lipd	ANOVA with genotype as fixed, and environments as random.	Found that cultivar, specifically those null for Wx-B1 GBSS, could be used successfully to identify wheat with high starch pasting quality and that accumulated high temperatures during the grain filling period affected the type of starch granules synthesised, and consequently the final pasting quality profile.
Allen and Pumpa, 1999	Gs=4 (hard-grained types) Yrs=3 and multiple Locs (NSW, VIC, SA and WA) Es=42	TWT, TKW, GP, FY, Minolta flour colours, WA, DDT, EXT, RMAX, YAN ΔL*, LV	Each year of data analysed separately, in some cases using ANOVA and LSD	Concluded that 13% protein Prime Hard cultivars grown in southern Australian environments were of interchangeable quality.
Panozzo and Eagles, 2000	Gs=7 (mixed hardness types) Yrs=2 and Locs=9 (VIC) Es=15 (varying management regimes)	FP, glutenin and gliadin percentages, DDT, BD, EXT, RMAX, LV	ANOVA with genotype as fixed, and environments as random.	Determined that genotype, environment and GxE all had a significant effect on quality trait variances. Environment was the dominant influence on the quality relative to the other effects. GxE had a greater influence than genotype for flour protein, farinograph DDT and loaf volume, but still less than environment.
Eagles *et al.*, 2002	Gs=2,377Gs (mixed hardness types) Es=94 (VIC and SA)	FY, FP, PSI, WA, DDT, EXT, RMAX	REML with genotypes and environment random. Calculated genotypic and environmental variance components, correlations and heritability	Found that the environmental effect had a bigger impact on FP, and EXT, with similar genotype and environment influence on FY, WA and RMAX. Hardness was dominated by genotype variance.
Pumpa *et al.*, 2002	Gs=11 (hard-grained types) Yrs=3 and Locs=12 (QLD, NSW, VIC, SA and WA) Es=22	TWT, TKW, GP, FY, Minolta flour colours, WA, EXT, RMAX, End product quality [WSN, YAN, FB and PB]	A linear mixed model producing predicted means and variance components. Region and trial (= unique yr x loc combinations) were fixed, with genotype and all interactions random	Only found small GxE influence, although RMAX was higher than all other traits. Genotype rankings were the same across environments. They noted that some quality traits had very high error levels and these made assigning variance difficult, and suggested that care was needed to minimise sources of laboratory error.
Skerritt *et al.*, 2003	Gs= 4 DH populations (hard-grained) Yrs=3 Locs=4 (QLD, NSW and VIC)	TWT, TKW, GP, SDS, FY, L*, WA, DDT, EXT, RMAX, dough probe tests, LV and LS	Due to seasonal protein differences sites were paired for ANOVA with multiple models used	Comparison of dough and baking properties for samples at similar protein levels showed the quality to be comparable between production regions, noting that significant interactions were detected.

ANOVA = Analysis of variance; BS = Bread score; BV = Bread volume; DB = Farinograph dough breakdown; DDT = Farinograph dough development time; DH = double haploid; Es = Environments; EXT = Extensograph extensibility; FB = Flat bread; FFN = Flour Falling Number; FP = Flour protein; FY = Flour yield; GBSS = Granule starch bound synthase; GP = Grain protein; Gs = Genotypes; GxE = Genotype x environment interaction; L* = Minolta L*; Locs = Trial locations; LS = Loaf score; LSD = least significance difference; LV=Loaf volume; NSW = New South Wales; PB = Pan bread; PSI = Hardness; QLD = Queensland; REML = Residual maximum likelihood analysis; RMAX = Extensograph maximum resistance; RP = Residue protein test (Orth and O'Brien, 1976); SA = South Australia; SDS = SDS sedimentation volume; TKW = Thousand kernel weight; TWT = Test weight; VIC = Victoria; WA = Farinograph water absorption; WA = Western Australia; WSN = White salted noodles; YAN <L* = Change in yellow alkaline noodle Minolta L* readings 0-24hrs; YAN = Yellow alkaline noodles; Yrs = Years

In contrast, some geographically restricted studies have reported influential levels of G×E. Bhatt and Derera (1975) considered G×E to be at a level that warranted wide spread quality evaluation in order to identify the best quality breeding lines. They had studied a collection of genotypes (Eagle, Festiguay, Gamenya, Gamut, Gatcher, Penjamo 62, Spica, Timgalen) and advanced breeding lines in north-west New South Wales. The relative narrow variety pool and location, restricting possible genotype and environment effects, reinforcing the point of how important random genotype and environment factors are to any conclusion. Fabrizius et al. (1997) reported that G×E was influential on protein content, though they qualified that by saying the degree of interaction varied upon the genotype assessed. Panozzo and Eagles (2000) found that the relative influence of G×E was greater than that of genotype on the variability of flour protein, farinograph dough development time and loaf volume, but this was always less than the influence of environment. Skerritt et al. (2003) reported similarities between different production locations, but noted significant G×E. In contrast to Bhatt and Derera (1975), Skerritt et al (2003) had used doubled haploid and crossbred line populations tested across geographically wide spread locations from Queensland (Roma) and Northern NSW (Narrabri) to southern NSW (Ariah Park) and north western Victoria (Walpeup).

On face value, it would be easy to presume that geographically diverse Australian studies should have more potential to produce the potentially confusing effects of G×E, but the literature selected for review places doubt over that assumption. When agro-ecological or agro-climatic divisions of Australia are considered, they point to commonality between east and west portions of the wheat-belt and differences in production areas between northern and southern areas(Nix, 1975, Williams et al., 2002). Until tested further it would appear that cares needs to be taken in the genotypes and environments selected for any Australian quality study since there is growing evidence to suggest that despite the climatic diversity of Australia, G×E on certain quality parameters is small relative to genotypic and environmental factors.

The capacity to assess that viewpoint was made by comparing the observations from 7 of the selected Australian studies on protein quality trait measurements. Eagles et al. (2002a) considered the influence of genotype to be greater or equivalent to that of environment for protein quality measurements based on dough development time and

maximum resistance tests. O'Brien and Orth (1977) and Panozzo et al. (1983) had previously reported that genotypic variance was larger for the protein quality related tests they performed – in these instances it was based on residue protein, dough breakdown, SDS, Zeleny and Pelshenke tests. Pumpa and Allen (2002) reported variable responses between genotypes and environments, concluding that residual variance was the biggest source of variation on maximum resistance. Panozzo and Eagles (2000) found that genotype, environment and G×E all had significant effects on protein quality related measurements, but environmental variance was larger than either that of G×E or genotype. The conclusion made by Skerritt et al. (2003) was that protein quality parameters were similar between the northern and southern locations tested. Taken as a whole, these studies suggest protein quality is more influenced by genetic factors than environment. The contrary observation to this by Panozzo and Eagles (2000) might be linked to their assessment of varieties with mixed grain hardness and different adaptation profiles, but also illustrates that short-term experiments might experience certain climatic conditions that can bias results, as was commented on by Skerritt et al. (2003).

2.5.2 Quality similarities between different environments

The primary focus of genotype and environment quality studies has been on the performance of varieties or extent of environmental influence on a certain quality trait or set of traits. Few have aimed at grouping similar quality performing environments together. The situation with yield is quite different, with a larger proportion of the overall yield literature having focused on identifying subregions of like performance, such as those described by Atlin et al. (2000). However, while examples of research with the explicit objective of identifying environments of similar quality are limited (Collaku et al., 2002), results from other studies can be elucidated to determine quality similarities between different environments. Since the focus of this study is the Australian wheat-belt, the literature considered will be restricted to that production area.

Experiments that concurrently considered major growing regions of the entire Australian wheat-belt were Allen and Pumpa (1999) and Pumpa et al. (2002). In the case of the former it encapsulated the preceding publications Oliver et al. (1996),

Oliver et al. (1997) and Allen et al. (1998). In the latter, it summarised Allen and Pumpa (2000) and Pumpa and Allen (2001). While Allen and Pumpa (1999) and Pumpa et al. (2002) were national studies, in the sense that they tested samples grown at locations in each wheat-growing state, a possible limitation was that individual locations were considered to be representative of a larger geographical area (Table 11). Furthermore, the locations and their numbers varied in the years studied. Pumpa et al. (2002) had greater consistency among the locations sampled and tested, but single locations were still linked to large geographical areas of wheat production.

Table 11 Growing locations of trials analysed in 2 Australian research projects

Region	Prime Hard in the South Source Allen and Pumpa (1999)				Flexibility of wheat use – benchmarking across Australia Source Pumpa et al. (2002)			
	Locations sampled	Years Tested			Locations sampled	Years Tested		
		1995	1996	1997		1998	1999	2000
	Blank location-year combinations were not sampled							
QLD					Dalby	✓		
					Meandarra		✓	
					Moonie			✓
					Pirrinuan		✓	
					Roma	✓		
NNSW	Coonamble	✓	✓					
	Cryon		✓	✓				
	Gilgandra	✓	✓	✓				
	Moree	✓	✓	✓	Moree	✓		
					Narrabri	✓		
CNSW	Condobolin	✓	✓	✓				
SNSW	AriahPark	✓	✓	✓				
	Cowra			✓				
	Kyalite	✓						
	Nangus	✓						
	Young	✓	✓					
					Wagga Wagga	✓	✓	✓
VIC	Horsham	✓	✓		Horsham			✓
	Walpeup	✓			Walpeup			✓
					Woomelang	✓		
SA	Loxton	✓						
	Minnipa	✓	✓	✓				
	Nangari			✓				
					Palmer			✓
					Roseworthy	✓	✓	✓
	Wunkar			✓				
WA	Dalwalinu		✓					
	Goodlands			✓				
	Merredin			✓				
	Morawa			✓				
					Newdegate	✓	✓	✓
	SalmonGums		✓					
	Varley			✓				
					Wongan Hills	✓	✓	✓

The conclusions of Allen and Pumpa (1999) and Pumpa et al. (2002) were similar. Both found the effect of G×E was minimal compared with other factors owing to the fact the variety quality rankings were generally the same across the different regions. Pumpa et al. (2002) made note that of the traits tested, extensograph dough strength had the greatest level of G×E. However, Allen and Pumpa (1999) concluded that 13% protein Prime Hard varieties grown across southern Australian environments were of interchangeable quality results, suggesting that the environments were of similar quality potential. In contrast, Pumpa et al (2002) reported differences between regions based on flour yield, extensograph dough strength and yellow alkaline noodle L* measurements. They also noted that extensograph extensibility measurements varied by 3.5cm from the lowest to highest regional mean, but it was unclear whether this was merely a function of differing protein levels between the regions.

Supporting the findings of Allen and Pumpa (1999) was further work conducted by Skerritt et al. (2003) on the production of Prime Hard. Skerritt et al. (2003) reported that at equivalent protein levels southern locations had grain, dough and baking quality comparable with what was produced from northern locations (the traditional production area of Prime Hard). However, they noted that while the quality might have been similar, the capacity to achieve protein level at the southern locations could be impaired by either drought or wet conditions late in the growing season.

Another inference that quality differences existed between production regions was shown by Archer and O'Brien (1987) who assessed a single variety within a narrow geographical corridor (2 adjoining production regions in southern New South Wales and Victoria). They found the 2 environments to produce different quality profiles for the same variety, Condor. It is now known that Condor has mixed high molecular weight glutenin composition and this could have been a contributing factor to the differences reported (L. O'Brien, pers. comm., 2006). More recently, at AWB National Pool Wheat Breeding Forums between 2003 and 2006 differences in milling and dough properties between Australian classification regions were discussed.

The other Australian studies either did not consider locations across what would be considered a suitably broad geographical range (Bhatt and Derera, 1975) or the presentation of results did not allow for any inference on areas of similar quality to be made. Consequently, there is insufficient information available in the published literature as to whether different regions of the Australian wheat-belt could be grouped together based on their capacity to produce similar quality wheat.

2.5.3 Statistical approaches used in genotype and environment studies

Early genotype and environment studies were predominantly regression analyses (Busch et al., 1969, McGuire and McNeal, 1974) based on the concepts outlined by Finlay and Wilkinson (1963) and Eberhart and Russell (1966). The focus of those early studies was a desire to identify varieties with stable quality performance (Busch et al., 1969). Peterson et al. (1992) described a variety with optimal stability as having a low *b*-value, indicative of small deviations to the average performance across environments.

By far the most popular method to determine if significant variation existed for a particular quality trait has been analysis of variance (ANOVA) with determination of the relative importance between significant factors made using ratios of variance components (Baenziger et al., 1985, Peterson et al., 1986, Peterson et al., 1992). Commonly, the ratios of the variance components analysed have been genetic (σ^2_g), environmental (σ^2_e), and G×E ($\sigma^2_{g\times e}$) allowing assessment of which had the greatest effect. Over time, the use of estimated variance component ratios has expanded to allow for comparison of the influence of main effects to one another, but also comparisons of main effects to various other interaction combinations. Similarly, over time ANOVA's have become more complex, including genotype, year and location main effects, with the addition of treatments such as fertiliser application and timing, or moisture regimes, and corresponding interactions (Borghi et al., 1997, Johansson et al., 2000, Geleta et al., 2002, Souza et al., 2004). Most studies have had a univariate approach since they have analysed quality traits independently, with few multivariate examples (Bhatt, 1976, Eskridge et al., 1994).

Researchers in the US have been leaders in integrating analyses of stability and variance in the study of G×E of quality traits (Baenziger et al., 1985, Peterson et al., 1986, Peterson et al., 1992). A feature of such integration is that it has allowed both the relative contribution to quality variation by genotype, environment and G×E to be identified, as well as varieties that would be useful parents in targeting quality improvements. The extent to which those 3 publications have been cited in the literature suggests that their statistical approach could be considered the global standard for such research (Baenziger et al., 1985, Peterson et al., 1986, Peterson et al., 1992). However, while there is a global link to the overall approach, the use of fixed and random effects, particularly for genotype and environment, has varied.

The availability of both better computer hardware and software has resulted in an emerging use of ordination and classification techniques to identify relative influences on quality traits of genotype, environment and their interactions (Robert, 1997, van Lill and Smith, 1997, Nel et al., 2000a, b, Collaku et al., 2002, Faergestad et al., 2004). Similarly, canonical variate analysis has been reported as an approach for assessing stability (Mamuya et al., 2000). However, such studies have also used conventional tests of significance since "pattern analysis is invariably aimed at the simplification of data; or, perhaps more accurately, at the efficient ordering of data. It is not, or should not be, concerned at all with probability" (Williams, 1976).

Common to all of the immediate preceding discussion of statistical approaches has been the use of balanced data. Payne et al. (2003) described balanced as:

> "The condition of first-order balance required for a design and its specification to be analysable by the ANOVA directive is explained algorithmically by Wilkinson (1970) and mathematically by James and Wilkinson (1971) and Payne and Tobias (1992). Essentially it is that the contrasts of each term should all have a single efficiency factor, wherever the term is estimated. In the example…all the terms have only one degree of freedom, and so represent only one contrast. There is thus no difficulty in verifying that the design is balanced."

It is suggested that this is why the prevailing international statistical approach (Baenziger et al., 1985, Peterson et al., 1986, Peterson et al., 1992) was not used in the Australian genotype and environment quality studies previously mentioned (Table 10). A common feature of Australian genotype and environment experiments has been unbalanced data due to uncontrollable circumstances such as crop failures or by choice for example by changing experimental design part way through an experiment. For example, Allen and Pumpa (1999) used ANOVA to independently analyse each of their 4 years of quality data, attributed to the 4 years of data being different. Due to seasonal protein differences Skerritt et al. (2003) made pair-wise comparisons using multiple ANOVA models. An alternative to ANOVA for the analysis of more unbalanced data is residual maximum likelihood (REML). Such an approach has been used to produce multiple variance component estimates for studies having greater levels of unbalanced data to analyse (Fabrizius et al., 1997, Eagles et al., 2002a, Pumpa et al., 2002).

The REML approach is based on the theory published by Patterson and Thompson (1971) who wanted to improve the estimation of variance components by incorporating degrees of freedom, such as those generated by ANOVA on balanced data. As background, Payne et al. (2003) described REML as an algorithm that:

> "estimates the treatment effects and variance components in a linear mixed model: that is, a linear model with both fixed and random effects. Like regression, REML can be used to analyse unbalanced data sets; but, unlike regression, it can account for more than one source of variation in the data, providing an estimate of the variance components associated with the random terms in the model.
>
> The REML method has many applications. It can be used to obtain information on sources and sizes of variability in data sets. This can be of interest where the relative size of different sources of variability must be assessed, for example to identify the least reliable stages in an industrial process, or to design more effective experiments. REML provides efficient estimates of treatment effects in unbalanced designs with more than one source of error. For example, it can be used to provide estimates of treatment effects that combine information from all the strata of an unbalanced design.

> It can also be used to combine information over similar experiments conducted at different times or in different places. So you can obtain estimates that make use of the information from all the experiments, as well as the separate estimates from each individual experiment".

The estimates obtained from REML have generally not been used to perform ordination and classification computations. That observation is based on how results of Australian studies have been reported (Eagles et al., 2002a, Pumpa et al., 2002, Cane et al., 2004) and the findings from a keyword search of CAB Abstracts that showed that while many hits were found for the words classification, ordination and cluster, these were not found in connection with the REML term (Table 12). Fabrizius et al. (1997), however, did use principal component analysis on standardised estimated mean values of grain yield and wheat protein, although the data were balanced in the sense of same set of genotypes were grown, but the management regimes were different across trial locations.

Table 12 CAB Abstracts search for statistical and method keywords

Keyword(s) search in abstract, title, original title, broad terms, heading words	Publications identified
Classification	28,667
Ordination	2,053
Cluster	19,135
REML	715
REML classification	0
REML Ordination	0
REML Cluster	0
CAB Abstracts search performed on 29th May 2006	

Results from REML are enhanced by the use of large data sets, even if unbalanced. Large data sets have high levels of multiple observations and these make up for any lack of testing replication. The use of REML to analyse large sets of data appears accepted in other biological sciences based on recent publications listed in CAB Abstracts that reported the size of the data used in the abstract (Table 13). The same observation was noted by Smith et al. (2005) in their centenary review of mixed model analysis approaches used in assessing crop breeding trial data. In Australia, large (in terms of genotypes and environments [both locations and years]) quality databases are maintained by wheat breeding programs, but their use has been restricted to the geographical regions of southern NSW, Victoria and South Australia

(Eagles et al., 2002a, Eagles et al., 2002b, Cane et al., 2004, Eagles et al., 2004, Eagles et al., 2006a).

Table 13 Selection of experiments using REML procedures

Author(s)	Title of publication	Number of observations analysed
Lee et al. (2006)	Genetic parameter estimates for ultrasonic meat qualities in Hanwoo cows	10,596
Wierzbicki and Jagusiak (2006)	Breeding value evaluation in Polish fur animals: estimates of (co)variances due to direct and litter effects for fur coat and reproduction traits	5,540
Singh and Arora (2005)	Comparison of different methods of heritability estimates for body weights and wool yield traits in Avikalin crossbred sheep	1,313 lambs
Saatci et al (2006)	Genetic parameters from univariate and bivariate analyses of egg and weight traits in Japanese quail	1,808
Crews Jr (2006)	Age of dam and sex of calf adjustments and genetic parameters for gestation length in Charolais cattle	40,356
Kealey et al. (2006)	Genetic parameter estimates for scrotal circumference and semen characteristics of Line 1 Hereford bulls	841
Maia et al. (2005)	Genetic variation of the hair coat properties and the milk yield of Holstein cows managed under shade in a tropical environment	449
Galindez et al. (2004)	Genetics parameters of survival at birth in pigs	15,308
Barbosa et al (2005)	Selection of sugarcane families and parents by Reml/Blup	113 full-sib families of sugarcane
Missio et al., (2005)	Estimates of genetic parameters and prediction of additive genetic values in Pinus kesya progenies	30 progenies and 3 replications

2.5.3.1 Importance of residual error

A source of variation not often discussed, irrespective of the statistical method used, has been residual error. Consideration of unexplained error is important, particularly if the knowledge generated from genotype and environment quality studies is to guide breeding.. For example, Pumpa et al. (2002) found that the error component was the most influential factor based on variance component calculations. Fowler et al. (1998) found unexplained error to be the major source of variation for Falling Number and FSV, and also found error levels greater than >20% for mixograph - development time and energy to peak. Hazen et al. (1997) observed that error was the major source of variance for flour yield and cookie measurements.

An effective tool in minimising error, as was noted previously, has been to analyse results from a single laboratory (Robert, 1997). However, that can give the illusion

of reducing error while increasing bias if the laboratory in question was an outlier in its prediction of quality relative to other laboratories. The traditional tool to controlling error has been the testing of replicated samples. However, due to cost and size considerations single samples are often used for quality testing, raising questions about levels of error (Allen et al., 2000, Smith et al., 2001). What is emerging is that it is important to partition the sources of error (Smith et al., 2001, Kuchel et al., 2006). Such direction, however, cannot be applied to the decision made by researchers regarding the balance of representativeness and cost.

2.6 Summary of literature

Due to the inter-related nature of wheat quality traits, all traits need to be considered holistically in order to determine a variety's quality profile. Complicating quality profile determinations is the issue that quality traits have different heritabilities, with some traits relatively independent of prevailing environmental conditions while others are strongly associated with those conditions. The classification of varieties into appropriate quality grades is an important step in trying to supply a consistent quality to users of wheat. The Australian wheat variety classification system has gained international recognition, however, its Achilles heel is that decisions are made on testing of samples grown in regions not reflecting possible genotype, environment or their interaction effects. The current use of political state boundaries for classification purposes thus increases the chance of producing inconsistent quality.

Escalating pressure from processors for quality consistency has seen a strong worldwide interest in genotype and environment quality studies. The main focus of studies has been whether genotype or environment factors have the greatest influence on quality, and the identification of superior genotypes. As the body of knowledge has expanded, research has begun to explore specific quality traits, rather than an over-all quality profile, although univariate analysis has been a common feature of both. Only a small number of studies have examined grouping similar environments together. The most popular statistical analysis approach has been the use of ANOVA, estimation of variance components and comparison of variance component ratios. These methods relying on balanced data to elucidate meaningful conclusions.

However, alternative methods of analysing unbalanced data, such as REML, are beginning to be used more often.

Chapter 3 Materials and methods – an overview

As was outlined in the Introduction this research was conducted in 4 steps and these have been aligned to the 4 following chapters (Figure 14). The first of these 4 chapters outlines the construction of a relational database in Microsoft Access (Chapter 4). The second focuses on how low levels of G×E associated with the quality data were determined (Chapter 5). That low level of G×E gave confidence to proceed with the investigation of the hypothesis and that was to determine that better boundaries could be identified for wheat variety classification purposes (Chapter 6). The fourth chapter discusses several analyses that were conducted to substantiate the divisions of the wheat-belt identified (Chapter 7). The statistical software package Genstat® was used throughout the research to analyse data. Before the research commenced, however, 2 important issues were required to be resolved.

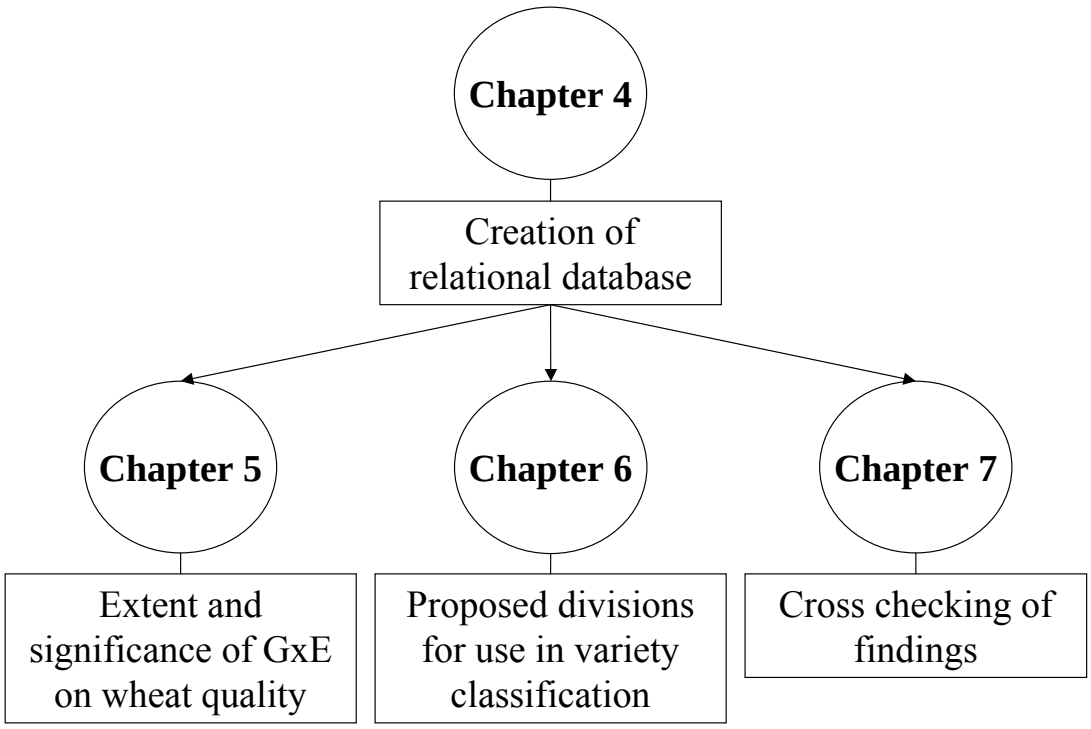


Figure 14 Diagrammatic summary of the research conducted

The first issue was how to manage an extensive set of data originating from different sources representing many unconnected trials. The solution was to create a relational database that represented historical quality results of varieties grown at locations across the wheat-belt from 1982 to 2003. The database created was unique, because never before had such a large set of quality results been drawn together into a single

collection of measurements to represent the entire Australian wheat-belt. The value of the data in that relational database was also significant. To replicate the number of tests in the database it was estimated to cost between $8.5 and $11.5 million in today's terms (L. Iyer, J. Panozzo, and M.Southan pers comm., 2006). My negotiations with the management of breeding programs allowed free access to the quality results with due consideration of confidentiality and proprietary value. Without such access, due to budget limitations and the inability to generate sufficient data in spatial and temporal terms, this research could not have commenced.

The use of databases has come into prominence in the last 20 years as the most efficient means of manipulating large volumes of data and information (Hoffer et al., 2005). Specifically, the relational model is the most commonly used. The key features of a relational database are that it contains tables of data in columns and rows, and that each row is unique. Linking different tables are primary keys and together these allow for precise selection of data. Two random examples of researchers recently choosing to use the power of relational databases were Zhou et al. (2003) in their analysis of spliced genes in plants and Veeger et al. (2004) who concluded that a relational database was of benefit in assessing the impact of geology on land use.

The importance of creating a relational database, as opposed to using data sets in spreadsheets, was a key decision in this research. The relational database provided flexibility both in managing the data, but also in selecting and assembling data sets and their transfer to Genstat® for analyses. The use of spreadsheets would have been inefficient and unwieldy due to the size of the data assembled. Hoffer et al. (2005) described 5 major disadvantages of such file processing systems and these were program-data dependence, duplication of data, limited data sharing, lengthy development times and excessive program maintenance.

The second issue was how best to analyse highly unbalanced data. In this situation the approach adopted followed published wheat quality studies using unbalanced data. Conventional statistical analyses of agricultural experiments are based on design principles of balance and replication. However, unbalanced data can be successfully used to answer research questions (Smith et al., 2005). Examples of

Australian research that have used unbalanced data and focussed on wheat quality are Eagles et al. (2002a, 2002b), Cane et al. (2004) and Eagles et al. (2004). A feature of these studies has been the use of large data sets. As with this research, an underlying rationale for using a large data set was that potential bias could be controlled with appropriate mixed-model statistical methodologies. Furthermore, the determination of variances to understand differences between production areas has been successfully achieved by allocating testing locations to production areas of interest (Pritchard et al., 2000, Bell, 2003). Consequently, this research was undertaken knowing that previous studies had successfully used unbalanced data examining wheat quality issues and compared variance levels based on groupings of locations together.

Chapter 4 Creation of a relational database

The creation of a single relational database containing quality measurements of samples grown at locations across the Australian wheat-belt is described in this chapter. Such a database was considered critical to providing a platform from which to efficiently select, and transfer data for the subsequent statistical analysis components of this research.

4.1 Methodology

4.1.1 Source and selection of data

Australian breeding programs each have large, independent quality data sets, representative of the varieties they have developed, for the geographical areas they target. To undertake this research, however, a national quality dataset was required. Consequently, negotiations with Australian breeding programs secured the use of commercial-in-confidence data, enabling the creation of a single, relational database representative of quality testing performed on samples grown at locations across the entire wheat-belt. A schematic of the relationships between the tables in the database is shown in Figure 15. The primary keys are in bold, and illustrate the relationships between unique identifiers (denoted as 1) and many observations (denoted as ∞).

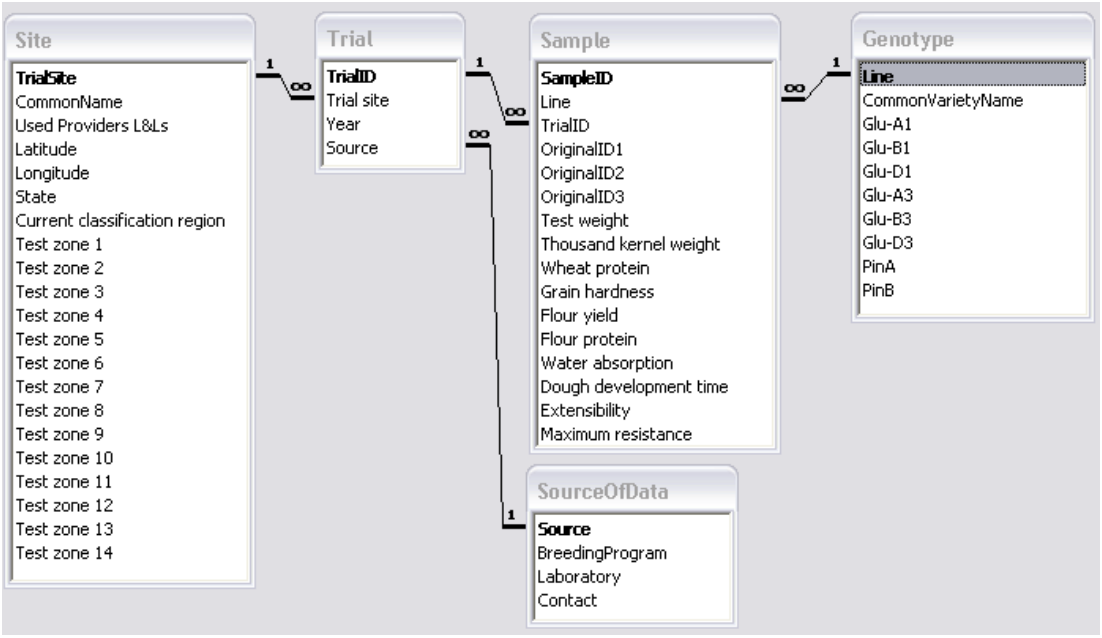


Figure 15 Schematic of relational database primary key linkages between tables

The sources of data have been listed in Table 14 and these were divided into 4 categories. These were established breeding programs, new breeding programs, coordinated regional testing and industry funded research projects. The majority of data came from established breeding programs, but importantly for areas in the eastern portion of the wheat-belt, these were supplemented by results from regionally coordinated regional and industry funded research testing.

The data initially received from those sources was expansive. It included observations for each of the 10 tests that were ultimately selected to form the relational database (see Section 4.2.1 *Summary of selected quality traits*) plus other tests. Measurements not included in the relational database were from instruments used in single laboratory. For example, Agtron measurements of flour colour and purity were only conducted by the Department of Agriculture and Food Western Australia. Measurements were also not included when different methods were used for a generic in name tests such as a bake test. These measurements were not included because there was no common basis for comparison across all the 'sources of data'. Furthermore, some observations had not been tested for important inherent quality traits such as flour yield, mixing and dough properties, only having had physical analyses carried out on them. These too were omitted from the data selected to make up the relational database because the study was focused on inherently linked quality traits associated with making a classification decision. The criteria for an observation to be included in the relational database was that it had a near complete set of measurements for protein, flour yield, water absorption, dough development time, extensibility, and maximum resistance.

The selected data represented 24,032 unique observations, or rows, in the relational database (Table 14). Each row had results for a maximum of 10 quality traits, plus ancillary information such as latitude and longitude. Collectively, the data represented a large number of testing locations across the wheat-belt and a wide range of genetic material, the bulk of which were unreleased breeding lines (generally advanced homozygous material given the quality tested performed) and, released or named varieties. For the purposes of this research all were considered homozygous. In chapters Chapter 4 to Chapter 7 these collectively will be referred to as 'lines'.

Table 14 Summary of selected data used to create the relational database

Source of quality data (testing laboratory in parenthesis)	Number of lines	Number of unique observations (equates to rows in database)	Number of locations	Number of harvests	Time span of harvests sampled
Established breeding programs					
Department of Agriculture and Food Western Australia (tested at Perth laboratory)	1,395	7,773	110	20	1983-2002
NSW Agriculture (tested at Wagga Wagga laboratory)	337	2,523	21	11	1993-2003
QDPI [Composites] (tested at Toowoomba laboratory)	162	362	-	10	1994-2003
SA[1] (tested at SARDI Adelaide)	340	6,467	70	21	1982-2002
Manual Entries – SA	21	61	5	1	1995
SunPrime Seeds Pty Ltd (tested at BRI Australia laboratory)	239	631	8	6	1997-2002
Victorian Department of Agriculture (tested at Horsham laboratory)	243	2,671	42	12	1990-2001
New breeding program					
LongReachPlant Breeders (tested at Agrifood Technology, Horsham and BRI Australia Limited laboratories)	25	110	9	3	2001-2003
Coordinated-regional testing					
Interstate Wheat Variety Trials (tested at BRI Australia laboratory)	286	1,525	8	12	1983-1994
NSW Uniform Quality Testing (tested at Agrifood Technology)	36	182	26	7	1995-2001
Industry-funded research					
Flexibility of Wheat Use (tested at Wagga Wagga laboratory)	15	350	15	4	1998-2001
Prime Hard in the South[2] (tested at Wagga Wagga laboratory)	4 2	335 2	22	3	1995-1997
Manual Entries – "Prime Hard in the South Project"	2	7	1	1	1995
Sponge and Dough (tested at Toowoomba laboratory)	30	417	3	3	2000-2002
Skerritt et al (2003)[3] (tested at Wagga Wagga laboratory)	157	618 3	4	3	1997-1999

Notes

SA[1] represents testing of lines developed by the 2 former streams of breeding undertaken by the University of Adelaide, now under the control of Australian Grain Technology

Prime Hard in the South[2] Excludes the 2 tests of VI252

Skerritt et al (2003)[3] Includes replicated sites used from different sources

Locations were geographic places throughout the wheat-belt, at which single or multiple trials had been grown and from which samples had been harvested and quality tested. Irrespective of the number of trials harvested each year at a given geographical site, in the relational database and for subsequent statistical analyses they were considered as a single location. The only exception to this rule was the inclusion of the long-term QDPI composite measurements. That was a compromise decision, because without the QDPI composite measurements this research would have had to stop at the NSW-Queensland border. The use of location composite samples is not favoured because it loses any differentiation ability.

The measurements from 'all sources of data' originated from a single testing laboratory. The data from LongReach Plant Breeders was an exception with Agrifood Technology testing samples in 2001 and 2002, VIDA tested the 2003 samples, and 3 observations included from the National Wheat Quality Testing conducted at BRI Australia.

It was assumed that the replicated trials used to produce the samples for quality testing were grown to the agronomic standards of the day for that production area. As is the norm for advanced quality testing of lines by Australia's breeding programs, quality testing was performed on composite samples, compiled from the replications within those trials. It was also assumed that the seed grown and tested was true to type as it related to each line.

Samples were generally tested only once due to cost and efficiency with laboratories employing process control mechanisms to achieve accurate and precise measurements. However, limited repeat testing of the same line x environment combinations were available. Lines considered as checks were assessed at many environments so that complete confounding of the data had not occurred (Table 15). For example, some lines were tested many times across all states like Janz and Hartog, whereas the testing of others had been restricted to 2 or 3 states like Rosella, Spear and Machete, while the testing of some lines was dominated by testing in a 1 state such as Gutha, Molineux and Cascades.

Table 15 The top 15 lines based on their number of observations

Lines	New South Wales	Queensland	South Australia	Victoria	Western Australia
Spear	-	-	289	-	264
Machete	1	1	247	20	220
Janz	154	11	177	82	63
Rosella	95	-	115	187	13
Meering	9	5	198	171	13
Halberd	19	7	293	8	62
Gutha	-	-	3	-	349
Kite	74	13	207	10	12
Eradu	7	-	-	3	226
Molineux	2	-	211	1	1
Hartog	78	48	31	14	34
Goldmark	32	4	33	108	13
Cascades	3	-	14	-	172
Frame	22	4	93	55	11
Wilgoyne	8	5	26	4	131

4.1.2 Data that required amendment for inclusion in the relational database

The SA quality measurements (see Table 14 for description of the SA source) were initially received as 3 separate sub-sets. They were a cereal chemistry laboratory archive data sub-set for 1985-1998, the SARDI S4 trial data sub-set from 1981-2002, and the Roseworthy breeding quality data sub-set from 1982 –1996. Duplication and triplication occurred across the 3 sub-sets. Since a database cannot contain duplication, the 'archive sub-set' was considered as the default as it was the most comprehensive sub-set. Additional observations were included from the other 2 sub-sets if not contained in the 'archive sub-set'. It was this single set of combined SA data that was used in the relational database.

The standard reporting of extensibility is to 1 decimal place. Approximately 57% of the SA extensibility results were received having whole numbers, and this was attributed to formatting of the original spreadsheets compiled in SA. However, some of these observations had both flour protein and an E/P ratio records (E/P equates to an extensibility per unit of protein ratio). For such observations a 1 decimal place extensibility prediction could be calculated and these were included in the relational database. Observations without extensibility to 1 decimal place were omitted from the relational database.

The SA data sets, as originally received, were referenced in some instances to trial managers instead of a geographic location. In some cases it was to a single trial collaborator, but in other cases multiple collaborators conducted trials at or around the same location. In both these instances the name of the single closest geographical location was chosen to replace the name of the trial collaborator(s).

The relational database was finalised after running searches to identify any observations with the same maximum resistance, flour yield, grain hardness and year values. Where duplicates were identified, 1 was removed. In some cases this extended to deleting line synonyms as was the case for (WR*HZ)MKRK/11/4 WT7 and WI960EP(C8).

4.1.3 Line names and synonyms

Breeding programs maintain a unique coding system for their lines. At the time of a line being released, this code is converted into a unique name. Therefore, to avoid synonym duplication, codes were converted to a line name based on available information (Ferns et al., 1975, Fitzsimmons et al., 1983, 1985, Gore, 1989, Wrigley et al., 2001, Whiting, 2004).

4.1.4 Latitudes and longitudes

For each location, the latitude and longitude in degrees and minutes to an accuracy of within 1 minute of latitude/longitude (approximately 1.8 km) were obtained from the Australian Government GeoScience Australia Place Name Search engine found at http://www.ga.gov.au/map/names/. Where no GeoScience latitude and longitude for a particular location was available (in the case of obscure locations) the latitude and longitude from the original source was used for the location. Latitude and longitude coordinates were changed to decimal degrees so that maps could be plotted using Geographical Information System software. Latitude and longitude details for each trial location are in the Appendices.

4.2 Results

4.2.1 Summary of selected quality traits

Ten quality trait measurements were selected for inclusion in the relational database (Table 16). These traits were selected because of their commonality between sources of data and that the same instrument had been used to perform the test by the different sources of data. For example, flour yield was determined using a Buhler Test mill, water absorption and dough development time using a Farinograph, and extensibility and maximum resistance using an extensograph. Furthermore, an underlining criterion was that the quality results must be representative of a single location, noting the exception of Queensland composite results as previously discussed. It was assumed that the quality samples tested were free of weather damage and therefore sound.

Table 16 Summary of quality traits contained in the relational database

Quality Trait	Number of observations	Mean	Min	Max	Skewness	Kurtosis
Test weight (kg/hl)	20,793	80.3	58.2	89.1	-0.96	1.79
Thousand-kernel weight (g)	15,268	35.5	17.0	58.2	-0.04	0.13
Grain hardness (PSI)	22,717	18.9	1.1	40.0	0.49	-0.05
Wheat Protein - (%)	16,070	11.8	6.7	18.8	0.14	-0.16
Flour Yield (%)	24,001	74.2	50.4	82.7	-0.50	3.10
Flour protein (%)	14,926	10.3	5.8	21.0	0.39	0.28
Water absorption (%)	24,018	60.8	46.6	87.9	0.02	0.48
Dough development time (min)	24,013	4.4	0.5	30.0	2.42	14.25
Extensibility (cm)	24,003	20.3	10.2	30.2	-0.02	-0.24
Maximum resistance (BU)	24,019	333	20	1,000	0.48	0.54
Protein* (%)	24,032	10.6	5.6	21.0	0.27	0.03
Protein* every observation contained either an original flour protein value, or a predicted flour protein value						

When the results from the various sources were pooled together, each quality trait generally was considered to have a normal distribution based on tests of skewness and kurtosis. Dough development time was a notable exception with high skewness and kurtosis values. These non-normal measurements were attributed to the standard laboratory procedure stopping at 15 minutes, and 121 measurements recorded beyond that time.

It should also be noted that the range for some quality traits might be considered outside the normal range expected with grain hardness, flour yield, water absorption and extensibility falling into this category. All the data received from the various

sources was used without prejudice. Therefore, because it was assumed that data provided to this study had undergone in-house checking, all observations were used even if they seemed unusually high or low.

All observations had either a wheat or flour protein measurement, but some did not have both. To ensure compatibility, an estimated flour protein was calculated on the basis of the strong correlation between wheat and flour protein measurements (Baker et al., 1971, Fischer et al., 1989, van Lill et al., 1995b, Eagles et al., 2006a). To make that calculation, observations with both wheat and flour protein values were identified. These 6,559 pairs had a correlation (r) of 0.95. The mean difference between the wheat and flour protein values of these pairs was 1.1%. Consequently, for observations that did not have an original flour protein, that mean difference was used to estimate a flour protein level. In the relational database, the original and estimated flour protein levels were simply referred to as 'protein'.

The number of observations with a full complement of quality trait measurements varied across the relational database. The only trait for which every observation had a result was 'protein'. Traits with a minimum number of missing measurements were maximum resistance (missing 13), water absorption (missing 14), dough development time (missing 19), extensibility (missing 29), and flour yield (missing 31). These traits were considered the full data set. The remaining traits had missing measurements such that they were considered as part data. These were grain hardness (missing 1,315), test weight (missing 3,239) and thousand-kernel weight (missing 8,764 values). All measurements had been determined according to standard industry methods

4.2.2 Genotypes and environments

The relational database contained observations for 2,793 lines. The number of different environments, equating to unique location x year combinations, was 978.

4.2.3 Locations

The data represented samples collected from 287 locations across the entire wheat-belt (Figure 16). That total was composed of 286 individual locations and the

Queensland composite measurements (red = individual locations and blue = locations used in making Queensland composites). Not all locations were tested every year, but multiple observations (≥10) were available for 84% of locations, with the top 15 locations shown in Table 17. Each state, with the exception of Victoria, was represented in the top 15, although the 2 locations with the highest number in Victoria were not that much smaller than the 15th ranked location (Table 17).

Table 17 Top 15 locations based on number of observations

Location (State)	Number of observations at that location	Location (State)	Number of observations at that location
Wongan Hills (WA)	2,235	Temora (NSW)	436
Merredin (WA)	872	Queensland Composite	362
Wagga Wagga (NSW)	776	Urania (SA)	358
Narrabri (NSW)	708	Minnipa (SA)	323
Newdegate (WA)	699	Bordertown (SA)	321
Stow (SA)	615	Roma (QLD)	296
Turretfield (SA)	507	Roseworthy (SA)	287
Chapman (WA)	500	*Rutherglen and Dooen (VIC)*	*241 and 240*

The number of locations used to make up each Queensland composite is shown in Table 18. The number of samples used to make the composites ranged from 2 locations used to make the 2001 Main series composite to 13 locations used to make composites in 1995 and 2002.

Table 18 Preparation of Queensland composite samples that were quality tested

Harvest	Trial series descriptor	Total number of locations in composite
1994	Intermediate	4
	Midseason	3
	Quick	5
1995	Intermediate	13
	Midseason	11
	Quick	13
1996	Intermediate	8
	Midseason	9
	Quick	11
1997	Quick/Intermediate	8
	Slow	12
1998	Quick/Intermediate	5
	Slow	9
1999	Quick/Intermediate	4
	Slow	3
2000	Early	7
	Main	7
2001	Main	2
2002	Early	13
	Main	7
2003	Early	3
	Main	3

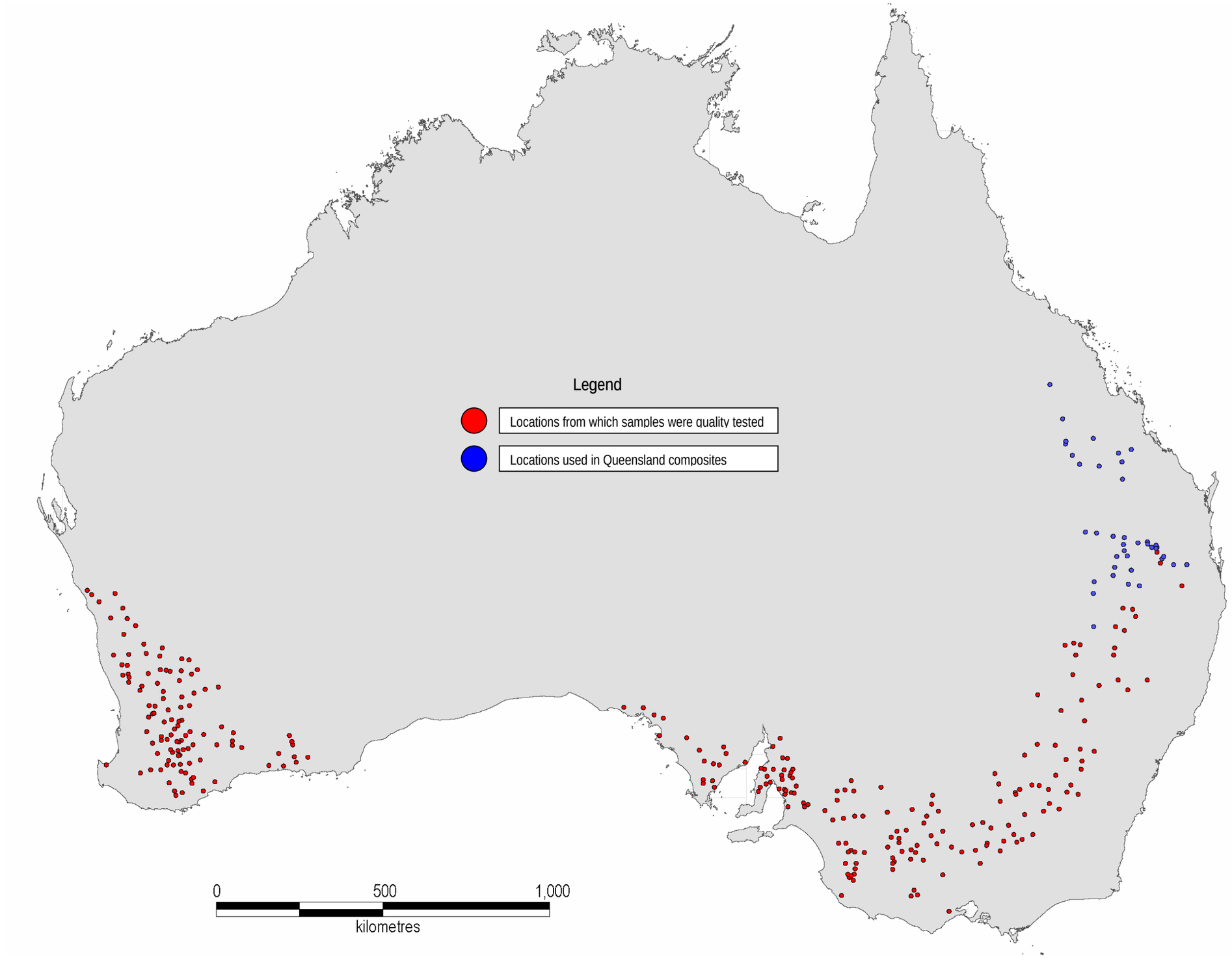


Figure 16 Distribution of locations from which samples were obtained for testing

4.2.4 Years

The observations in the relational database represented testing of samples grown in 22 different years from 1982 to 2003. The coverage of years by the different 'sources of data' varied in time and length. The SA data, and that from the Department of Agriculture and Food Western Australian were the largest; the former spanned 1982-2002 and the latter representative of testing in the seasons 1983-2002. The smallest data sets represented testing across 3 years (LongReach Plant Breeders, the Prime Hard in the South project, Sponge and Dough project, and Skerritt et al (2003)). The number of observations was not uniform across the years in the relational database. The most testing, occurred in 2000 while the lowest level of testing occurred in 1982, 1986 and 2003 (Figure 17).

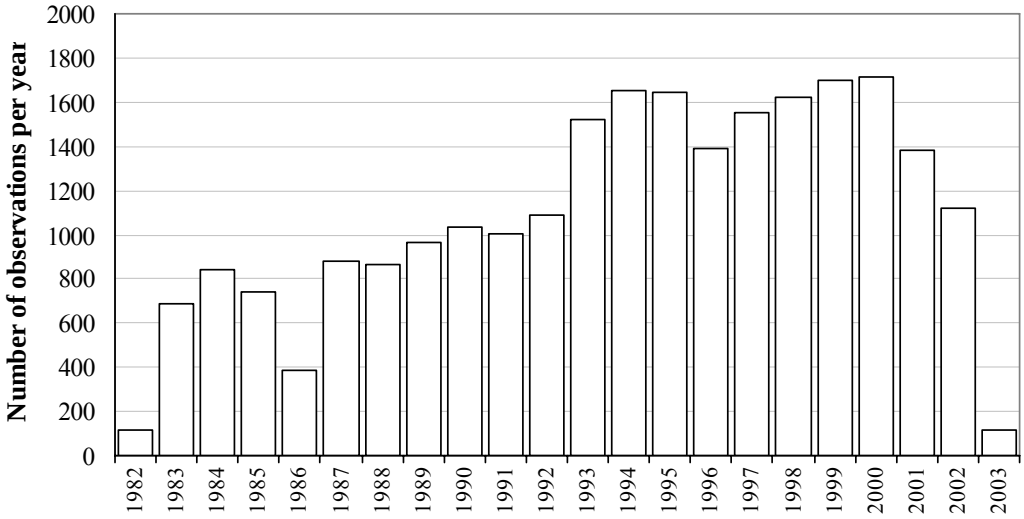


Figure 17 Distribution of observations in the relational database over time

4.2.5 Sources of data

In total, 14 different 'sources of data' were linked to the quality measurements in the relational database (see Table 14 Summary of selected data used to create the relational database page 75). The linking of source of data to measurements was important because it would allow 'source of data' to be used as a factor in subsequent statistical analyses. The importance of recognising differences in results from different laboratories discussed in the literature review (see Section 2.1.6 *Sources of testing error,* page 16).

4.3 Discussion

The relational database created was an efficient use of resources. To repeat the number of tests it was estimated that it would cost between $8.5-11 million dollars in today's terms (L. Iyer, J. Panozzo, and M.Southan pers comm., 2006). In addition, this was the first time that such a set of data in spatial and temporal terms had been put together representing quality assessments across the entire Australian wheat-belt. Whilst large, a feature of the data was that is was unbalanced, in that the same set of lines and locations had not being regularly tested across all years. Completely unbalanced data was avoided by repeat testing of both control lines and locations. Furthermore, the data was restricted to nine quality measurements and these did not include end-products.

Chapter 5 Evaluation of G×E on wheat quality

The research described in this chapter determined whether G×E had a significant effect on 8 wheat quality traits. A series of balanced data comparisons were used to generate results to make that determination. Finding an absence of significant G×E meant that rankings of genotypes and environments occurred in a predicted and consistent manner, thus offering simplification in the statistical models to be subsequently used in investigating the hypothesis.

5.1 Background

The presence of G×E is acknowledged as a hindrance to breeding progress and the selection of consistent performing lines (Kang and Gauch, 1996). To use the relational database created with confidence for the identification of alternative sets of zones to the current classification regions, it was important to know the level of G×E. An influential level of G×E related to inconsistent rankings of lines and or environments, and this would make it more challenging to use the data as planned in investigating the hypothesis.

5.2 Methodology

5.2.1 Source of data

Balanced line by location by year sub-sets (henceforth referred to as comparisons) were identified from the relational database representing testing conducted in New South Wales, South Australia, Victoria and Western Australia. Queensland was not sampled, since the long-term data were representative of composite samples and not individual locations.

The comparisons selected were considered balanced as they had the same lines, tested over multiple years (not necessarily consecutive) at the same set of locations. That criterion resulted in 44 balanced comparisons being identified from the relational database. The comparisons represented different combinations of grain hardness. Uniform hard-grained comparisons were identified for all states, while uniform soft-grained comparisons were only identified for South Australia and Western Australia. Mixed comparisons of hard and soft-grained lines were identified for all states (Table 19).

Table 19 The unique comparisons selected for analysis

State	Grain Hardness Type			State totals
	Hard	Soft	Mixed	
New South Wales	6	-	6	12
South Australia	8	2	3	13
Victoria	2	-	6	8
Western Australia	6	1	4	11
Grain hardness type totals	22	3	19	44

The combinations were generally of similar size, although the number of lines tested was noticeably greater for South Australia (Table 20). The South Australian and Victorian comparisons had a greater variability in the number of locations tested. The Victorian comparisons were tested for the least number of years.

Table 20 The specifications of 44 unique comparisons studied

Notes
The order of information from left to right is the grain hardness category (H = comparison made up of only hard-grained lines, S = comparison made up of only soft-grained lines, and M = comparison made up of both hard and soft-grained lines); the number of lines, locations and years in each comparison; and then the starting year of that comparison. Comparisons showing an * indicate that while the number of lines or locations or years were the same, the actual composition was different. Comparisons with [BRI] indicate that they were tested as part of the Interstate Wheat Variety Trial Program

New South Wales					South Australia					Victoria					Western Australia				
Grain hardness category	Lines	Locations	Years	Starting year	Grain hardness category	Genotypes	Locations	Years	Starting year	Grain hardness category	Genotypes	Locations	Years	Starting year	Grain hardness category	Genotypes	Locations	Years	Starting year
M [BRI]	3	2	6	1984	M	17	3	3	1982	M	2	4	3	1990	M	2	4	3	1983
M [BRI]	5	2	4	1984	S	4	4	2	1986	M	4	3	2	1993	M	2	4	5	1987
M [BRI]	5	2	3	1990	M	2	3	5	1987	M	3	8	2	1993	M	2	5	4	1989
H	5	3	2	1993	S	3	4	3	1989	M	8	7	2	1993	M	3	4	4	1989
H	4	2	2	1994	M	4	3	3	1989	M	5	4	2	1996	H	4	3	3	1992
H	2	4	3	1995	H	4	5	3	1990	M	3	4	2	1998	H	2	4	3	1993
H	3	3	3	1995	H	3	6	3	1994	H	2	5	2	2000	H	4	3*	3*	1993
H	3	4*	2*	1995	H	4	7	2	1995	H	3	4	2	2000	H	4	3*	3*	1993
M	3	4*	2*	1995	H	6	3*	3*	1997						S	2	2	4	1994
M	5	2	3	1996	H	7	3	4	1997						H	3	3	3	1998
H	4	2	2	1997	H	7	4	3	1997						H	3	4	3	1998
M	3	2	3	1999	H	10	3*	3*	1997										
					H	10	4	2	1997										

Care was taken to identify comparisons spread over time for each state. To illustrate this, the number of locations and years making up combinations were graphed (Figure 18 to Figure 21). The y-axis is the number of locations tested. The x-axis is

the first year of testing of that comparison. The bubble size equates to the number of years testing occurred for that comparison (further explanation has been provided on Figure 19). A limitation in the graphics software meant it was only able to show a single comparison when in fact 2 existed with the same number of locations and years.

In New South Wales, only 1 of the 2 comparisons that started in 1995, had 4 locations, and ran for 2 years, is visible (Figure 18). These 2 comparisons had the same number of locations and years, but the composition of lines, locations and years was different.

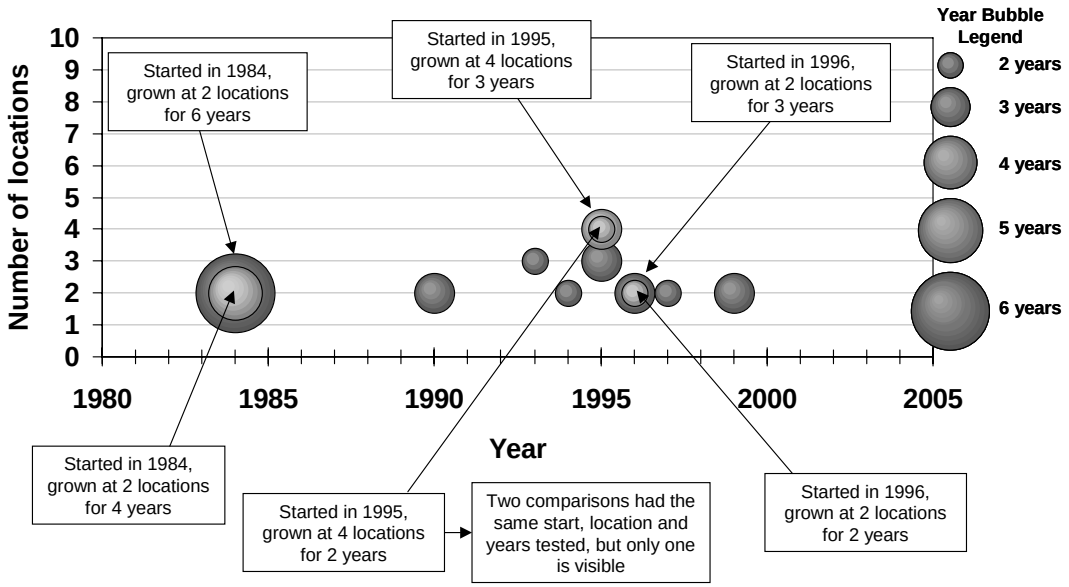


Figure 18 Spread over time of the comparisons selected for New South Wales

In South Australia, only 1 of 2 comparisons that started in 1997 having 3 locations and 3 seasons can be seen (Figure 19). These 2 comparisons differed in the composition of locations and lines.

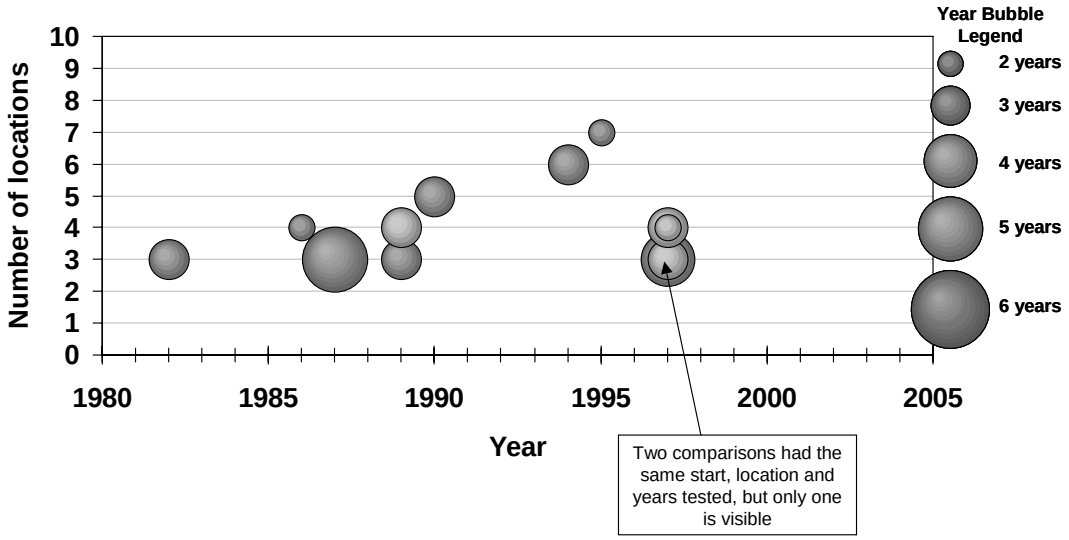


Figure 19 Spread over time of the comparisons selected for South Australia

None of the Victorian comparisons had the same number of locations and years, and started in the same year (Figure 20).

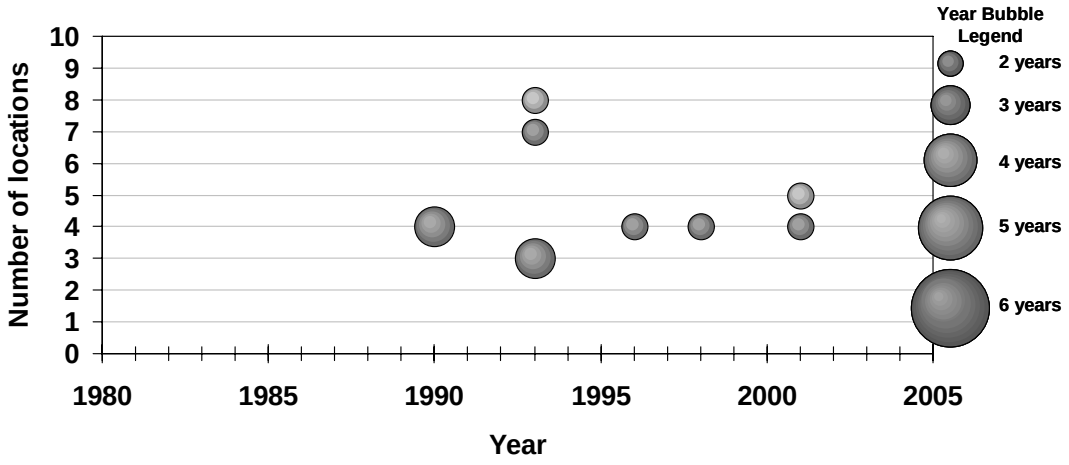


Figure 20 Spread over time of the comparisons selected for Victoria

In Western Australia, only 1 of 2 comparisons starting in 1993 that had 3 locations and 3 seasons can be seen (Figure 21). The comparisons differed in location and years composition.

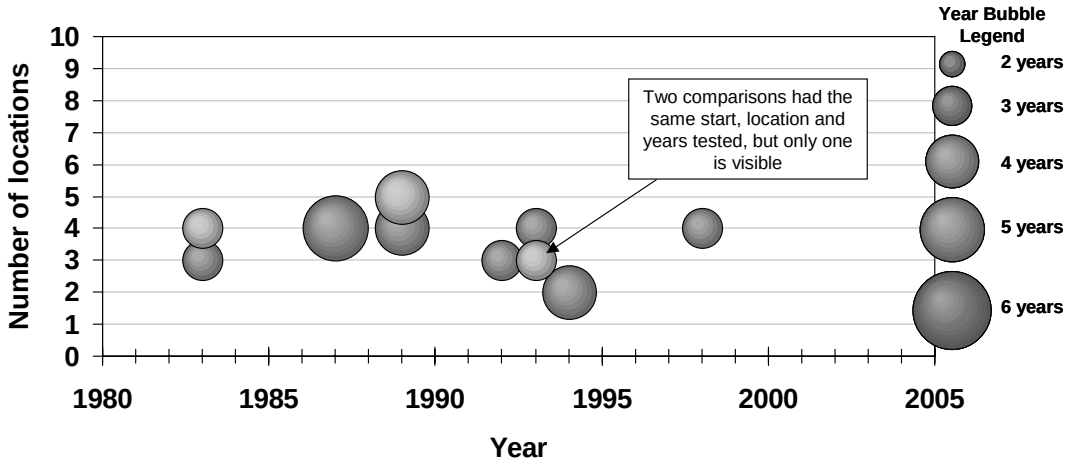


Figure 21 Spread over time of the comparisons selected for Western Australia

Each comparison had the following quality trait measurements - test weight, grain hardness, either grain or flour protein, flour yield, farinograph water absorption and dough development time, and extensograph extensibility and maximum resistance. The Victorian comparisons did, however, have no test weight measurements. No distinction was made between the wheat and flour protein measurements, due to the accepted relationship between grain protein and the resultant flour protein level (Baker et al., 1971, van Lill et al., 1995b, Eagles et al., 2006a). The minimum set of quality measurements, for each comparison, were single tests representative of each line by location by year observation. However, in 31 comparisons, multiple quality measurements of the same line were available for unique location and year combinations. In these comparisons the number of quality assessments were not the same for each line. In total, the 44 comparisons represented 3,115 line x location x year maximum quality observations.

The quality measurements of each comparison were from a single testing laboratory. The majority of results came from laboratories associated with the respective breeding programs (eg New South Wales – Wagga Wagga, South Australia – SARDI, Victoria – Horsham and Western Australia – Perth). However, measurements for 3 mixed New South Wales comparisons originating from trials at Narrabri and Wagga Wagga were conducted as part of the Interstate Wheat Variety Trials program, tested at the then Bread Research Institute in Sydney. No results from Pumpa et al. (2002) were used.

5.2.2 Statistical analyses

An analysis of variance was used to assess the significance of genotype and environment on the aforementioned quality measurements following the approaches taken by Baenziger et al. (1985) and Peterson et al. (1992) when analysing balanced data. However, since some comparisons (31 in total) were nested samples the unbalanced treatment structure in GENSTAT was used (Payne et al., 2003). That structure carries out the analysis of variance using regression facilities. The factors analysed were genotype, environment (considered unique location by year combinations) and G×E. For each state, the individual analyses of variances were used to determine the frequency of significant effects (at a level of $P < 0.05$). To appraise these frequencies, they were pictorially presented as a cumulative percentage, divided into 5 categories (0-19%, 20-39%, 40-59%, 60-79% and 80-100%).

In addition, variance components and standard errors were estimated using the restricted maximum likelihood (REML) directive in GENSTAT (Payne et al., 2003). REML was used because of the nested nature of the data described above. To avoid negative variance components, the 'average information' algorithm was used (as opposed to Fisher's Scoring) whereby negative variance components values were given an estimate of zero. Two models were run. The first treated genotype, environment, and G×E, all as random. The second model used genotype, location, and year (the available components of environment) as the random factors. In the second model the G×E was incorporated in the residual term because it had been observed from the first model that G×E had a negligible contribution to variance.

For each state, average percentages, based on the estimated variance components for each comparison, irrespective of grain hardness, were determined. In addition, average percentages were calculated for the 3 hardness groups: hard, soft and mixed.

5.3 Results

A systematic approach was taken to evaluating the level of G×E on quality traits. The summarised results from those analyses have been divided into the following 5

sub-sections. The first examines the frequency of significant effects (Section 5.3.1). The next 4 sections focus on assessments of estimated variance components. The first of these summarises the results from a REML model based on genotype, environment, and G×E random factors (Section 5.3.2). The next outlines the results from the REML model based on genotype, location, and year factors (Section 5.3.3). The third section reports on how genotypic differences altered variance components (Section 5.3.4) and the final section reports on the relative size of residual variance (Section 5.3.5).

5.3.1 Frequency of significant effects

To obtain an overview of how quality traits were influenced by genotype, environment or G×E, the analysis of variance results for each state were expressed as a frequency (Figure 22). The cumulative percentage of $P < 0.05$ represented the number of analyses for each state-quality trait pair significant at or below that level. For example, a state-quality trait pair that is red is representative of between 80-100% of the analyses for that pair being statistically significant at $P < 0.05$. In contrast, white is reflective of only 0-19%, equivalent to 1 or 2 analyses (depending on the total for that state) being statistically significant at $P < 0.05$. The rationale was that instead of considering just one combination, assessing the frequency of responses of all comparisons would provide a better understanding of what was the most important 'average' effect in each state considered.

Considered in that way, the frequency of state-quality trait pairs being statistically significant varied for the 3 factors of interest (Figure 22). The frequency of significant G×E was low compared with that for environment and genotype. In South Australia, G×E was not significant for any quality trait. The highest frequency of significant G×E was in the 40-59% range and this was observed for 2 state-quality trait pairs – grain hardness in Western Australia and flour yield in New South Wales. Lower frequency levels of statistically significant G×E were observed for other quality traits in New South Wales, Western Australia, and Victoria (Figure 22).

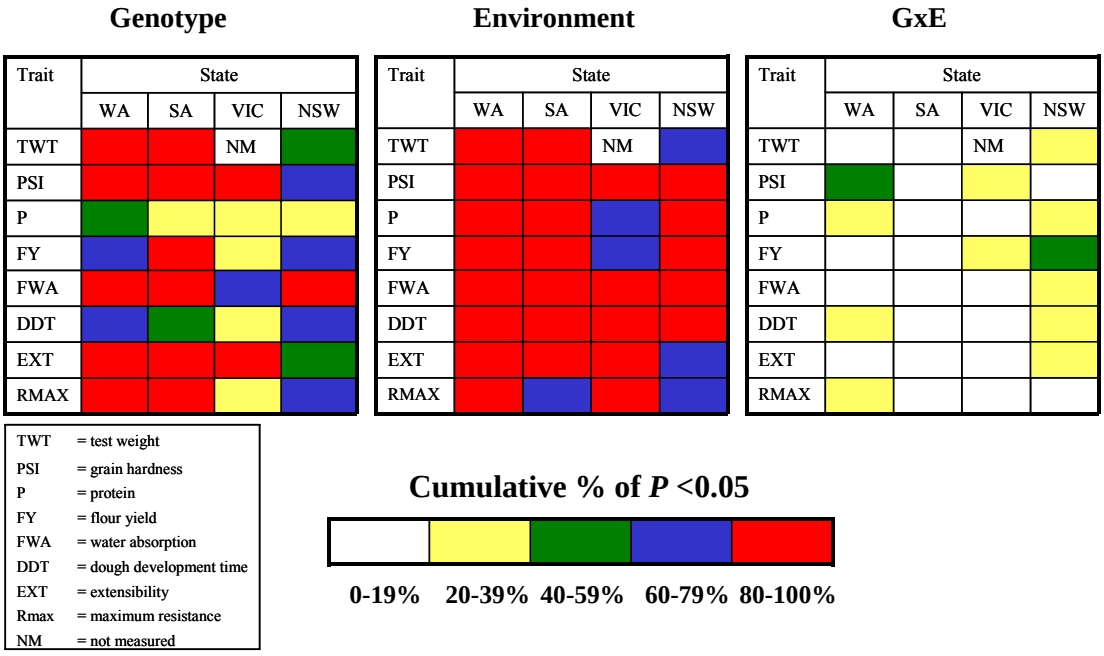


Figure 22 Significant sources of variance on 8 quality traits

The state with the greatest occurrence of G×E was New South Wales. Test weight and protein had statistically significant G×E for 3 out of 12 analyses (20-39% range). Water absorption, dough development time and extensibility had statistically significant G×E for 4 out of 12 analyses (20-39% range). However, the frequency of significant G×E for these quality traits, and flour yield, was always lower than that for both environment and genotype.

The other 2 states where significant G×E was observed were Western Australia and Victoria. In Western Australia, G×E had a significant effect on protein content for 3 out of 11 analyses (20-39% range), and on dough development time and maximum resistance in 4 out of 11 analyses (20-39% range). In Victoria, grain hardness and flour yield were statistically significant for 2 out of 8 analyses (20-39% range).

In contrast, the frequency of statistical significance for genotype and environment for all state-quality trait combinations was greater than 20% in all cases (Figure 22). It was observed that across the 4 states and 8 quality traits examined that environment had a greater impact than genotype. The number of state-quality trait pairs in the 80-100% bracket of cumulative frequency was 25 for environment, double the 14 for genotype (Figure 22).

5.3.2 Variance components summary (genotype, environment and G×E model)

Estimated variance component ratios were calculated to further investigate which factors had the most important affect on quality traits (Table 21). These ratios showed that environmental variance was generally larger compared with either genotype or G×E, but the relative size varied. The smallest ratio was 1.2 for maximum resistance in South Australia and the greatest was a 35.2 fold increase for protein content, also in South Australia. Exceptions were noted, with average genotypic variance across states greater than that for environment for 2 quality traits, grain hardness and water absorption (Table 21). The magnitude of environmental variance compared with that of G×E was even greater with the lowest ratio being 3.8 for grain hardness in New South Wales and the highest ratio being 4,412.1 for protein content in South Australia (Table 21).

Table 21 Average estimated variance component ratios for each state

Notes: $\hat{\sigma}_e$ = estimated environmental variance, $\hat{\sigma}_g$ = estimated genotypic variance, and $\hat{\sigma}_{g\times e}$ = estimated G×E variance and South Australia* test weight ratios were based on only 11 comparisons

Trait	Ratio	New South Wales (13 comparisons)	South Australia* (13 comparisons)	Victoria (8 comparisons)	Western Australia (11 comparisons)
Test weight	$\hat{\sigma}_e / \hat{\sigma}_g$	7.4	1.8	Not measured	2.8
	$\hat{\sigma}_e / \hat{\sigma}_{g\times e}$	19.0	27.4		14.0
Grain hardness	$\hat{\sigma}_e / \hat{\sigma}_g$	0.4	1.9	0.5	0.7
	$\hat{\sigma}_e / \hat{\sigma}_{g\times e}$	3.8	15.8	11.2	7.1
Protein	$\hat{\sigma}_e / \hat{\sigma}_g$	15.6	35.2	16.3	15.4
	$\hat{\sigma}_e / \hat{\sigma}_{g\times e}$	27.9	4,412.1	42.9	12.7
Flour yield	$\hat{\sigma}_e / \hat{\sigma}_g$	2.8	5.1	9.8	1.3
	$\hat{\sigma}_e / \hat{\sigma}_{g\times e}$	4.3	13.0	4.1	21.3
Water absorption	$\hat{\sigma}_e / \hat{\sigma}_g$	0.9	1.0	0.8	0.8
	$\hat{\sigma}_e / \hat{\sigma}_{g\times e}$	9.7	62.8	13.1	11.5
Dough development time	$\hat{\sigma}_e / \hat{\sigma}_g$	2.3	5.9	4.9	1.8
	$\hat{\sigma}_e / \hat{\sigma}_{g\times e}$	6.0	32.3	22.0	4.2
Extensibility	$\hat{\sigma}_e / \hat{\sigma}_g$	2.4	3.2	4.1	4.0
	$\hat{\sigma}_e / \hat{\sigma}_{g\times e}$	5.3	153.7	22.0	12.4
Maximum resistance	$\hat{\sigma}_e / \hat{\sigma}_g$	1.9	1.2	3.9	2.0
	$\hat{\sigma}_e / \hat{\sigma}_{g\times e}$	18.1	17.0	9.1	10.9

5.3.3 Variance components summary (genotype, location and year model)

The assessment of estimated variance components based on genotype, location and year, with G×E incorporated into the residual error, provided further insights into the relative variance of these factors on quality (Table 22). The discussion of results has focused on the genotype, location and year factors.

Table 22 Summary of estimated variance components for 8 quality traits

Trait	Factor	Average estimated variance components expressed as a percentage			
		NSW (12 comparisons)	**SA** (13 comparisons)	**VIC** (8 comparisons)	**WA** (11 comparisons)
Test weight	Genotype	7.7	25.9	Not measured	15.3
	Location	18.0	12.2		11.8
	Year	**38.8**	**27.7**		**23.6**
	Residual	*35.5*	*34.2*		*49.2*
Grain hardness	Genotype	**46.1**	**23.8**	**55.9**	**42.8**
	Location	12.0	16.3	6.2	5.6
	Year	4.9	20.6	19.3	11.8
	Residual	*37.0*	*39.3*	*18.6*	*39.8*
Protein	Genotype	3.9	1.3	3.5	2.3
	Location	16.7	**34.8**	**37.2**	12.5
	Year	**49.3**	28.5	25.2	**29.1**
	Residual	*30.2*	*35.4*	*34.1*	*56.1*
Flour yield	Genotype	14.4	10.5	4.2	**29.1**
	Location	16.5	15.6	15.8	17.5
	Year	**21.5**	**35.4**	**22.7**	11.5
	Residual	*47.6*	*38.5*	*57.3*	*41.9*
Water absorption	Genotype	**41.0**	**36.0**	34.3	**44.6**
	Location	6.1	14.3	3.9	10.4
	Year	29.8	10.0	**35.7**	21.2
	Residual	*23.1*	*39.7*	*26.1*	*23.8*
Dough development time	Genotype	20.2	8.5	9.8	20.4
	Location	13.6	**28.0**	**26.5**	5.2
	Year	**39.7**	15.0	13.4	**27.1**
	Residual	*26.6*	*48.4*	*50.3*	*47.3*
Extensibility	Genotype	17.0	18.0	13.3	11.1
	Location	10.5	**25.6**	20.5	6.8
	Year	**25.5**	19.7	**26.5**	**27.0**
	Residual	*47.0*	*36.7*	*39.7*	*55.1*
Maximum resistance	Genotype	22.8	**30.5**	13.6	23.2
	Location	19.6	16.2	**29.9**	13.9
	Year	**30.6**	17.1	4.3	**27.2**
	Residual	*27.0*	*36.3*	*52.2*	*35.7*

Values in **BOLD** are the highest of genotype, location or year
The residual estimated variance component is in *Italics*

In New South Wales, the size of the year variance component was generally larger than that for genotype or location (Table 22). The effect of year exemplified on test weight, protein, test weight, and dough development time. In contrast, genotype variance was the largest for grain hardness and water absorption, while for flour

yield the contributions of genotype, location and year to variance were similar in size to each other.

Like New South Wales, the size of the year variance compared with genotype and location was generally larger in Western Australia (Table 22). For example, the size of the year variance was most pronounced on protein and extensibility. In contrast, the relative size of genotype variance was notably larger for grain hardness and water absorption. For the other 4 traits, variance was more evenly spread across factors, with year generally the highest, exception being flour yield.

The results for South Australia, in contrast to New South Wales and Western Australia, showed that location differences were generally more important than year (Table 22). For example, the size of the location variance was largest for protein, dough development time and extensibility. Year-to-year differences were still important in South Australia, as the size of year variance was largest for test weight and flour yield. Genotype had the largest average variance component in South Australia compared with location or year for grain hardness, water absorption and maximum resistance (Table 22).

In Victoria, the ratio of variance components of genotype, location, and year, on quality traits varied (Table 22). Consistent with the other states, genotype had the largest average variance component for grain hardness. However, for water absorption the average variance component in Victoria of genotype and year were essentially the same, and both were larger than that of location (Table 22). Victorian location variance was the largest for protein, dough development time, and maximum resistance. Year though, had a higher variance component compared with genotype or location for flour yield and extensibility (Table 22).

5.3.4 Influence of different line combinations

Comparing the genotypic variance component of 2 subsets, uniform versus mixed grain hardness analyses, allowed for an assessment of how different combinations of lines affected observed quality (Table 23). With the exception of test weight, changing the grain hardness composition altered the average genotypic contribution

to variance for the other 7 quality traits (Table 23). Traits that the genotypic variance component changed the most were grain hardness (an average 8 fold increase across the states comparing uniform to mixed grain hardness analyses) and water absorption (an average 3 fold increase across New South Wales, South Australia and Western Australia comparing uniform to mixed grain hardness analyses, and this increased to a 8.5 fold increase when Victoria was included). Another consistent change in the genotype variance occurred for dough development time, with the average increase across the states for the results of uniform compared with mixed grain hardness analyses being 5 fold (Table 23).

Table 23 Comparison of genotypic variances based on grain hardness differences

Quality traits	New South Wales		South Australia		Victoria		Western Australia	
	6 hard-grained comparisons	6 mixed hardness comparisons	8 hard-grained comparisons	3 mixed hardness comparisons	2 hard-grained comparisons	6 mixed hardness comparisons	6 hard-grained comparisons	4 mixed hardness comparisons
Test weight	7.1	8.2	25.0	35.1	Not measured		18.2	14.9
Grain hardness	8.2	84.1	10.3	70.9	8.5	71.7	13.0	96.2
Protein	1.5	6.2	1.2	0.4	5.8	2.7	1.7	0.3
Flour yield	7.4	21.4	9.5	5.4	0.0	5.6	19.2	51.2
Water absorption	26.8	55.2	24.0	68.1	1.8	45.2	20.3	81.3
Dough development time	9.4	31.1	5.3	22.4	2.1	12.3	6.6	44.2
Extensibility	10.1	23.9	17.6	21.0	26.9	8.8	12.6	6.9
Maximum resistance	19.0	26.5	28.0	38.6	27.8	8.9	37.3	7.8

Changes to genotypic variance components for the remaining quality traits varied across the states. In New South Wales, the size of the genotype variance component was greater in the analyses of mixed comparisons, compared with that of the uniform grain hardness comparisons, for protein, flour yield, extensibility and maximum resistance (Table 23). In South Australia, the genetic variance component was also greater for the mixed hardness comparisons for extensibility and maximum

resistance, but differences between uniform hard-grained lines were greater for protein and flour yield (Table 23). In Victoria, the analyses of the uniform hard comparisons showed genotypic variance components for protein, extensibility and maximum resistance to be higher than the mixed hardness comparisons. In contrast, and also noted for Western Australia, was that in the analyses of the mixed hardness comparisons the genotypic variance was greater for flour yield than observed for the uniform comparisons (Table 23).

5.3.5 Summary of residual variance levels

It was observed that the residual variance component varied between the states, by quality trait and REML model. Common to all, was that the residual variance component was large, and for certain state-quality trait combinations it had the largest variance when compared with the other factors. To illustrate the relative size of variance components by factor, an average percentage of total variance, based on a state's analyses from the REML model with genotype, environment and G×E as the random factors, was calculated (Table 24). The proportion of variance attributable to residual variance ranged from a high of 40.9% for extensibility in Western Australia to a low of 13.3% for water absorption in New South Wales (Table 24). The average proportion of residual variance, across all the quality traits, and states, was 24.3%.

Table 24 Average residual variance percentages – genotype, environment and G×E model

Quality Trait	NSW (13 comparisons)	SA (13 comparisons)	VIC (8 comparisons)	WA (11 comparisons)
Test weight	20.5	15.5	Not measured	35.6
Grain hardness	29.0	20.9	10.7	22.8
Protein	15.2	15.3	22.8	32.4
Flour yield	29.3	24.5	36.9	32.9
Water absorption	13.3	22.7	25.7	18.4
Dough development time	14.2	30.8	28.9	37.2
Extensibility	28.0	17.0	18.9	40.9
Maximum resistance	20.5	27.1	23.0	23.6

When the random factors in the REML model were changed to genotype, location and year, the residual variance component levels also changed, noting that G×E was now incorporated in the residual (Table 25). Put side by side, the percentages

reported in Table 24 and Table 25 showed that the size of the residual variance component increased as a proportion of total variance when the REML model was changed to assessing genotype, location and year. Calculation of average variance components by grain hardness composition also showed that the mixed comparisons had the lowest level of unexplained error across the 8 quality traits (Table 25). The comparisons that were uniformly made up of hard-grained lines had the highest residual variance component levels. The size of residual variance was reduced in the mixed comparisons relative to that of genotype, environment or G×E because of the inherent differences between the lines assessed. Conversely, because the lines making up the soft and hard comparisons were 'more similar' the proportion of residual error was higher.

Table 25 Average residual variance percentages – genotype, location and year model

Trait	Grain hardness type of comparison		
	Soft	Hard	Mixed
Test weight	35.9	45.7	28.2
Grain hardness	66.0	46.1	11.8
Protein	30.7	40.8	41.7
Flour yield	39.3	45.8	49.3
Water absorption	22.8	37.7	16.2
Dough development time	36.9	48.0	39.2
Extensibility	37.4	49.8	43.2
Maximum resistance	24.8	34.9	42.1

5.4 Discussion

The aim of this phase of research was to determine the extent of G×E of quality traits in 4 wheat-growing states of Australia. No distinction was made regarding the type of G×E. It was clear from the assessments performed that the influence of G×E was minimal in comparison to the effects of environment and genotype. A lack of G×E was initially observed when the frequency of multiple comparisons were assessed, and then confirmed when estimated variance components were reviewed. The absence of significant G×E means there is a higher likelihood of rank ordering of genotypes and environments occurring in a predictable manner. Furthermore, orderly ranking of quality traits by genotype and environment meant that subsequent investigations could be undertaken with greater confidence in reaching a valid conclusion.

The finding that G×E variance was small compared with the size of genotype or environment variance is consistent with the findings of Pumpa et al. (2002). They assessed the quality of hard-grained lines sampled from limited locations in Queensland, New South Wales, Victoria, South Australia and Western Australia. However, other geographically restricted Australian studies have reported significant levels of G×E for a range of quality measurements (Bhatt and Derera, 1975, Fabrizius et al., 1997, Panozzo and Eagles, 2000). In this research the highest frequency of G×E was in New South Wales, and this might be related to 7 of the 12 comparisons only representing testing at 2 locations. That suggests it might be the number of observations that is related to the observed level of G×E, but as discussed in the literature review care is required when designing experiments because of the impact materials can have on the results observed. .

The observation that G×E was small for several quality traits needs to be considered in light of the lines and environments assessed. The lack of G×E could be attributed to breeding programs releasing lines that had good adaptation for their respective states (Lazenby et al., 1994, Leslie et al., 1997) and that many Australian lines are related (Wrigley et al., 1982, Cornish and Wrigley, 2000, Wrigley et al., 2001). Consequently, if lines selected for a study had similar alleles at important loci affecting quality, often because the genotypes were related, genotypic and perhaps G×E variance could be expected to be small. Conversely, when diverse lines have been selected, genotypic and G×E variances could be large. For example, Panozzo and Eagles (2000) reported significant levels of G×E when they tested a mixed grain hardness set of lines, that originated from the immediate Victorian breeding program but also those in New South Wales, Queensland, South Australia and Western Australia (the lines were Eradu, Halberd, Hartog, Insignia, Lillimur, Meering and Rosella). Bhatt and Derera (1975) also assessed a diverse range of lines across localised environments and found significant G×E. However, Pumpa and Allen (2002) tested 11 lines that originated from 6 diverse breeding programs and the influence of G×E was small (the lines were Amery, Dollarbird, Frame, Goldmark, Hartog, Janz, Krichauff, Meering, Ouyen, Sunco and Wilgoyne). The inconsistent detection of G×E supports the notion that comparing findings of different studies needs to be done with caution (Fowler and de la Roche, 1975, Baenziger et al., 1985,

Peltonen-Sainio and Peltonen, 1993, van Lill et al., 1995a, Morris et al., 1997, Zhang et al., 2004).

The importance of appropriate materials and methods can never be understated in agricultural research as has been highlighted in the previous paragraphs. To understand the potential influence of G×E on wheat quality, the approach taken in this research was to assess as many seasons as possible. Individual comparisons were assessed in a holistic manner, because balanced long-term data were not available. Others, in the pursuit of greater representation, have examined a collection of independent trials (Fowler and de la Roche, 1975, Baker and Kosmolak, 1977, Hucl et al., 1998, Oury et al., 1999). The rationale being that a greater number of data points equates to an increased confidence that the sub-samples analysed were representative of the true population (Morris et al., 1997). To enhance representativeness, the comparisons assessed in this research, covered a range of seasons (Figure 18 to Figure 21). That additional step ensuring that uncontrollable seasonal effects did not bias the observed outcomes (Borghi et al., 1997).

Environmental factors, in this instance restricted to location and year, had the greatest effect on the 8 quality parameters analysed. The effect of environment was more pronounced in South Australia and Western Australia, relative to New South Wales and Victoria. Given Australia's climate variability, the effect of environment is not surprising (National Land and Water Resources Audit, 2001). When environment was broken into its available components, growing year-to-year differences had more effect in New South Wales and Western Australia, while location differences were greater in South Australia and Victoria. The differences in whether year or location had greatest effect related to the larger geographical size of New South Wales and Western Australia compared with South Australia and Victoria. The former 2 states being longer along a north-south axis and this, for example, encompasses more seasonal rainfall patterns. The importance of location in South Australia and Victoria perhaps associated with the orientation of these states along an east-west axis that makes prevailing climatic conditions more similar. An implication arising from those observations is that different strategies may be required to assemble representative quality data. For example, more years might be required for New South Wales and Western Australia, and more locations required in

South Australia and Victoria. However, it is acknowledged that restricting assessment to location and year factors (or just environment) is a simplification of a much more complex set of influences that control wheat quality.

Any change to the manner in which quality samples are collected based upon state weightings for more years or more locations needs to be treated with caution. The level of residual variance in this research was found to be high, and in some cases larger than genotype, environment (and location and year). A high proportion of residual variance indicative of the need for more observations, particularly if greater certainty was required as to which factor had the greatest relative effect on quality.

One mechanism to improve the assessment of an environmental factor on quality, is to incorporate additional climatic factors such as grain filling temperatures (Randall and Moss, 1990, Blumenthal et al., 1993, Panozzo and Eagles, 2000, Panozzo et al., 2001, Wrigley, 2003). Therefore, before considering any changes to the manner in which samples might be collected for quality assessment, more observations are required to improve the certainty and distinction between factors, and the incorporation of climatic measurements such as temperature would be considered beneficial in that pursuit.

It was also apparent from the research conducted, that the selection of lines had an important role in determining the magnitude of genotypic variance. Based on comparisons made up of lines of different grain hardness, the quality traits with the greatest genotypic variance were grain hardness and water absorption. These 2 traits have previously been shown, based on data from New South Wales, Victoria and South Australia, to have a strong correlation (Eagles et al., 2002a) and that the relationship is determined by variation at the *Ha* locus (Cane et al., 2004, Eagles et al., 2006a). The importance of *Ha* locus differences was obvious when comparing the analyses of mixed and uniform grain hardness comparisons. For mixed hardness comparisons, the genotype influence on grain hardness ranged from 70.9 to 96.2% across the 4 states. Water absorption was lower, ranging from 45.2 to 81.3%, but was still relatively high compared with either location or year. For uniform hard-grained comparisons, the influence of genotype fell to a range of 8.2 – 13.0% for grain hardness and 1.8 – 26.8% for water absorption. Consequently, when lines of

mixed grain hardness type are analysed, their inherent differences need to be acknowledged in relation to any findings. Alternatively, using lines of uniform grain hardness will reduce the level of variance observed.

In summary, the lack of G×E for the 8 quality traits assessed suggests that in these 4 wheat-growing states of Australia, genotype and environment quality rankings should be the same. It was also observed that the relative influence of location and year differed between states, which means that care needs to be taken when choosing testing sites, and/or interpretation of limited years of results. The importance of line selection when designing an experiment was also evident, due to the analyses examining both uniform and mixed grain hardness groups of lines.

Chapter 6 Proposed divisions for use in variety classification

The research described in this chapter was aimed at identifying a set(s) of zones of the Australian wheat-belt that collectively had lower environmental variance compared with the existing 7 classification zones, while concurrently maximising differences between the zones of that set. To identify such a set(s) of zones, published divisions of the Australian wheat-belt were used to calculate environmental variances, predicted means and standard errors for important wheat quality traits. After identifying the 'best' set(s) of zones, analyses were conducted to determine the most quality representative location for each zone within a test division.

6.1 Background

The primary method of managing quality around the world has been to allocate individual lines into grades of wheat representing a certain quality profile (Cracknell and Williams, 2004). In Australia, new lines are classified into appropriate market grades based on their inherent quality attributes and that process is currently performed for 7 classification regions (AWB Limited, 2005b). The current classification regions, with the exception of NSW, are based on political boundaries and these do not represent potential environmental influences on the expression of genotypically controlled quality traits, upon which classifications decisions are focused.

6.2 Methodology

6.2.1 Source of data

The relational database described in Chapter 4 was the source of data for this research. The data represented 24,032 unique observations made up of 2,752 lines, 978 environments, 287 locations, 22 years and 14 different sources of data. Data were available for 9 quality traits (test weight, thousand-kernel weight, grain hardness, flour yield, protein, water absorption, dough development time, extensibility, and maximum resistance). The data were unbalanced since the same sets of lines were not consistently tested in all environments.

A search of the literature found 11 published divisions of the Australian wheat-belt that were potentially suitable for assessing reductions in environmental variance, henceforth referred to as test divisions (Table 26). They represented institutional recommendations to farmers, management, monthly average maximum temperature, temperature and humidity profiles, annual rainfall, seasonal rainfall, latitude divisions and 4 different agro-ecological perspectives on how the Australian wheat-belt could be divided.

Table 26 Divisions of the wheat-belt used to find better boundaries

Number of zones within each test division	Method of allocating zones to locations
7 control classification zones	Manual
31 Departments of Agriculture sowing recommendation zones/areas/silo groups	Manual
3 GRDC Management Regions	Manual
14 GRDC agroclimatic zones	Manual
9 Agro-ecological regions of Australia (Williams et al., 2002)	Manual
4 average maximum grain filling temperature profiles (for the months of August, September, October and November)	GIS
5 average annual rainfall zones	GIS
9 seasonal rainfall zones	GIS
3 temperature and humidity climate zones	GIS
Division of wheat-belt into 3 latitude zones	Manual
4 agroecological regions as reported in the Sustainable Agriculture: Assessing Australia's Recent Performance 1998 report	Manual
5 agro-seasonal soil zonations	Manual

The control, for all analyses was the set of existing 7 classification regions (Queensland, northern New South Wales, central New South Wales, southern New South Wales, Victoria, South Australia and Western Australia).

Each location was allocated to a single zone within each test division and the control. Pritchard et al (2000) and Bell (2003) had used similar approaches when they spatially analysed canola quality and wheat yields respectively. Two procedures were used to allocate the appropriate test division zones to each of the 286 individual locations (Table 26). The first involved the use of Arcview software (a Geographical Information System [GIS] program). The 2-step GIS process has been illustrated for 2 different test divisions in Figure 23 and Figure 24. Step 1 was the mapping of the locations using their latitude and longitude specifications. Step 2 involved

electronically overlaying the location map on a test division map, from which the appropriate zone for each location was determined and subsequently entered into the relational database.

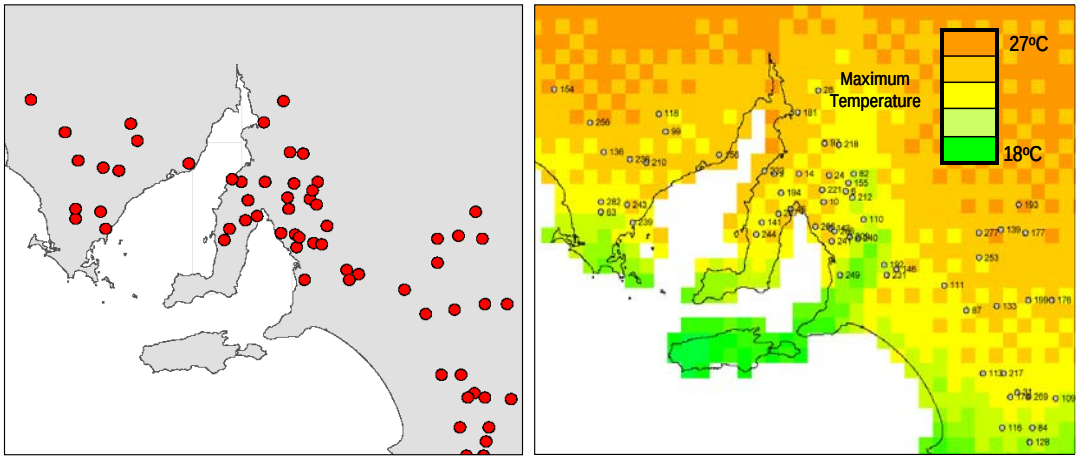


Figure 23 Location allocation process - average October maximum temperature in South Australia

Figure 23 shows how a select number of South Australian locations were allocated to the varying gradients representing average maximum temperatures in October. Another example of the 2-step GIS allocation process is shown in Figure 24 where the procedure was applied to locations in Western Australia for seasonal rainfall.

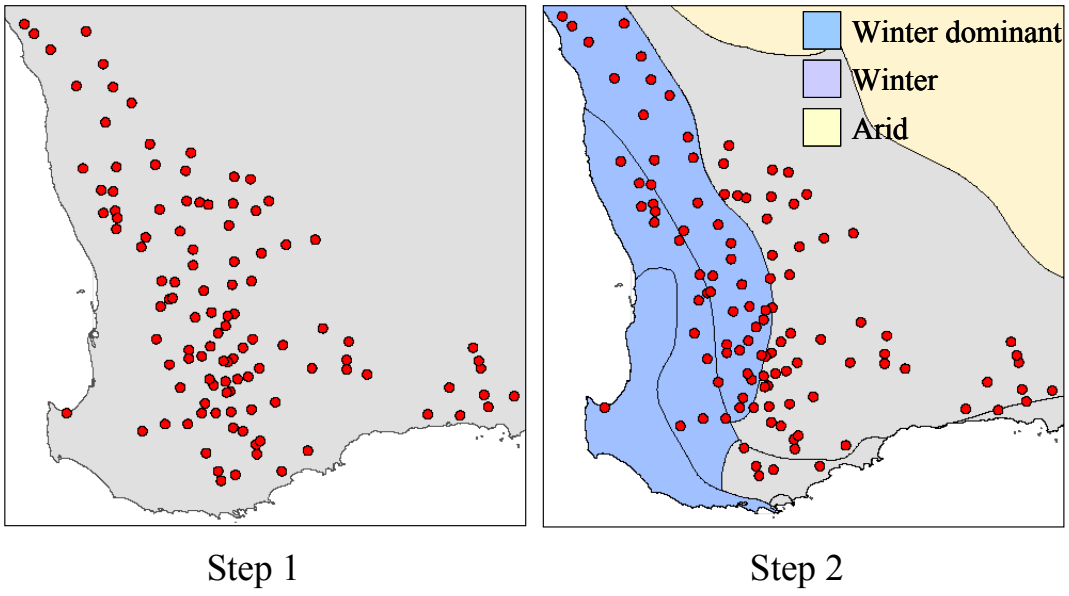


Figure 24 Location allocation process - seasonal rainfall across Western Australia

The second procedure was a manual method based on the 2-step GIS process. To ensure accurate location allocation, the location and test division maps were first aligned to the same scale. A triangulated cross-reference system, based on 3 points, was then used to ensure that the maps were correctly orientated. Having overlayed the location map on the test division map, the appropriate zones were determined for each location and entered into the relational database. The choice of GIS or manual procedure used in allocating the zones to the locations is listed in Table 26.

An alternative method was required in the allocation of the 287th location, the Queensland composite, because this 'single location' was spread across multiple zones of the 14 test divisions. The decision as to which zone of each test division the Queensland composite was allocated was based on how the composites were originally compiled. When the component locations of the composites were mapped (see Figure 16, page 82) it was obvious that the locations used were grouped as to what has been referred to as Central or Southern Queensland (Brennan and Sheppard, 1983, Sheppard et al., 1996, Sheppard et al., 1999). However, the annual composites were never made from the same set of locations, nor contained the same percentage of locations from the Central and Southern regions of Queensland (Table 27). However, across the 10 years of Queensland composite results a consistent feature was that the southern locations were the major component of the composite. Therefore, the Queensland composite was allocated on the basis of where the southern locations were located in each test division.

Grain yield was used to assess whether it would change the environmental variance relativities between the test divisions and the control. Grain yield was considered an ideal covariate because it is probably the single best factor that represents gross environmental influences on wheat production (J.F. Angus and C.J. Peterson, pers. comm., 2005).

Individual grain yield levels were not available for all 24,032 observations in the relational database. Consequently, the use of simulated shire yields was negotiated with the Agricultural Production Systems Research Unit (A.B. Potgieter, pers. comm., 2006). The simulated yields by shire are based on 2005 technology,

predicted in the manner described by Potgieter et al. (2002). The simulated shire yields were provided in a spreadsheet, accompanied by a GIS map of shires.

Table 27 Make-up of Queensland composite samples

Harvest	Total Number of Trial in Composite	Trial Series	Percentage of Southern Locations
1994	4	Intermediate	100%
	3	Midseason	33%
	5	Quick	80%
1995	13	Intermediate	77%
	11	Midseason	73%
	13	Quick	77%
1996	8	Intermediate	50%
	9	Midseason	78%
	11	Quick	55%
1997	8	Quick/Intermediate	75%
	12	Slow	58%
1998	5	Quick/Intermediate	100%
	9	Slow	78%
1999	4	Quick/Intermediate	100%
	3	Slow	67%
2000	7	Early	43%
	7	Main	29%
2001	2	Main	50%
2002	13	Early	69%
	7	Main	86%
2003	3	Early	100%
	3	Main	67%

To make use of the simulated yield data locations had to be first allocated to shires. To achieve this, the previously described location GIS map was overlayed on the shire map provided (A.B. Potgieter, pers. comm., 2006). The same 2-step GIS procedure was then performed to allocate locations to shires as described previously, with a shire code for each location entered into the relational database. During that process 12 individual locations were identified as not being linked to a shire having simulated yield data. These were Vasse (Western Australia) and the Waite Campus (South Australia). The remaining locations were spread across the south-east corner of South Australia (Bool Lagoon, Glenroy, Koppamurra, Moyall, Streatham, Struan, and Tantanoola) and southern Victoria (Gnarwarre, Lake Bolac, and Tatyoon). The omission of these southern locations meant that a zone of test division code 1 was lost since these locations were the only ones in it. In addition, none of the Queensland composite results were included since there was no easy way to allocate it to the multiple shires in Queensland of which have considerable yield variation.

The second requirement needed to make use of the yield data was a cross-reference between the simulated shire yield for each year, and the unique environment already in the relational database that represented each location and year combination. Once that link was created, data were extracted for analysis with each environment having an appropriate simulated yield.

Extracted from the relational database were 23,115 observations, representing 2,623 genotypes, 930 environments, 274 locations, and 22 years. All observations had a protein and yield measurements, but low numbers of flour yield, water absorption, dough development time, extensibility, and maximum resistance measurements were missing. The trait with the most missing values, 31, was flour yield.

Identification of the most quality representative locations was conducted for the test divisions considered to have most merit, and the control. The rationale for performing this work was that if field trials were considered necessary to verify the findings of this research, then such information would guide researchers as to the 'most quality representative' locations. In addition, knowing which locations were the most representative, would guide breeding programs where best to conduct future trials that were to be used in quality testing.

The analyses focused on the 'full' data sets (these were maximum resistance, extensibility, dough development time, water absorption, protein, and flour yield). Two locations were excluded because they only had a single quality observation (Lameroo and Tumby, both in South Australia). In addition, Galong, in southern New South Wales, was excluded from the flour yield analysis because the flour yield measurements were all same. These 3 locations were excluded because the REML models could not generate meaningful predictions. That resulted in the prediction of 285 location quality trait means for maximum resistance, extensibility, dough development time, water absorption, protein and 284 location means for flour yield.

6.2.2 Statistical analyses

Variance components, means and their standard errors were estimated using the REML directive in GENSTAT (Payne et al., 2003). Two models, each with 2 variations, were fitted to the data.

The approach to analysing the nine quality traits differed due to the completeness of the data. For the quality traits that were considered a full set of data (flour yield, protein, water absorption, dough development time, extensibility and maximum resistance) the REML models sequentially analysed the quality traits for each test division in a single run. The quality traits that had missing values, considered as a part data set (test weight, thousand-kernel weight and grain hardness) the models were run individually for each test division and quality trait combination, so adjustments could be made for missing values.

The first model, referred to as the 'environment' model, had 3 factors. Genotype (equating to lines) and environments (location-year combinations) were considered random, with 'test division' fixed. Variance components and standard errors were estimated for genotype, environment, G×E, and residual error. The variation to the environment model, referred to as 'environment +', was the inclusion of an additional fixed factor – 'source of data'. The same variance components were estimated as described for the 'environment' model.

The second model, referred to as 'site-year', had 4 factors, with genotype, location and year considered the random factors, and test division the fixed factor. The variance components estimated from the 'site-year' model were for genotype, location, year, genotype × location, genotype × year, location × year interactions, and the residual. The variation to the 'site-year' model, referred to as the 'site-year +', included the additional fixed factor – 'source of data'. The same variance components were estimated as described for the 'site-year' model.

Different laboratories had provided varying proportions of the data. To determine what level the laboratories performing the quality testing contributed to variance, 'source of data' was used as an additional fixed factor. In terms of the variance components from models with and without this additional fixed factor, they showed

that ‘source of data’ reduced variation for some traits, but did not change the variance relativities between the test divisions and control.

It was also observed that ‘source of data’ could bias the results of the predicted means for zones within a test division. Exploratory analyses using the control, showed that predicted protein values in the ‘environment +’ model increased relative to the ‘environment’ model. In the case of Victoria it went from 10.2% (‘environment’ model) to 12.3% (‘environment +’ model). The changes in predicted means related to some ‘sources of data’ measurements only representing short-term experiments, and that they represented the extreme range for that quality trait. Consequently, the decision was made to only use predicted mean results from either the ‘environment’ or ‘site-year’ models because of the doubts raised about the accuracy of the predicted means from models containing the additional ‘source of data’ fixed effect.

During those exploratory analyses, it was also found that the unbalanced nature of the data meant that the ‘site-year’ model was unable to calculate quality trait predicted means and standard errors for all zones. The ‘site-year’ model did, however, produce variance components and standard errors for all division types, and these were similar to those from the ‘environment’ model. On the basis that the ‘environment’ model provided results for both predicted means of individual zones, and variance components for division types, this model was chosen as the preferred model and the focus of all subsequent analyses. The ‘environment +’ model was used discriminately in the analysis of variance components of test divisions.

In relation to the first half aim of this research phase, the comparison of environmental variance components between test divisions and the control, assessments were made on the basis of the size of the estimated variance component and its standard error. The comparisons were limited to that approach since there are no recognised descriptive statistical procedures for comparing variance components calculated by different models.

The second half of the aim was to assess differences between the zones of each test division. The predicted quality trait means were used for this purpose. To assess the

significance of differences between the zones making up a test division, the following equation was used, based on a t-test:

$$Estimated\ Standardised\ Mean\ Difference = \frac{\bar{x}_{ZjDi} - \bar{x}_{ZkDi}}{\sqrt{\left(SE^2_{ZjDi} + SE^2_{ZkDi}\right)}} \qquad \text{Equation 1}$$

where $\bar{x}_{ZjDi} - \bar{x}_{ZkDi}$ were the predicted means for the *j* and *k* zones in test division *i, and* SE^2_{ZjDi} and SE^2_{ZkDi} the standard errors for the *j* and *k* zones in test division *i* respectively.

To assess whether the zones within each test division were more precise compared with each other, an aggregated error index was devised. The rationale for an error index was that the test divisions ultimately assessed, had varying numbers of zones (2 to 5) and an average error value would bias those with low zone numbers. Consequently the devised error index equation was calculated for each division type and quality trait combination:

$$ErrorIndex = Mean_{SE} \times \left(Max_{SE} - Min_{SE}\right) \qquad \text{Equation 2}$$

where $Mean_{SE}$ equated to the average standard error of test division, with Max_{SE} and Min_{SE} representing the highest and lowest zone standard errors for the test division.

The calculated test division error indexes for each quality trait were ranked from lowest to highest. In addition to the error index, an average rank order for each test division based on the individual quality trait rankings was calculated. To complement that average, a standard deviation of the average rank order was determined. A low standard deviation (<1) meant that the test division had a consistent rank order position irrespective of quality trait. A high standard deviation (>1) was indicative of a test division that varied in its rank order position across the quality traits.

Based on the zones described in Table 26 (page 104), matrices of predicted maximum resistance means showed that some zones were not statistically different to each other. Subsequently, a step-wise process of amalgamation was made until all zones within a test division were different (Table 28). Maximum resistance was

selected as the amalgamation tool since it was considered the most independent quality trait, based on comparisons of the mean estimated variance components and a correlation analyses (see Appendices). The revised number of zones, were re-fitted to the 'environment' and 'environment +' models for those test divisions as required. Henceforth, the code numbers listed in Table 28 will be used to described test divisions.

Table 28 The final test division zone numbers used in analyses

Test divisions	Code number	Initial number of zones	1st revision	2nd and 3rd revisions	Number of zones used
Aggregated Department of Agriculture zones	1	31	9	6 and 5	5
GRDC management zones	2	3	-	-	3
GRDC agro-ecological zones	3	14	4	6 and 3	3
Agro-ecological zones Williams et al. (2002)	4	9	5	4	4
Seasonal rainfall	5	9	4	3	3
Average November maximum temperature	6	5	4	-	4
Average October maximum temperature	7	4	3	-	3
Average September maximum temperature	8	6	3	-	3
Average August maximum temperature	9	4	3	-	3
Annual average rainfall	10	5	4	-	4
Temperature and humidity climate zones	11	3	2	-	2
Latitude divisions	12	3	-	-	3
Agro-ecological regions after SCARM (1998)	13	4	3*	3*	3
Agro-seasonal-soil zones	14	5	3	-	3

3* different combination of zones

6.2.2.1 Covariate analyses

Two covariates were used in re-analysing the data assembled. Protein was used as a covariate in the 'environment' and 'environment +' models and run for both the full and part data sets. The same comparisons, as described previously for variance components and quality trait predicted means, were performed. The rationale for using protein as a covariate was not to try to explain the inter-relationships of protein with other quality traits, but rather to bring the results from the different laboratories back to an equivalent protein level. Despite the aggregated protein data in the relational database being normally distributed (see Section 4.2.1 *Summary of selected quality traits*), individual sources of data in some instances were distorted towards a particular protein range. For example, in Queensland, the target grade for classification purposes is Prime Hard, which has a minimum protein level of 13%. Therefore, to obtain a Prime Hard classification, samples must be tested at or around

this level for a decision to be made on a new line's eligibility into the Prime Hard grade. Seasonal variation means that there is some variation, but in general as seen in Figure 26, the Queensland composites were skewed towards higher protein levels. All 'sources of data' had to some degree selected (or more precisely rejected) samples for detailed quality evaluation, due to the combination of ultimately using their quality results for classification purposes and also costs (not every sample collected each year can be tested).

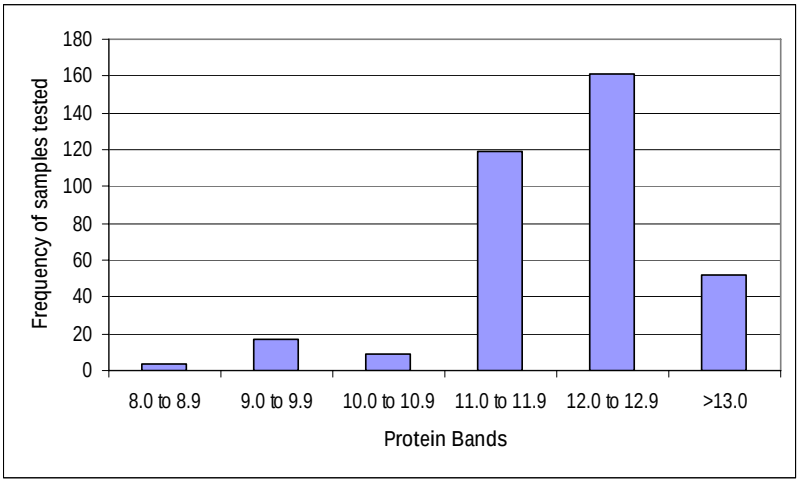


Figure 25 The frequency of Queensland composite samples tested by protein bands

The second covariate to be used was predicted grain yield. Modified 'environment' and 'environment +' models were run using the REML directive for test divisions and the control. The modification to the models was that the random factors were only genotype and environment, with G×E incorporated in the residual variance.

The outputs of interest were estimated environmental variances and standard errors because variance of genotype and residual variances did not did change as was observed in earlier analyses. For comparison purposes, the environmental variances and standard errors were graphed, and ratios of differences between test divisions and the control for each quality trait-model combination calculated

6.2.2.2 Most quality representative location

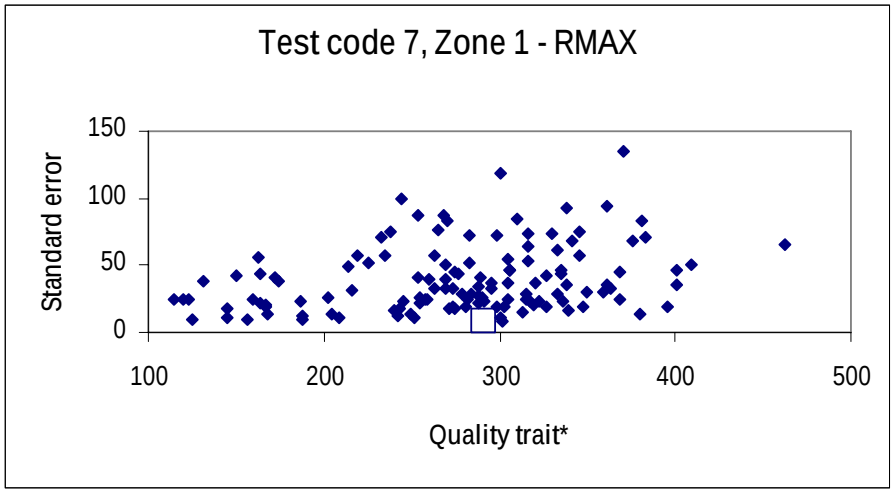
To identify the most quality representative locations, the REML directive in GENSTAT (Payne et al., 2003) was used to run a modified 'environment +' model to predict the quality trait means of locations. The modification to the 'environment +'

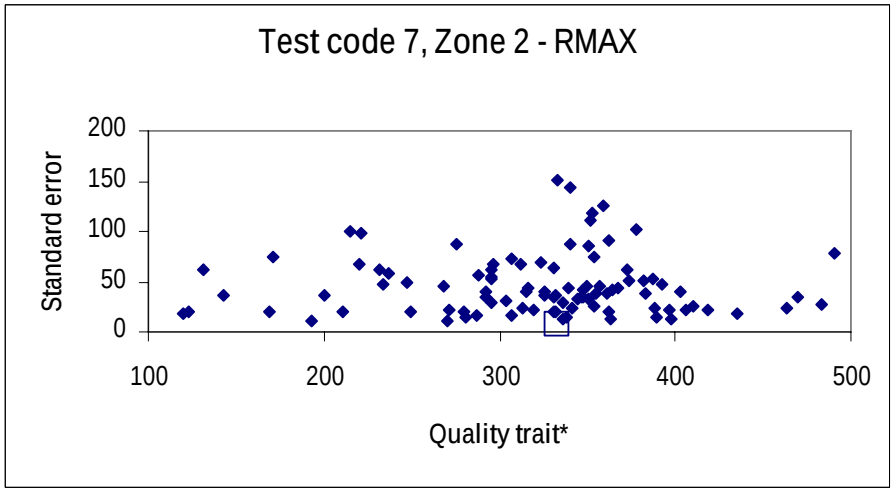
model was that the random effects were only genotype and environment, with G×E incorporated into the residual. The number of observations used in the analyses of maximum resistance, extensibility, dough development time, water absorption, and protein were 24,030; representing 2,752 genotypes, 285 locations, 976 environments, 22 years and 14 different 'sources of data'. The flour yield analyses were based on 24,024 observations, reflecting the same number of genotypes, years and sources described above, but only 974 environments and 284 locations.

The analyses were restricted to the test divisions considered as having the greatest potential for adoption in the classification of lines, plus the control. They were test division code 7 (average October maximum temperature profile), code 4 (consolidated agro-ecological zones reported by Williams et al. (2002), code 10 (consolidated annual average rainfall zones), code 1 (consolidated Department of Agriculture recommendation zones), and the control.

Predicted means and standard errors for each location and zone were plotted on a scatter graph to identify a single location with the closest quality profile to each zone (Figure 26). In total, 138 scatter graphs were constructed. From these graphs, the nearest neighbour(s) to the zone predicted mean/standard error point was visually identified. In the case that multiple locations were close to the predicted mean of the zone, Equation 3 was used to rank locations and the location with the lowest value selected. Locations with a standard error more than double that of the predicted zone standard error, or those that had an REML error message were excluded from this ranking procedure. These exclusions were based on avoiding locations with high variability and the error messages were indicative of locations with only a small number of observations making their predicted mean and standard error unreliable.

$$LocationQualityIndex = ABS\left(\frac{\bar{\hat{x}}_{Loc_j} - \bar{\hat{x}}_{Zone}}{\sqrt{\left(SE^2_{Locj} + SE^2_{Zone}\right)}}\right) \times \left(\frac{SE_{Zone\,\mathrm{Pr}edictedMean}}{SE_{Loc\,\mathrm{Pr}edictedMean_j}}\right) \qquad \text{Equation 3}$$





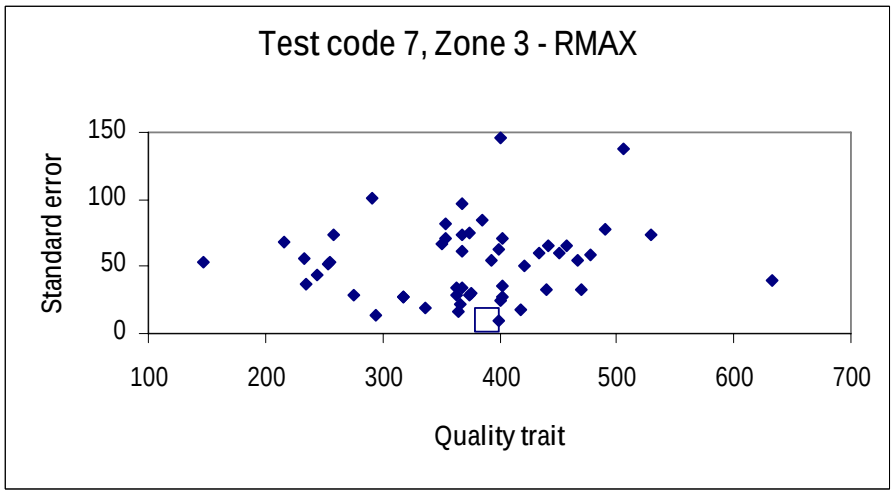


Figure 26 Example of scatter graphs used to visually identify the closest predicting quality locations by zone

Notes on scatter graph - The open squares represent the zone predicted means and diamond shapes location predicted means. The examples shown represent the predicted maximum resistance means of locations and zones of test division 7.

6.3 Results

The presentation of results has been divided into 5 sub-sections. The first examines the environmental variances differences between the control and those of the test divisions (Section 6.3.1). The second deals with the differences between zones of each division (Section 6.3.2). The third details the results showing which factors had the largest variance for the nine quality traits assessed (Section 6.3.3). The fourth section reports on the analyses using covariates (Section 6.3.4). The fifth and final section details the most quality representative locations for selected test divisions.

6.3.1 Reduction of environmental variance

Estimated environmental variance components and standard errors were used to determine whether any of the 14 test divisions had improved capacity to lower the effect of environment compared with the current set of classification regions (Table 29 and Table 30). The comparisons between test divisions and control focused on environmental variance components, because this was the only variance component that changed when the different test divisions were analysed. The change associated with the different allocation patterns of the 287 locations for each test division. In contrast, genotype, G×E, and residual variance components essentially remained unchanged. A universal observation was that the 'environment +' model, reduced the environmental variance differences between the test divisions and control, more than the results from the 'environment' model. That trend was most evident with maximum resistance, dough development time, protein, (Table 29) and thousand-kernel weight (Table 30). The test divisions with the most quality traits having lower environmental variance compared with the control based on 'environment +' model results were codes 1, 3, 4 and 12. A number of other test divisions had lower environmental variances for 3 traits and these were 6, 7, 9 and 10 (Table 29 and Table 30).

In contrast, the levels of test division environmental variances were high for flour yield, extensibility, test weight, and water absorption, when compared with the control. In the case of flour yield, no test divisions had environmental variance levels that were lower than the control for any model. Several test divisions had lower environmental variance levels compared with the control for extensibility, test

weight, and water absorption. These low levels were only observed for analyses based on the 'environment +' model. The test divisions were code 4 for extensibility, codes 1 and 13 for test weight test divisions, and codes 4, 7 and 10 for water absorption (Table 29 and Table 30).

Table 29 Estimated environmental variance component and standard errors from 2 REML models (A)

Test division code	REML model used for assessment									
	Environment	Environment+	Environment	Environment+	Environment	Environment+	Environment	Environment+	Environment	Environment+
	Maximum resistance		Extensibility		Dough development time		Water absorption		Protein	
Control	4585±218	4261±205	4.97±0.24	4.75±0.23	1.80±0.09	1.71±0.08	6.11±0.29	5.76±0.27	2.28±0.11	2.19±0.10
1	4440±211	4091±197	5.45±0.26	4.80±0.23	1.80±0.09	1.65±0.08	6.94±0.33	5.77±0.27	2.36±0.11	2.11±0.108
2	4778±226	4282±205	5.20±0.25	4.87±0.23	1.86±0.09	1.72±0.09	6.45±0.31	5.78±0.27	2.30±0.11	2.21±0.10
3	4906±232	4229±203	5.38±0.25	4.86±0.23	1.86±0.09	1.68±0.08	6.95±0.33	5.78±0.27	2.48±0.12	2.16±0.10
4	4658±221	4230±203	5.27±0.25	4.70±0.22	1.78±0.09	1.66±0.08	6.58±0.31	5.74±0.27	2.22±0.10	2.12±0.10
5	4686±222	4224±203	5.48±0.26	4.86±0.23	1.84±0.09	1.70±0.08	7.01±0.33	5.77±0.27	2.39±0.11	2.19±0.10
6	4661±221	4194±201	5.66±0.27	4.91±0.23	1.88±0.09	1.69±0.08	6.97±0.33	5.81±0.28	2.46±0.11	2.17±0.10
7	4661±221	4218±202	5.44±0.26	4.85±0.23	1.86±0.09	1.68±0.08	6.99±0.33	5.75±0.27	2.44±0.11	2.15±0.10
8	4677±222	4246±204	5.68±0.27	4.99±0.24	1.90±0.09	1.71±0.08	6.98±0.33	5.80±0.27	2.50±0.12	2.21±0.10
9	4658±221	4185±201	5.61±0.26	4.84±0.23	1.88±0.09	1.67±0.08	6.93±0.33	5.83±0.28	2.43±0.11	2.12±0.10
10	4798±228	4172±201	5.96±0.28	4.97±0.24	1.98±0.10	1.70±0.08	7.01±0.33	5.72±0.27	2.53±0.12	2.16±0.10
11	4825±229	4237±203	5.65±0.27	5.01±0.24	1.95±0.10	1.72±0.09	7.02±0.33	5.83±0.28	2.55±0.12	2.22±0.10
12	4597±218	4221±203	5.45±0.26	4.85±0.23	1.88±0.09	1.68±0.08	6.80±0.32	5.78±0.27	2.52±0.12	2.17±0.10
13	4684±222	4213±202	5.39±0.25	4.84±0.23	1.84±0.09	1.70±0.08	7.03±0.33	5.77±0.27	2.39±0.11	2.19±0.10
14	4655±221	4265±205	5.26±0.25	4.79±0.23	1.79±0.09	1.69±0.08	7.01±0.33	5.71±0.27	2.37±0.11	2.18±0.10

Table 30 Estimated environmental variance components and standard errors from 2 REML models (B)

Test division code	REML model used for assessment							
	Environment	Environment+	Environment	Environment+	Environment	Environment+	Environment	Environment+
	Flour yield		Grain hardness		Thousand-kernel weight		Test weight	
Control	3.22±0.15	3.38±0.16	9.90±0.47	9.01±0.43	13.97±0.85	14.25±0.88	5.28±0.27	5.51±0.29
1	4.15±0.20	3.72±0.18	9.86±0.47	8.61±0.42	14.01±0.85	13.89±0.86	5.27±0.27	5.36±0.28
2	3.96±0.19	3.41±0.17	10.26±0.50	9.21±0.44	14.43±0.88	14.24±0.87	5.28±0.27	5.60±0.29
3	4.07±0.19	3.72±0.18	10.17±0.49	8.97±0.43	14.45±0.88	13.99±0.86	5.55±0.28	5.65±0.29
4	3.97±0.19	3.54±0.17	10.08±0.48	9.05±0.44	14.01±0.85	14.04±0.86	5.44±0.28	5.65±0.29
5	4.00±0.19	3.58±0.17	10.11±0.48	9.02±0.44	14.06±0.86	13.92±0.86	5.47±0.28	5.60±0.29
6	4.22±0.20	3.74±0.18	10.37±0.50	9.11±0.44	14.84±0.90	14.28±0.88	5.55±0.29	5.64±0.29
7	4.15±0.20	3.68±0.18	10.30±0.49	9.14±0.44	14.74±0.89	14.28±0.88	5.55±0.28	5.65±0.29
8	4.13±0.20	3.68±0.18	10.34±0.49	9.21±0.45	14.78±0.90	14.26±0.88	5.58±0.29	5.67±0.30
9	4.27±0.20	3.75±0.18	10.24±0.49	9.13±0.44	14.65±0.89	14.23±0.88	5.46±0.28	5.62±0.29
10	4.18±0.20	3.64±0.18	10.37±0.50	9.08±0.44	14.71±0.89	14.00±0.86	5.43±0.28	5.62±0.29
11	4.17±0.20	3.77±0.18	10.49±0.50	9.23±0.45	14.86±0.90	14.26±0.88	5.52±0.28	5.64±0.29
12	3.90±0.19	3.70±0.18	10.17±0.49	8.99±0.43	14.69±0.89	14.12±0.87	5.51±0.28	5.65±0.29
13	4.01±0.19	3.38±0.16	9.87±0.47	8.81±0.43	14.53±0.88	14.32±0.88	5.31±0.27	5.47±0.28
14	3.88±0.18	3.72±0.18	10.33±0.49	9.12±0.44	14.66±0.89	14.32±0.88	5.40±0.28	5.61±0.29

To rate the relative improvement of test divisions in their capacity to lower environmental variance, compared with the control, 4 quality traits were focused upon (Table 31). These were maximum resistance, water absorption, grain hardness and dough development time. The rationale in focusing on these traits were that they were considered to be more independent of environmental factors in comparison to the other traits available for analysis (this was verified when the variance components were assessed as discussed in Section 6.3.3 *The factors with the greatest effect on the quality traits assessed*). Furthermore, these are traits of interest in deciding a classification for a new line. When all 4 traits were considered, only test division codes 1, 3, 4, 7, 10 and 13 had lower environmental variance in 3 out of 4 instances (Table 31). Removal of grain hardness from the calculation changed that frequency. The only test divisions that had lower estimated environmental variances compared with the control for maximum resistance, water absorption and dough development time, were codes 4, 7, and 10 (Table 31). It should be noted that for both the 'environment' and 'environment +' models, test division code 2 only a lower environmental variance compared with the control for thousand-kernel weight.

Table 31 Frequency of quality traits with low environmental variance based on 'environment +' model results

Test division code	Number of quality traits[1] with lower environmental variance than control Traits = 4	Number of quality traits[2] with lower environmental variance than control Traits = 3
1	3	2
2	None	None
3	3	2
4	3	All
5	2	2
6	2	2
7	3	All
8	1	1
9	2	2
10	3	All
11	1	1
12	2	2
13	3	2
14	2	2

Quality traits[1] = maximum resistance, water absorption, grain hardness and dough development time
Quality traits[2] = maximum resistance, water absorption and dough development time

The lack of reduction of environmental variance by the test divisions compared with the control came as a surprise. It was thought that since the test divisions were based on environmental boundaries, they should have accounted for environmental

variance better than the politically based boundaries of the existing classification regions. When it was considered how the data had been initially assembled, a plausible explanation evolved. The data represented results from the various breeding programs, and the major ones (Department of Agriculture and Food Western Australia, NSW Agriculture, SA, Victorian Department of Agriculture) all had a regional, state based focus. Environments (considered as location x year combinations), therefore, were aligned to the state boundaries and this was beneficial to the estimate of environmental variance due to more, and also uniform numbers, of observations. When split, as was the case for test divisions, the number of environments (or alternatively locations and years independently) was reduced and not uniformly spread across the zones of the test division (Table 32). Consequently, since the current classification regions considered the data as 'whole' pieces, they appeared to account for environmental variance better, than when 'parts' of the data were analysed as occurred for the test divisions.

Table 32 The number of locations and environment observations in each zone

Test division codes	Number of zones in division	The number of locations and environment observations (in parenthesis) in each zone [increasing in order from left to right]. The total number of locations = 287; environments = 978.						
Control	7	2 (6)	11 (28)	20 (51)	33 (97)	40 (140)	70 (352)	111 (304)
1	5	2 (11)	8 (28)	57 (149)	72 (243)	148 (547)		
2	3	33 (85)	111 (304)	143 (589)				
3	3	54 (175)	59 (181)	174 (622)				
4	4	25 (67)	65 (178)	84 (293)	113 (440)			
5	3	24 (64)	48 (145)	215 (769)				
6	4	6 (9)	21 (44)	72 (257)	188 (688)			
7	3	53 (164)	101 (338)	133 (476)				
8	3	24 (73)	26 (80)	237 (825)				
9	3	41 (169)	117 (399)	129 (410)				
10	4	22 (74)	56 (203)	68 (238)	141 (463)			
11	2	94 (344)	193 (634)					
12	3	51 (163)	68 (253)	168 (562)				
13	3	21 (62)	25 (67)	241 (849)				
14	3	33 (87)	46 (193)	208 (698)				

Based on the distribution of observations across zones, some test divisions were more likely to approach the variance levels of the control. The test divisions that had a better balance of environment observations were test division codes 1, 4, 7, 10, and 12 (Table 32). In these test divisions, the zone with the most environmental

observations was less than 60% of the total observations. For the other nine test divisions, a single zone had more than 60% of the total environment observations (Table 32). In the case of test division codes 8 and 13 this was exacerbated with more than 80% of the total environment observations in a single zone.

6.3.2 Maximising the differences between zones of test divisions

Predicted means and standard errors from the 'environment' model were used to assemble matrices for determining whether the zones within each test divisions were different to each other. Earlier, the process was outlined how it was ensured all zones within a test division were different to each other for maximum resistance (see discussion of Table 28, page 112). When zones within test divisions were compared with each other for the remaining quality traits, different responses were observed. These different responses can be summarised as:

Type I. Some of the paired zone comparisons of predicted means for a quality trait were different, while others were considered the same;

Type II. All of the paired zone comparisons of predicted means for a quality trait were the same and;

Type III. No ability to make comparisons because the model was unable to calculate a predicted mean, and or associated standard error for a zone.

No test division had a set of zones that were all different to each other for all quality traits (Table 33). The closest to that ideal scenario were test divisions that had a mixture of quality traits that were different between all zones and had Type I differences. Test divisions falling into such a category were codes 2, 5 and 9 (Table 33). A number of other test divisions were not included in that category because they had a single quality trait with no significant differences between the zones within the division – these were codes 3, 6, 7, 10 and 12 (Table 33). The remaining test divisions either had Type II differences for more than a single quality trait or Type III problems.

Table 33 Categorisation of differences between the zones of test divisions

Test division code	TWT	TKW	PSI	FY	P	FWA	DDT	EXT	RMAX
1	Type III	Type III	All	Type I	Type III	Type III	All	Type I	All
2	Type I	All	Type I	All	All	All	Type I	All	All
3	Type I	Type I	All	All	All	Type II	All	All	All
4	Type I	All	Type I	Type I	Type III	Type I	Type I	All	All
5	Type I	All	All	Type I	All	All	All	Type I	All
6	Type I	Type II	Type I	Type I	Type I	Type I	Type I	Type I	All
7	Type I	Type II	All	Type I	All	Type I	All	All	All
8	Type II	Type II	Type I	All	Type I	Type II	All	Type I	All
9	Type I	Type I	All	Type I	Type I	Type I	All	All	All
10	Type I	Type II	Type I	Type I	Type I	Type I	Type I	Type I	All
11	All	Type II	Type II	All	All	All	All	All	All
12	Type I	Type II	Type I	Type I	Type I	Type I	All	All	All
13	Type III	Type I	All	Type I	Type I	Type III	Type III	All	All
14	All	Type I	Type I	All	Type III	All	All	All	All

All = all comparisons different
Type I = some zone comparisons were different to each other
Type II = all zone comparisons were the same
Type III =No estimates available

TWT = test weight; TKW = thousand-kernel weight; P = protein; PSI = grain hardness; FY = flour yield; FWA = farinograph water absorption; DDT = dough development time; EXT = extensibility; RMAX = dough strength

When only maximum resistance, water absorption, grain hardness and dough development time were considered, test division code 5 was the only division to have all of its zones different to each other for these 4 quality traits. Other test divisions for which their zones were all different except for 1 of these quality traits, considered as Type I differences, were codes 1, 3, 7, 9, 11 and 14 (Table 33).

An objective assessment as to the precision of predicted means was conducted based on the error index described in Section 6.2.2 *Statistical analysis* (page 111). The results of those calculations have been summarised in Table 34 as rank orders. The test divisions with the lowest average rank order scores were codes 3, 7, 9, 11 and 12 (these had the lowest mean error indexes) and were considered the 'best 5' test divisions (Table 34). To put the error index rankings into perspective, the control always had the highest quality trait error index, with the exception of grain hardness and test weight, for which test division code 6 had worse predictability. Test division codes 7, 9 and 12 had rank order standard deviations >1 (1.7, 2.1 and 1.1, respectively) but their position order was never higher than 6 (equating to the lower half of the test divisions error indexes).

Table 34 Error index rank orders of test divisions

Note: rank order from lowest error index (1) to highest error index (14)

Test division code	RMAX	EXT	DDT	FWA	P	FY	PSI	TKW	TWT	Average rank order score and standard deviation
1	11	14	10	13	14	14	13	=3	13	*12±3.5*
2	7	7	8	7	7	6	5	7	7	*7±0.8*
3	4	6	=3	5	=4	=4	4	5	6	*5±1.0*
4	10	4	7	9	3	9	8	10	10	*8±2.6*
5	12	8	11	10	8	10	11	11	11	*10±1.4*
6	14	13	14	14	13	13	15	14	15	*14±0.8*
7	5	=2	5	2	=4	=1	1	=1	2	*3±1.7*
8	8	12	13	12	12	10	9	=8	8	*10±2.0*
9	2	5	2	4	2	=4	6	=8	3	*4±2.1*
10	6	10	=3	6	10	8	7	=3	4	*6±2.7*
11	1	1	1	1	1	=1	3	=1	1	*1±0.7*
12	3	=2	5	3	4	3	2	5	4	*3±1.1*
13	13	11	11	11	10	12	12	13	12	*12±1.0*
14	9	9	9	8	8	7	10	12	9	*9±1.4*

TWT = test weight; TKW = thousand-kernel weight; P = protein; PSI = grain hardness; FY = flour yield; FWA = farinograph water absorption; DDT = dough development time; EXT = extensibility; RMAX = dough strength

6.3.3 The factors with the greatest effect on the quality traits assessed

Estimated variance components showed that genotype, environment, and G×E, affected the quality traits studied differently (Table 35). When 'source of data' was added as a fixed factor into the 'environment +' model the ratios of variance components between factors was considered the same as for results from the 'environment' model. The genotypic variance component for maximum resistance, water absorption, and grain hardness, was larger than that of the environment or G×E (Table 35). The ratio of genotype to environment variance components from the 'environment' model (reflected by the ratio $\hat{\sigma}_g / \hat{\sigma}_e$) was 1.35 for maximum resistance, 1.46 for water absorption and 2.73 for grain hardness. The genotypic variance of dough development time was also larger than the other factors, but its $\hat{\sigma}_g / \hat{\sigma}_e$ ratio was lower at 1.20. For these 4 quality traits the residual variance component varied. Unexplained error contributed a minimum of 6.4% to the total variance of grain hardness, while it was highest for dough development time estimated to be 18.5%. The G×E only contributed a small proportion of the

variance. It was highest for dough development time at 9.0%, and less than 4% for maximum resistance, water absorption, and grain hardness (Table 35).

Table 35 Summary of variance components and standard errors from 2 REML models

Quality trait	Variance components	Environment model			Environment + model		
		Average variance component	Average standard error	Range of variance components	Average variance component	Average standard error	Range of variance components
Maximum resistance	Genotype	6321	198	36	6075	190	36
	Environment	4685	222	466	4218	203	191
	G×E	518	35	2	520	35	4
	Residual	1602	35	1	1574	34	3
Extensibility	Genotype	2.03	0.08	<0.1	2.00	0.08	<0.1
	Environment	5.46	0.26	1.0	4.86	0.23	0.3
	G×E	0.25	0.03	<0.1	0.22	0.03	<0.1
	Residual	1.85	0.03	<0.1	1.86	0.03	<0.1
Dough development time	Genotype	2.23	0.08	<0.1	2.22	0.08	<0.1
	Environment	1.86	0.09	0.2	1.69	0.08	0.1
	G×E	0.51	0.03	<0.1	0.49	0.03	<0.1
	Residual	1.04	0.03	<0.1	1.05	0.03	<0.1
Water absorption	Genotype	9.98	0.30	<0.1	9.85	0.29	<0.1
	Environment	6.86	0.32	0.9	5.77	0.27	0.1
	G×E	0.68	0.03	<0.1	0.60	0.03	<0.1
	Residual	1.47	0.03	0.0	1.46	0.03	<0.1
Protein	Genotype	0.30	0.01	<0.1	0.29	0.01	<0.1
	Environment	2.41	0.11	0.3	2.17	0.10	0.1
	G×E	0.04	0.01	0.0	0.02	0.01	<0.1
	Residual	0.47	0.01	<0.1	0.47	0.01	<0.1
Flour yield	Genotype	1.55	0.06	<0.1	1.51	0.05	<0.1
	Environment	4.02	0.19	1.0	3.63	0.18	0.4
	G×E	0.37	0.02	0.0	0.36	0.02	<0.1
	Residual	1.09	0.02	<0.1	1.00	0.02	<0.1
Grain hardness	Genotype	27.81	0.84	0.1	26.99	0.82	0.1
	Environment	10.19	0.49	0.6	9.05	0.44	0.6
	G×E	1.00	0.06	<0.1	0.90	0.06	<0.1
	Residual	2.65	0.06	<0.1	2.57	0.06	<0.1
Thousand-kernel weight	Genotype	8.32	0.33	<0.1	8.31	0.33	<0.1
	Environment	14.49	0.88	0.9	14.16	0.87	0.4
	G×E	1.58	0.12	<0.1	1.39	0.12	<0.1
	Residual	4.73	0.12	<0.1	4.74	0.12	<0.1
Test weight	Genotype	1.94	0.08	<0.1	1.91	0.07	<0.1
	Environment	5.44	0.28	0.3	5.60	0.29	0.3
	G×E	0.48	0.03	<0.1	0.44	0.03	<0.1
	Residual	1.44	0.03	<0.1	1.41	0.03	<0.1

The environmental variance of protein, test weight, extensibility, flour yield, and thousand-kernel weight, was larger than that of either genotype or G×E (Table 35). Its relative size, based on 'environment' model results of the $\hat{\sigma}_g / \hat{\sigma}_e$ ratio showed protein to have a ratio of 0.12, test weight 0.36, extensibility 0.37, flour yield 0.39 and thousand-kernel weight 0.57. The residual variance component of these 5 traits was more consistent, but higher overall, than compared with those traits previously

discussed with larger genotypic variance (Table 35). Residual variance ranged from a low of 14.6% for protein, to a high of 19.3% for extensibility. The contribution of G×E to overall variance was minimal, with the variance components of protein, test weight, extensibility, flour yield, and thousand-kernel weight, less the 5.5% of the total.

It was observed that the level of variance differed between the 2 models. The trend was that the inclusion of the additional fixed 'source of data' factor in the 'environment +' model, reduced the genotype, environment and G×E variance, with the exception of test weight, when compared with the results from the 'environment' model (Table 35).

6.3.4 Covariate analyses

6.3.4.1 Protein

The inclusion of protein as a covariate in both the 'environment' and 'environment+' models reduced the level of environmental variance for extensibility, dough development time and water absorption (Figures 26 to 30). The order of reduction was greatest for extensibility, a fall of nearly 3 times when protein was added to the 'environment +' model (Figure 28). The smallest ratio drop was for water absorption with a reduction of 1.28 when protein was added into the 'environment +' model (Figure 30). In comparison, the effect of the protein covariate on maximum resistance was less pronounced (Figure 27). In the case of flour yield, the effect of the protein covariate was to marginally increase the level of environmental variance (Figure 31).

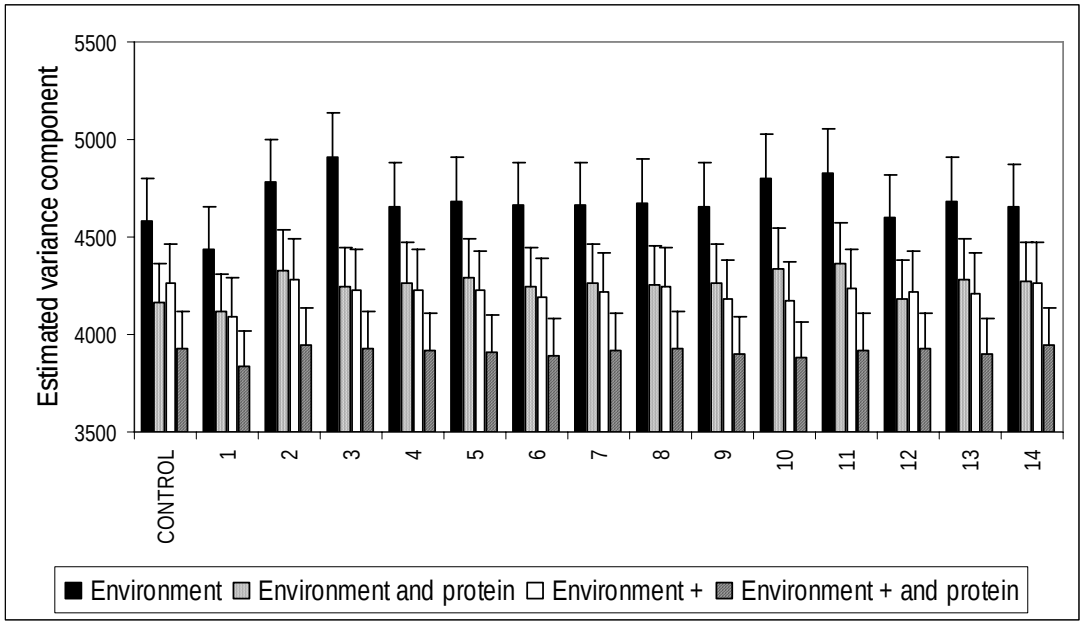


Figure 27 Estimated environmental variance and standard error comparisons of maximum resistance

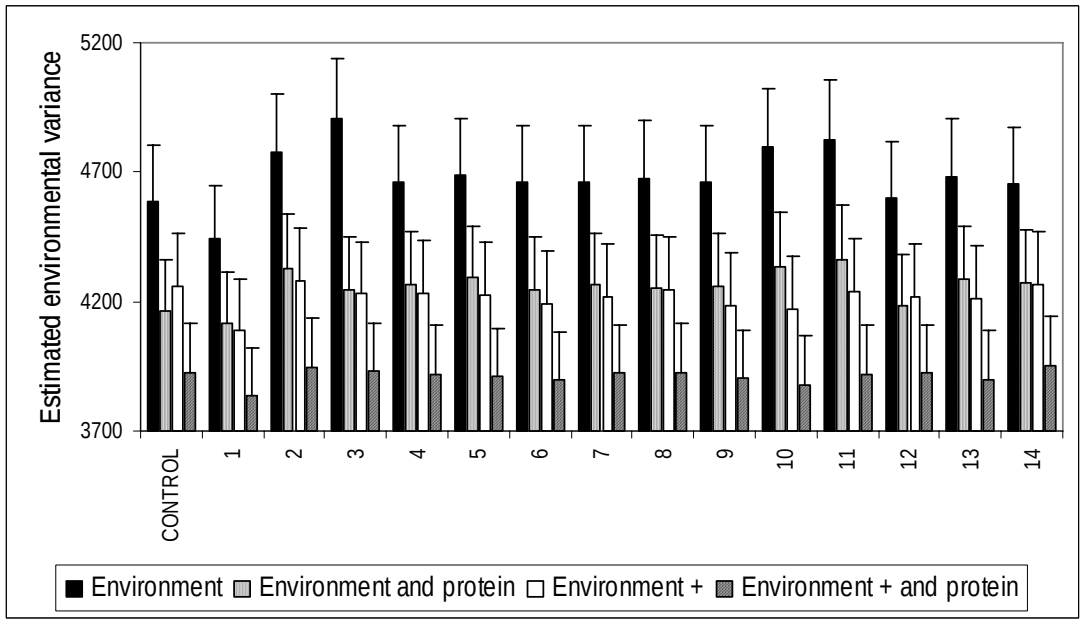


Figure 28 Estimated environmental variance and standard error comparisons of extensibility

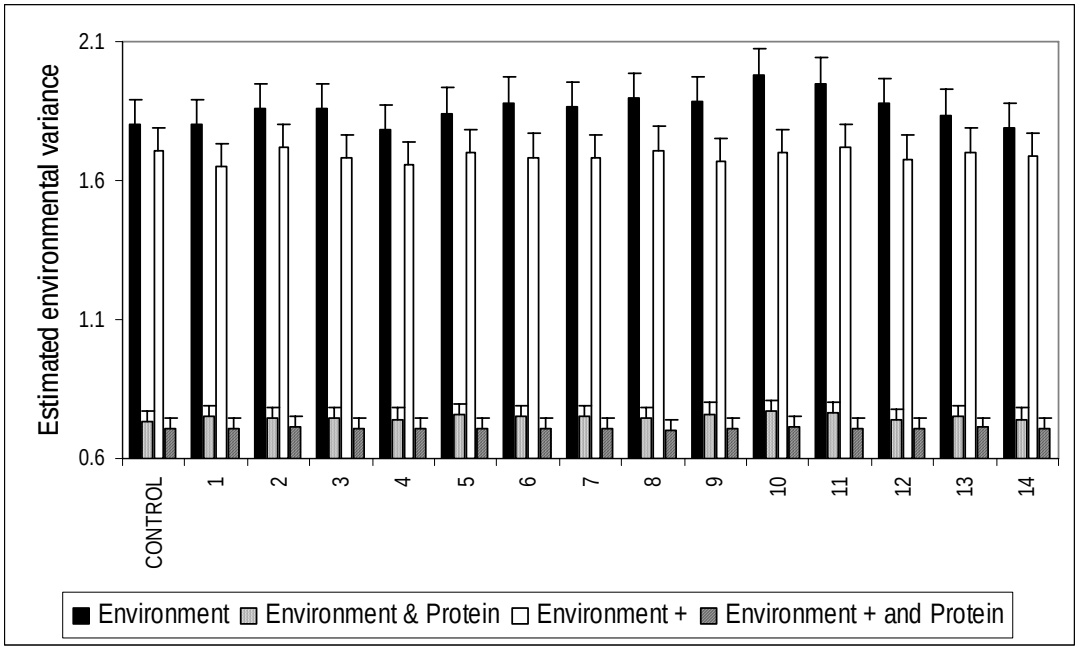


Figure 29 Estimated environmental variance and standard error comparisons of dough development time

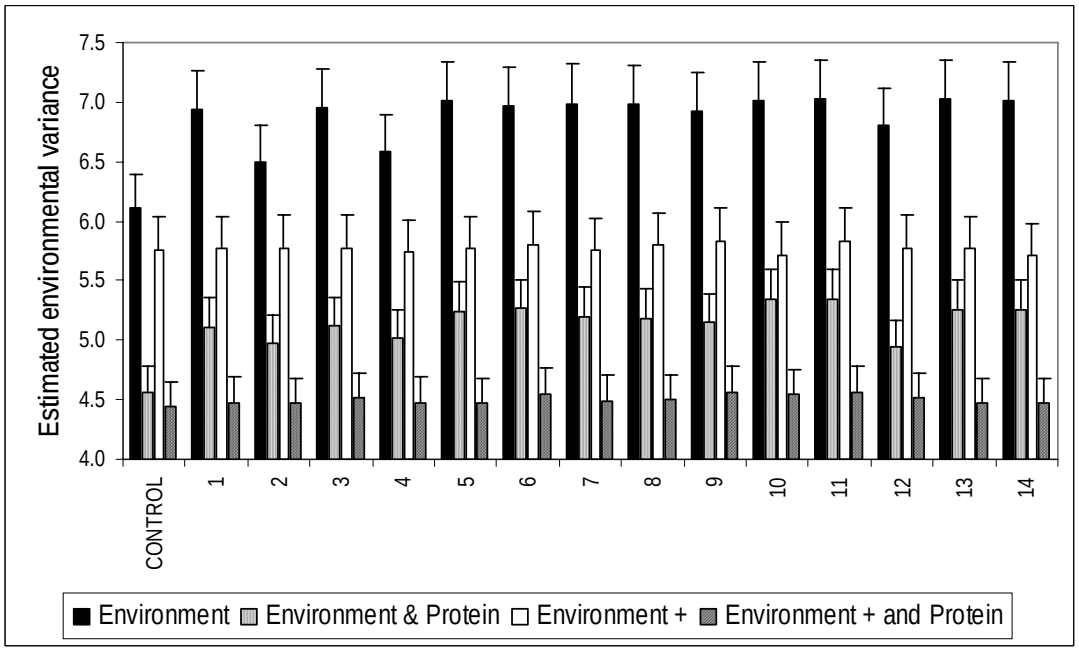


Figure 30 Estimated environmental variance and standard error comparisons of water absorption

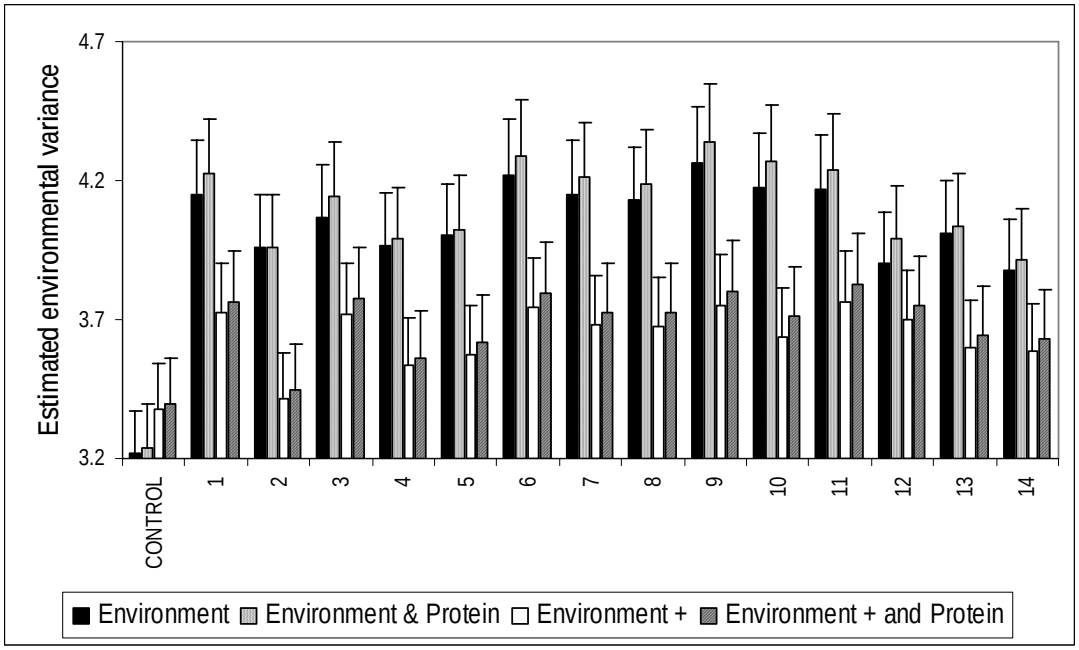


Figure 31 Estimated environmental variance and standard error comparisons of flour yield

The other observation noted from the inclusion of the covariate in the models was how it affected the environmental variance differences between the test divisions and control. When a ratio of the average difference between test divisions and the control was calculated, the protein covariate changed the ratios for extensibility (Figure 28). The average ratio difference was 0.91 for the 'environment' model. The addition of the protein covariate in the model reduced the average ratio of differences between test divisions and the control to 0.77. However, the same average ratios were unchanged when protein was added as a covariate to the 'environment +' model. For maximum resistance, dough development time, water absorption and flour yield, the ratio differences between the test divisions and the control were unchanged when the protein covariate was included in either the 'environment' or 'environment +' models.

6.3.4.2 Grain yield

The common, and striking observation from Figure 32 to Figure 37 was that 'source of data' (the additional fixed factor in the 'environment +' model) had a greater impact on reducing the level of estimated environmental variance compared with that of the grain yield covariate. It was noted that traits known to be influenced by environmental conditions, such as protein, dough development time, and water

absorption, that the covariate further reduced the level of environmental variance in the 'environment +' model (Figure 37, Figure 34 and Figure 35 respectively). The capacity of 'source of data' to lower variance in these analyses (Figure 32 to Figure 37) was consistent with previous findings reported in Section 6.3.1 *Reduction of environmental variance*, and Section 6.3.4 *Covariate*. However, in the analysis of flour yield, while the 'environment +' model reduced the variance levels of the test divisions, for the control the variance increased (Figure 36). The increase suggests that the differences between testing laboratories was greater than any environmental effect represented by grain yield.

The inclusion of the covariate in both models either reduced the environmental variance or had no effect. Across all models, the yield covariate reduced the environmental variance the greatest for protein (Figure 37), and the least for maximum resistance (Figure 32). The reduction of environmental variance of dough development time (Figure 34) and water absorption (Figure 35) by the yield covariate was between protein and maximum resistance. The yield covariate had no influence on the environmental variance of either extensibility or flour yield, with the variance levels of these 2 traits the same when models with, and without, the covariate were compared (Figure 33 and Figure 36).

The yield covariate in the models did not change the environmental variance trends previously observed between test divisions and the control. Unlike the change observed for extensibility in the 'environment' model when the protein covariate was included, the changes between test divisions and the control when the yield covariate was added to the 2 models were consistent. However, the yield covariate did change the relative variance reductions between some test divisions for certain traits. For example, such changes were observed for dough development time and water absorption, with the change possibly linked to yield being better correlated with these traits (Figure 34 and Figure 35).

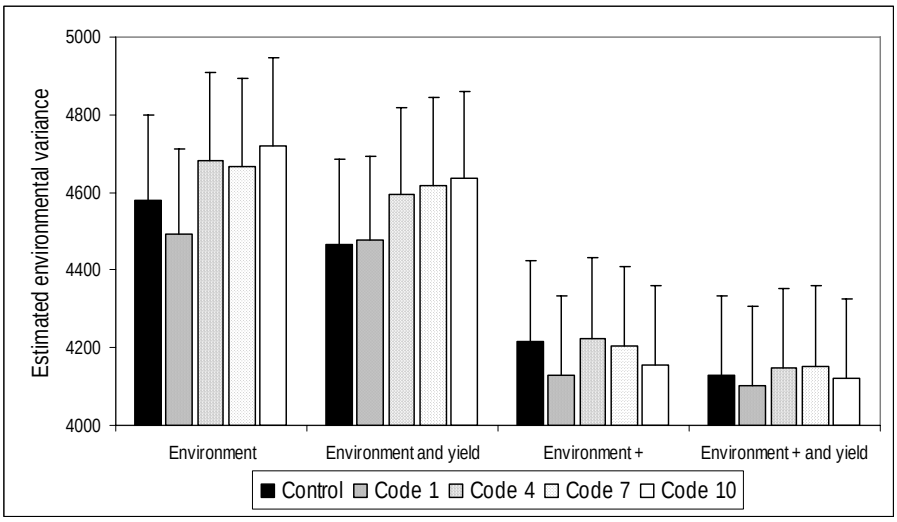


Figure 32 Influence of grain yield covariate on environmental variance of maximum resistance

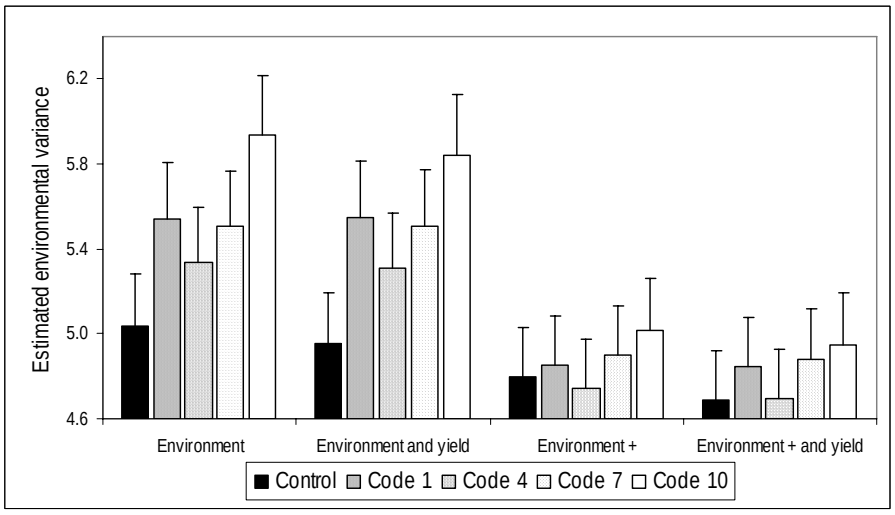


Figure 33 Influence of grain yield covariate on environmental variance of extensibility

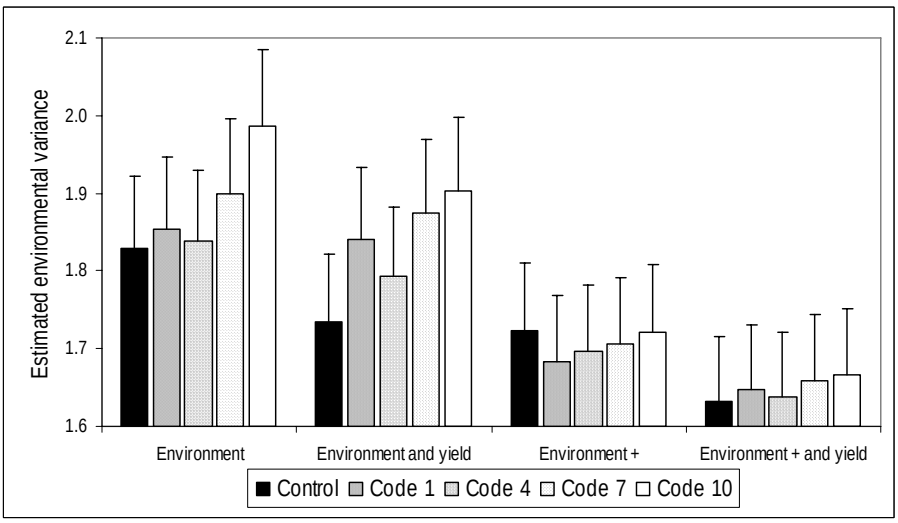


Figure 34 Influence of grain yield covariate on environmental variance of dough development time

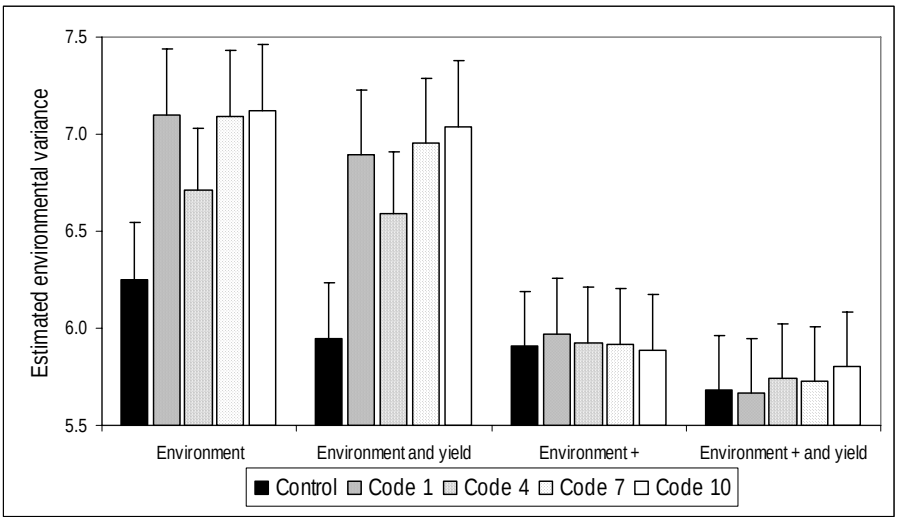


Figure 35 Influence of grain yield covariate on environmental variance of water absorption

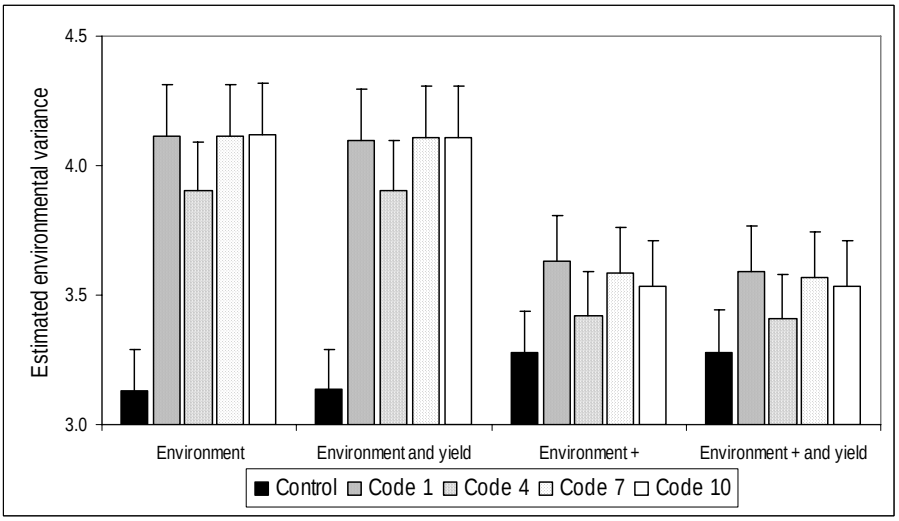


Figure 36 Influence of grain yield covariate on environmental variance of flour yield

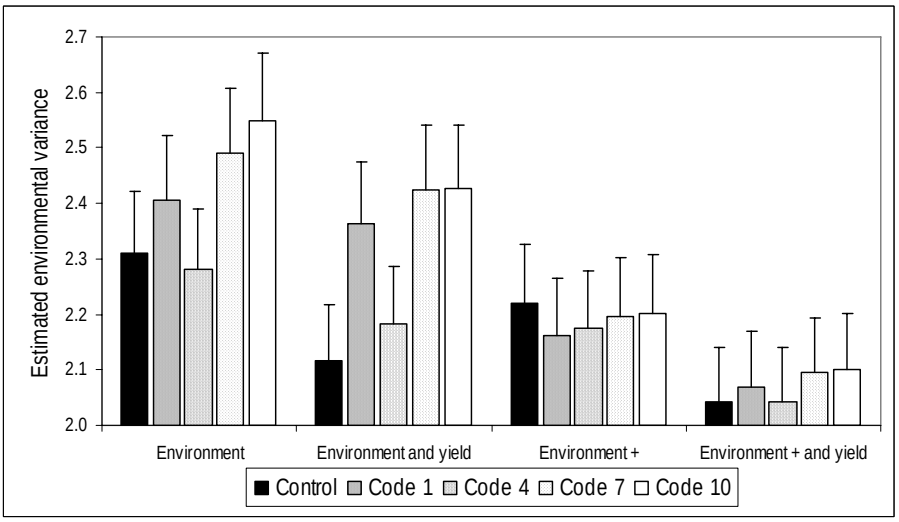


Figure 37 Influence of grain yield covariate on environmental variance of protein

6.3.5 Most quality representative locations

The results will be discussed in the following order. Firstly the control, then test division codes 7, 4, 10 and 1.

Across the 7 zones of the control different locations were closet to zone average for the 6 quality traits assessed. Exceptions to that rule were found in Queensland, central New South Wales, and Western Australia (Table 36), and in these zones certain locations were consistently closest to zone quality trait means. In Queensland, the composite sample was consistently closest to the zone mean, with Moonie and Norwin each having the next closest quality profiles for 2 traits. Additional locations to the composite were reported, since it would be difficult to replicate the composite in any future field trial. In central New South Wales, Condobolin had the closest quality profile across all traits and this can be attributed to the limited number of locations representing this zone. That places some doubt over the true representativeness of Condobolin for this zone. In Western Australia, the predicted extensibility and water absorption values of Wongan Hills were closest to the state's mean, and this is probably is a reasonably valid prediction since Wongan Hills was regularly sampled and quality tested.

Table 36 Locations with closest quality profile to those of the control predicted zone means

Quality trait	Current classification regions						
	Queensland	**NNSW**	**CNSW**	**SNSW**	**Victoria**	**South Australia**	**Western Australia**
RMAX	Qld* and Moonie	Narrabri	Condobolin	Junee	Woomelang	Urania	Chapman
EXT	Qld* and Norwin	Walgett	Condobolin	Temora	Tarranyurk	Saddleworth	Wongan Hills
DDT	Qld* and Moonie	Narrabri	Condobolin	Gerogery	Merinee	Winulta	Mount Madden
FWA	Norwin	Narrabri	Condobolin	Goolgowi	Kerang	Stow	Wongan Hills
P	Qld* and Moonie	Biniguy	Condobolin	Wagga Wagga	Tatyoon	Mudamuckla	Munglinup
FY	Qld* and Wellcamp	Narrabri	Condobolin	Colinroobie	Ultima	Minnipa	Kendenup

RMAX = dough strength; EXT = extensibility; DDT = dough development time; FWA = farinograph water absorption; P = protein; FY = flour yield
Qld* = Locations representing Queensland composite samples; NNSW = Northern NSW; CNSW = Central NSW; SSNW = Southern NSW

The 3 zones of test division code 7 (Table 37) had different location and quality trait combinations for the 6 quality traits, except for zone 2, where Wongan Hills was the closest to the zone mean for dough strength and extensibility, and Walgett had the closet extensibility and dough development times in zone 3.

Table 37 Locations with closest quality profile to those of test division code 7 predicted zone means

Quality trait	Zone codes		
	1	2	3
RMAX	Stow and Avondale	Wongan Hills	Wilgoyne
EXT	Datatine	Wongan Hills	Walgett
DDT	Tarranyurk	Urania	Walgett
FWA	Roseworthy	Newdegate	Carrabin
P	Yarrawonga	Greenhills	Come by chance
FY	Wallendbeen	Regans Ford	Narrabri

RMAX = dough strength; EXT = extensibility; DDT = dough development time; FWA = farinograph water absorption; P = protein; FY = flour yield

The 4 zones of test division code 4 (Table 38) had different location and quality trait combinations for the 6 quality traits, except for Qld*, Walgett and Narrabri in zone 4 which were the closest locations to zone mean for multiple quality traits. Additional locations to the composite were reported, since it would be difficult to replicate the average of the composite in any future field trial.

Table 38 Locations with the closest quality profile to that of test division code 4 predicted zone means

Quality trait	Zone codes			
	1	2	3	4
RMAX	Donald	Mintaro	Newdegate	Coonamble
EXT	Straun	Blyth	Kukerin	Qld* and Walgett
DDT	Bolgart	Windsor	Varley	Walgett
FWA	Dooen	Urania	Wongan Hills	Narrabri
P	Corack	Nyngan	Dalwallinu	Narrabri
FY	York	Wagga Wagga	Carrabin	Qld* and Narrabri

RMAX = dough strength; EXT = extensibility; DDT = dough development time; FWA = farinograph water absorption; P = protein; FY = flour yield; Qld* = Locations representing Queensland composite samples

In test division code 10, all of the quality traits across the 4 zones were represented by different locations being closest to the zone predicted means (Table 40).

Table 39 Locations with the closest quality profile of test division code 10 predicted zone means

Quality trait	Zone codes			
	1	2	3	4
RMAX	Turretfield	Donald	Wilgoyne	Kalanbi
EXT	Diggora	Deniliquin	Badjerin Rock	Wunkar
DDT	Wannamal	Stow	Tuckey	Bruce Rock
FWA	Wunghnu	Newdegate	Carrabin	Mitchellville
P	Yarrawonga	Greenhills	Varley	Balranald
FY	Temora	Watheroo	Carrabin	Kalannie

RMAX = dough strength; EXT = extensibility; DDT = dough development time; FWA = farinograph water absorption; P = protein; FY = flour yield

The majority of the zones in test division 1 had different location and quality trait combinations (Table 40). Glenroy was the location closest to the mean of zone 1 for all quality traits. The repetition of Glenroy is associated with numbers of observations since there were only 2 locations in this zone, with the bulk of observations originating from Glenroy. In zone 2, Kybybolite was closest to the zone mean for extensibility and protein, while Straun was closest to the water absorption and flour yield zone means. In zone 4, Wongan Hills was the location closest to the zone mean for dough strength and flour yield.

Table 40 Location with closest quality profile to test division code 1 predicted zone means

Quality trait	Zones				
	1	2	3	4	5
RMAX	Glenroy	Bool Lagoon	Mitiamo	Wongan Hills	Wilgoyne
EXT	Glenroy	Kybybolite	York	Newdegate	Northampton
DDT	Glenroy	Koppamurra	Wolseley	Mount Madden	Walgett
FWA	Glenroy	Straun	Gairdner River	Urania	Carrabin
P	Glenroy	Kybybolite	Vasse	Junee	Narrabri
FY	Glenroy	Straun	Esperance Downs	Wongan Hills	Kalannie

RMAX = dough strength; EXT = extensibility; DDT = dough development time; FWA = farinograph water absorption; P = protein; FY = flour yield

6.4 Discussion

The aim of this phase in the research was to identify a set(s) of zones that had features that made them better options for classification purposes compared with the existing set of classification regions. Two key attributes were that a set(s) of zones had low levels of environmental variance for important quality traits, and concurrently the zones within a set had different quality profiles. Low environmental variance is important from a classification perspective because it enhances the chance of differentiating between lines for important inherent quality traits. It was also important for any set of zones identified, that it's zones had different profiles, otherwise zones may well have been merged together.

From the analyses conducted, 4 test divisions were identified as having a selection of desired features, with no test division having the ideal requirements for all the quality traits studied. In order of their importance, the features that will be discussed in relation to those 4 test divisions are, low environmental variance of inherently related quality traits, the frequency and, then precision, of different quality profiles between the zones of test divisions. The 4 identified test divisions will be discussed in order of merit. It should be noted that these four test divisions were identified as having a more even distribution of observations across their zones. It is believed that this gave these test divisions a comparative advantage when their results were compared against the control, because other test divisions not only split apart single quality source of data but they did so in a manner that a single test division zone had the bulk of available observations for analysis. The consequence was that variance estimations for these test divisions were predisposed as being higher than the control because of the way boundaries of the test divisions divided up the available quality data.

The test division that was considered to best represent the features required for classification purposes was test code 7 - the average October maximum temperature across the Australian wheat-belt (Figure 38). It was observed that the average October maximum temperature profile reduced the environmental variance of maximum resistance and dough development time when compared with the current classification regions. That reduction is possibly linked to the influence of grain-filling temperature on protein quality (Blumenthal et al., 1993, Wrigley, 2003).

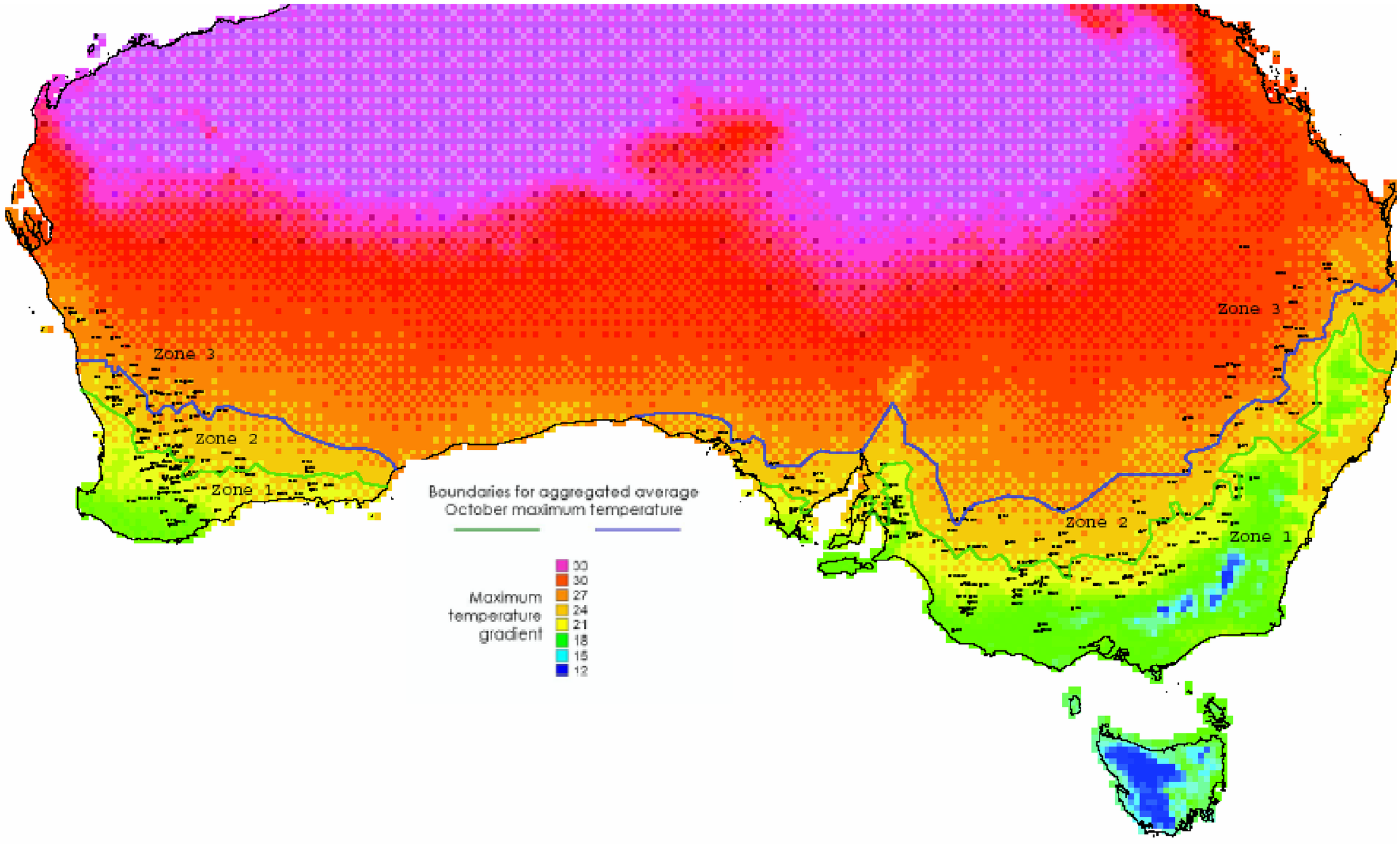


Figure 38 Wheat-belt division based on aggregated average October maximum temperature

Note - The blue and green lines indiciate common boundaries between zones.

The lower levels of environmental variance for test division code 7 compared with the control were only observed when 'source of data' was included as an additional factor in the 'environment +' model. The influence of 'source of data' suggests that while the empirical values of quality traits might have been different between 'sources of data', when the same line and or environment was tested across different 'sources of data', rankings were similar.

The environmental variance level, however, of water absorption for the average October maximum temperature profile of the wheat-belt was similar to that of the control. Furthermore, this division of the wheat-belt did not reduce the environmental variance relative to the control for extensibility, flour yield, grain hardness, thousand-kernel weight or test weight. The lack of reduction of these traits was not considered as a negative since, with the exception of flour yield and grain hardness, they have been associated more with environmental influences rather than genetic (Simmonds, 1989).

The 3 zones of the average October maximum temperature profile of the wheat-belt all were different to each other for maximum resistance, dough development time, extensibility, protein, and grain hardness based on 'environment' model results (Table 41). Across all quality traits, the overall precision of this test division was third. The high rank order was supported by low standard errors of the predicted quality trait means. These features were associated with the relatively even spread across its 3 zones of environmental observations - 476, 338 and 164.

Table 41 The estimated quality profiles of 3 wheat-belt zones based on October maximum temperatures

Quality trait	1	2	3
Test weight	79.3±0.3	79.4±0.2	80.4±0.3
Thousand kernel weight	36.1±0.6	35.1±0.4	34.6±0.5
Protein	10.6±0.2	10.9±0.1	11.8±0.2
Grain hardness	20.8±0.5	19.4±0.3	18.4±0.3
Flour yield	73.9±0.2	74.2±0.2	75.2±0.2
Water absorption	61.7±0.3	61.3±0.3	61.8±0.3
Dough development time	4.2±0.2	4.4±0.1	5.4±0.2
Extensibility	20.2±0.3	20.1±0.2	22.2±0.3
Maximum resistance	294±8	333±7	389±10

Two boundaries, which ran across the entire wheat-belt, separated the 3 zones of the average October maximum temperature profile (Figure 38). These boundaries were loosely orientated in an east-west axis direction, and this meant that sections of the Western Australian wheat-belt were linked with portions of South Australia, Victoria, New South Wales, and Queensland (Figure 38). Such boundary orientation is consistent with global and Australian viewpoints (Nix, 1975, Diamond, 1998, O'Brien, 2000)

Two other test divisions, test codes 4 and 10, were also identified as having low environmental variance levels compared with the control for important quality traits, but differentiation between their zones was inferior to the zones of the average October maximum temperature profile. Test division code 4 was a consolidation of the agro-ecological regions reported by Williams et al. (2002) (Figure 39). Test division code 10 was a consolidation of annual average rainfall zones across the wheat-belt (Figure 40).

The use of wheat-belt divisions based upon a agro-ecological regions reported by Williams et al. (2002) in the 'environment +' model produced lower environmental variance levels for maximum resistance, extensibility, dough development time, water absorption, protein, and thousand-kernel weight, compared with the control. The 4 consolidated zones of this division were different to each other for maximum resistance, extensibility, and thousand-kernel weight based on 'environmental' model results (Table 42). Type I differences were found for dough development time, water absorption, flour yield, grain hardness, and test weight. Unfortunately, the precision of predicted means was poor, with the average rank order position of maximum resistance, water absorption, and dough development time error indexes rated as ninth, indicating that the precision of these predictions was not good compared with the average October maximum temperature profile (across all nine quality traits the rank order of a wheat-belt divided upon agro-ecological regions reported by Williams et al. (2002) was eighth). The lack of precision related to the number of environments not evenly spread across the 4 zones of this division (the 4 zones had 440, 293, 178 and 67 environments each).

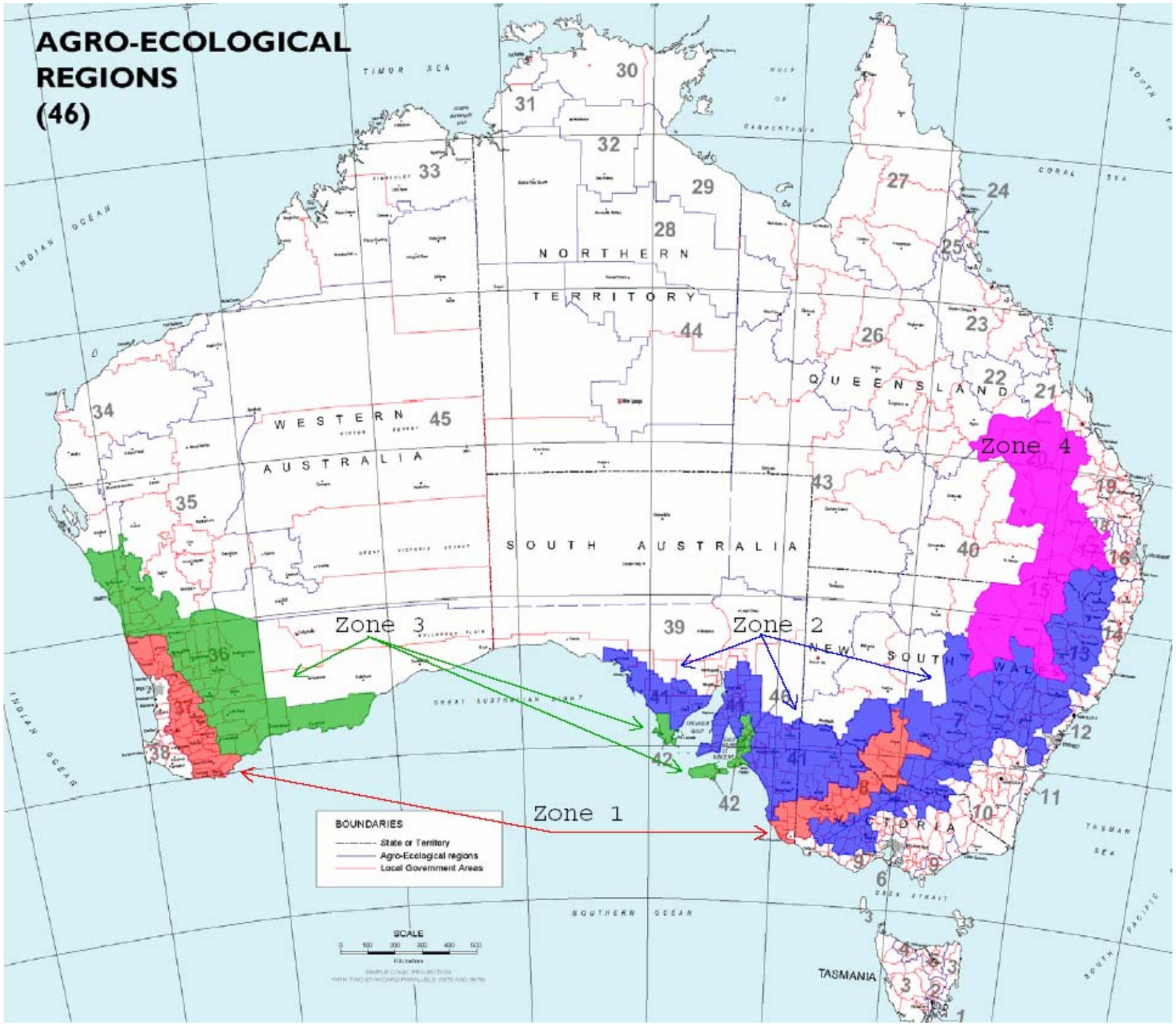


Figure 39 Wheat-belt division based on aggregated agro-ecological regions reported by Williams et al (2002)

Note - Regions shaded in the same colour are the same zone**.**

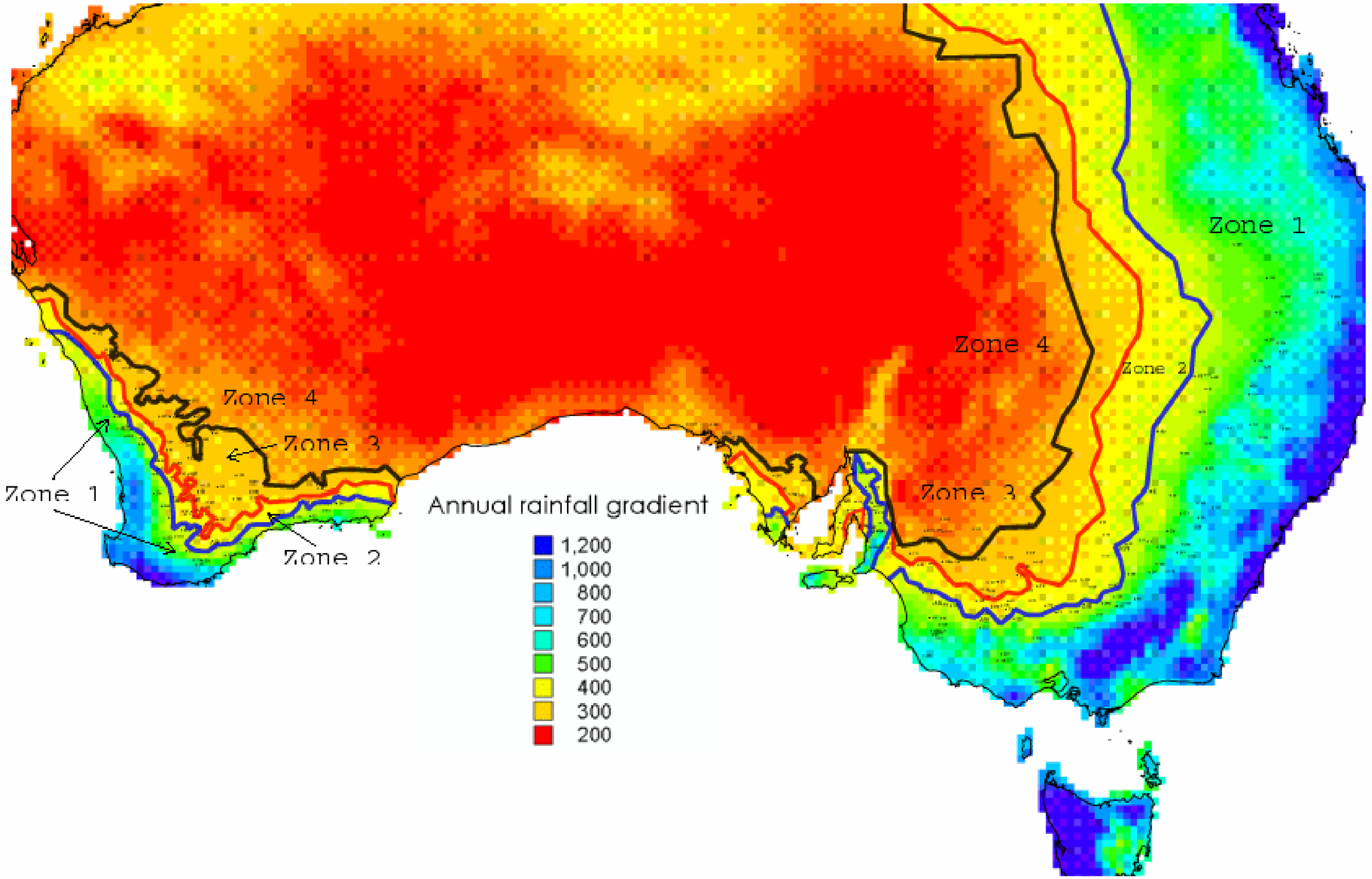


Figure 40 Wheat-belt division based on aggregated annual average rainfall patterns

Note - The black, red and blue lines indicate common boundaries between zones.

Table 42 The estimated quality profiles of 4 wheat-belt zones based on a Williams et al. (2002)

Quality traits	1	2	3	4
Test weight	81.1±0.5	79.8±0.3	80.0±0.4	79.5±0.5
Thousand kernel weight	39.7±1.3	35.2±0.5	35.8±0.8	34.1±0.7
Protein	Not able to be calculated	11.1±0.1	10.3±0.3	12.0±0.2
Grain hardness	21.0±0.6	20.3±0.4	20.1±0.5	17.0±0.3
Flour yield	72.7±0.4	74.5±0.2	73.1±0.3	76.0±0.2
Water absorption	60.6±0.5	61.9±0.3	60.7±0.4	61.2±0.5
Dough development time	3.7±0.2	4.6±0.2	4.2±0.3	5.4±0.3
Extensibility	19.4±0.4	20.4±0.2	19.5±0.4	22.7±0.3
Maximum resistance	278±12	325±8	350±11	369±15

The use of consolidated annual average rainfall zones across the wheat-belt in the 'environment +' model produced lower environmental variance levels for maximum resistance, water absorption, protein, and thousand-kernel weight. The four zones making up this test division were only different to each other for maximum resistance, with Type I differences for all other traits except thousand-kernel weight for which the zones had the same predicted means (Table 43). The precision of maximum resistance, water absorption, and dough development time, predicted means was considered good, each having a rank order of fifth. Across the nine quality traits the average rank order was sixth. The rank order position of a wheat-belt division based upon consolidated annual average rainfall zones associated with a relatively even spread of environments across its zones (the four zones contained 463, 238, 203 and 74 environments each).

Table 43 The estimated quality profiles of the 4 wheat-belt zones based on average annual rainfall

Quality traits	1	2	3	4
Test weight	79.5±0.3	79.4±0.5	80.0±0.3	80.2±0.8
Thousand kernel weight	35.3±0.5	35.4±0.9	34.7±0.7	35.2±1.1
Protein	10.8±0.1	10.8±0.3	11.4±0.2	11.4±0.4
Grain hardness	19.4±0.4	20.6±0.7	20.6±0.4	16.8±0.7
Flour yield	75.1±0.2	73.8±0.4	73.1±0.2	74.8±0.4
Water absorption	61.4±0.3	61.4±0.5	61.9±0.4	62.4±0.6
Dough development time	4.6±0.2	4.1±0.2	5.0±0.2	4.6±0.3
Extensibility	20.4±0.2	19.6±0.4	20.9±0.3	20.6±0.6
Maximum resistance	333±8	278±12	400±0.3	359±16

The orientation of boundaries in divisions of the wheat-belt based upon the consolidated agro-ecological zones reported by Williams et al. (2002) and annual average rainfall zones had some common features (Figure 39 and Figure 40). Common to both was the division of the Western Australian wheat-belt. In the case of the former test division, it was into 2 zones, while latter divided Western Australia along 3 boundaries making 4 annual average rainfall zones. Both test divisions had zones with interstate linkages. The consolidated agro-ecological zones as reported by Williams et al. (2002) linked a south western portion of the Western Australian wheat-belt with parts of South Australia and Victoria, while the remainder of Western Australia was linked with parts of the 2 peninsulas in South Australia. The 4 rainfall zones, linked areas in each state via a crescent shape across the wheat-belt (Figure 40).

A final test division warranting discussion was test code 1; representative of an amalgamation of farmer recommendation regions published independently by 5 state Departments of Agriculture (Figure 41). The environmental variances of maximum resistance, dough development time, protein, grain hardness, thousand-kernel weight and test weight were lower compared with control based on 'environment +' model results. The environmental variance of water absorption was equivalent to the control. In addition, this test division had lower levels of environmental variance for maximum resistance, grain hardness and test weight based on 'environment' model results with the lower levels associated with the link between quality testing by regional breeding programs and these zones having a state bias. The impact of that link, however, was reduced when zones were amalgamated on the basis of maximum resistance. In contrast, the predicted quality trait means of this test division were poor, with high standard errors compared with all the other test divisions and this meant several zone means could not be predicted and or they were not different to each other (Table 44). Furthermore this test division had a rank order position of 13th and this was attributed to the uneven distribution of environments across its 5 zones (11, 28, 149, 243 and 547). A division of the wheat-belt based on aggregated Department of Agriculture recommendation zones was highlighted because it consistently reduced environmental variance levels compared with the control. However, a major limitation regarding any adoption of this division for classification purposes was its poor differentiation between its zones and a lack of accuracy with regard to its predicted quality trait means. The 2 zones in the south-east region of South Australia are also potentially anomalies because they represented testing of predominantly low protein, soft-grained lines.

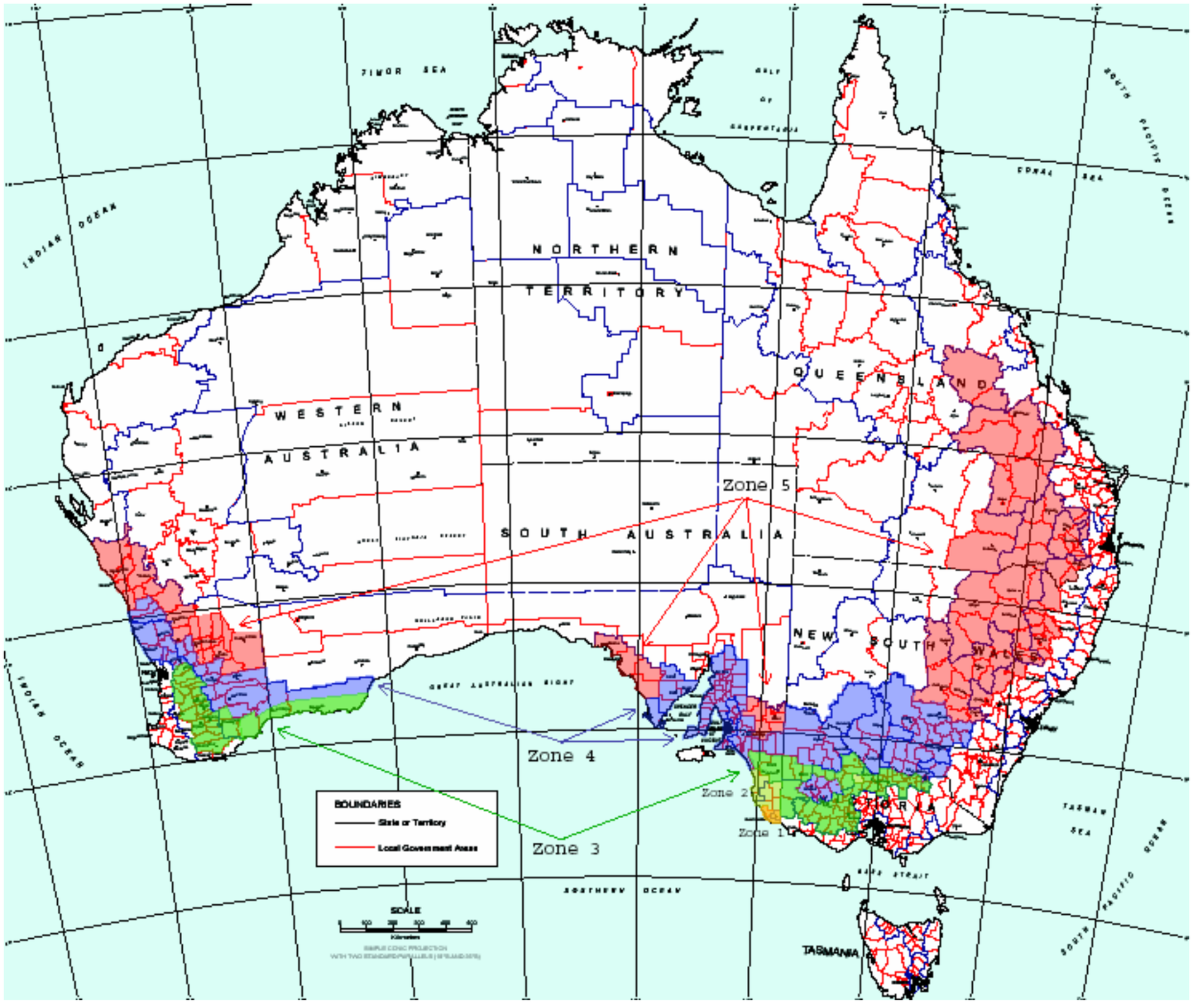


Figure 41 Wheat-belt division based on aggregated Departments of Agriculture recommendation areas

Note - Regions shaded in the same colour are the same zone**.**

Table 44 The estimated quality profiles of the 5 wheat-belt zones based on Departments of Agriculture recommendations zones

Quality trait	1	2	3	4	5
Test weight	NATOC	77.4±0.5	NATOC	79.9±0.3	79.6±0.2
Thousand kernel weight	NATOC	NATOC	NATOC	NATOC	NATOC
Protein	9.1±0.4	NATOC	9.4±0.1	10.8±0.2	12.0±0.1
Grain hardness	27.9±0.8	22.8±0.8	21.2±0.3	20.1±0.4	18.3±0.2
Flour yield	73.2±0.7	74.6±0.8	74.3±0.2	73.7±0.2	75.1±0.2
Water absorption	56.4±0.7	NATOC	59.2±0.2	62.0±0.3	61.7±0.2
Dough development time	2.1±0.2	2.7±0.3	3.2±0.1	4.4±0.2	5.4±0.2
Extensibility	17.4±0.7	19.0±0.7	18.8±0.2	20.2±0.3	21.7±0.2
Maximum resistance	187±11	217±17	271±6	327±8	389±7

NATOC = Not able to be calculated-

The orientation of the boundaries dividing the zones of aggregated Departments of Agriculture recommendation zones were similar to those observed for the average October maximum temperature profile (Figure 38 and Figure 41). Boundaries were roughly aligned along east-west axes, with each zone having linkages across the entire wheat-belt, ignoring state borders (Figure 41).

The remaining 10 test divisions were not considered worthy of any discussion because they showed no lowering trends of environmental variance compared with the control, had poor differentiation between their zones or combined both these negative features

The lack of difference between the test divisions identified as improvements compared with the current classification regions was attributed to the manner in which the data was originally aligned. The current classification regions are state based and these are connected to the largest 'sources of data' represented in the relational database (these are southern New South Wales –NSW Agriculture, South Australia – South Australia, Victoria – Victorian Department of Agriculture and Western Australia – Department of Agriculture and Food Western Australia; refer Table 14, page 75). The number of environment observations for these 4 classification regions was also high – 97, 352, 140 and 304 respectively. A consequence was that the environmental variances of the classification regions were

low even before any analysis commenced, since they did not divide the data as the test divisions did. Nix (1975) had drawn a similar conclusion about state bias after conducting a national studying involving simulated phasic development patterns.

The importance of including relevant additional factors in models cannot be understated. The most obvious was the impact 'source of data' had on reducing the variance associated with flour yield. Previously, Eagles et al. (2002a) had observed 16-fold a decrease in the level of environmental variance of flour yield when the 2 different milling regimes were incorporated into their analysis. Such a decrease was not found in this research, but 'source of data' was important in reducing variance and this made use of the 'environmental +' model the preferred one. Reduction in variance attributed to laboratories having, for example, varying mill set-up and conditioning regimes, despite using the same piece of equipment and reporting on the same flour extraction basis. The use of protein as a covariate also reduced variance, particularly for those traits with known linkages to protein level such as extensibility and water absorption (O'Brien and Ronalds, 1984, Eagles et al., 2002a). However, such results need to be considered in the context of why protein had been used as a covariate. Laboratories select samples for testing based on protein levels, potentially skewing levels either up or down. Such distortion occurring when results are to be used for classification purposes and the requirement to have samples at protein levels equivalent to grades targeted for classification. Overall, 'source of data' as a fixed effect in the model was of critical importance in obtaining meaningful results from the analyses of measurements from different laboratories.

Several other observations are worthy of discussion, despite not contributing to the identification of better boundaries for classification purposes. Based on variance component analyses, the size of either genotype or environment factors on quality traits studies were consistent with the literature. In ascending order of genotypic variance size compared with that of environmental variance were, dough development time, maximum resistance, water absorption and, grain hardness. The high level of genotypic variance for water absorption and grain hardness associated with the data analysed being composed of both hard and soft-grained lines. Such line divergence possibly overstates the size of the genotypic variance, and supports the analysis of a single hard type to ascertain the true effect genotype may have on

these 2 traits. The traits that had the largest environmental variance levels were protein, test weight, extensibility, flour yield and thousand-kernel weight. The relative size of genotypic variance of maximum resistance, dough development time, and water absorption compared with environmental variance supports the focus on these 3 traits in identifying boundaries for classification purposes.

To better understand the effect different lines have on the variance of water absorption, the selection and analysis of data representing uniform grain hardness is recommended. Puroindoline composition could be used to select hard grain lines, thus allowing a more refined determination as to the relative genotype and environment influence on this trait. Hard-grained lines would be preferable to soft-grained lines since they are more frequent in the data. In addition, hard-grained varieties can be divided into 2 puroindoline groups, allowing for a stepwise analysis to be performed, assessing the effect of different puroindoline combinations on water absorption, and other quality traits.

It was also observed from the variance component analyses that G×E had a minimal influence on the quality traits studied, and this finding supports what was discussed in Chapter 5. Other Australian studies have reported the same observation (Allen and Pumpa, 1999, Pumpa et al., 2002). The small size of G×E variance suggests that to improve the capacity of the REML models to predict quality trait means, G×E could be readily incorporated into the residual factor.

Furthermore, high standard errors of predicted means, or worse the inability to estimate a predicted mean, were found during the research described in this chapter. Those problems were associated with a lack of observations per zone. The data represented a span of 23 years, but only the Department of Agriculture and Food Western Australia and SA data sets covered all years. Consequently, it is suggested that to improve the calculation of predicted quality trait means, a more even spread of years across all the ‘sources of data’ be considered. However, reducing the number of observations analysed will affect the level of residual variance since its level in the analyses described in this chapter were noticeable smaller than those discuss in Chapter 5, reflective of the larger data set used here.

The consolidation of zones within test divisions based on maximum resistance showed that irrespective of the division, the consolidation occurred in a similar manner. There was commonality of areas along an east-west axis, and separation between zones along a north-south axis. Such was the submission made by Diamond (1998) who viewed the expansion of important agricultural crops from the Fertile Crescent to have occurred in an east-west direction. That submission based on commonality of rainfall and hours of sunlight along an east-west axis.

Weaker dough properties (low maximum resistance) were associated with the extreme southwest corner and southern coastal portions of Western Australia, the lower southeast portion of South Australia and southern portions of Victoria. A common feature of trials from these areas was that soft-grained 'biscuit' lines were grown and these have inherently weak dough properties. In Western Australia 'biscuit' lines include Datatine and Tincurrin, in South Australia Anlace and Bindawarra are common 'biscuit' lines, and in Victoria Bowie and Tatiara fall into this category. High maximum resistance values were associated with the northern and eastern parts of Western Australia, northern parts of South Australia, central and northern New South Wales and Queensland. In these regions, the data represented almost exclusively hard-grained lines that are inherently stronger than soft grain lines. Across southern New South Wales/northern Victoria, through central South Australia, and central Western Australia along an east-west axis, the profile was of medium maximum resistance levels. The level in these regions attributed to the testing of both hard and soft-grained lines, though included with the soft-grained 'biscuit' lines were stronger 'noodle' types such as Cadoux, Eradu and Rosella. Testing regimes may affect variance levels of different test divisions, and therefore it is suggested that in the crosschecking investigations, the assessment of a single hardness type be considered.

The use of yield as a covariate was beneficial in lowering the level of estimated environmental variance for some important quality traits, but it did not change the trends between test division and control environmental variance differences.

The most quality representative locations identified provide a guide for future field trials on the basis of the 4 possible divisions of the wheat-belt that could be adopted.

Within a division type, some locations were the closest to their zone mean for a number of different quality traits. There was less commonality of locations between the divisions assessed. However, Narrabri and Walgett were common among the control and test division codes 7, 4 and 1. Test division code 10 was the most unique, having the least number of locations common to the other divisions assessed. Since not all locations were sampled every year, care needs to be taken in the true representative nature of these predictions since they were influenced by the number of observations at each location, as well seasonal conditions experienced in the year sampled.

In summary, 4 divisions of the wheat-belt offer the potential to be adopted by industry participants in the classification of wheat lines. Each set of zones had lower levels of environmental variance, compared with the current classification regions, for certain inherent quality traits. The responses interpreted as the zones of these test divisions having similar environmental effects on the expression of important genetically controlled quality traits. The importance of such commonality could lead to potentially greater consistency of the wheat segregated across the entire wheat-belt. The 4 divisions identified were also made up of less number of zones than the existing number of classification regions. From this perspective, they also offer important monetary savings with respect to trial and quality testing costs.

Chapter 7 Crosschecking of findings

The research described in this chapter used alternative data sets and assessment methods, to confirm the selection of the 4 wheat-belt divisions reported in Chapter 6. In addition, the capacity of those divisions to have consistent environmental variance was assessed. Normally referred to as validation, the term crosschecking has been used since a new, or independent, data set was not available for assessment.

7.1 Background

Validation is an important step in assessing veracity of research findings. In the context of this research validation was considered an important experimental step because if industry participants adopted any new set of zones identified by this research, they would require a degree of assurance as to their application. The general theory regarding validation is that it is usually performed on an independent sample to that of the test sample. However, in this instance, an alternative sample of sufficient size in both spatial and temporal terms was not available. Therefore, to corroborate the findings of preceding research phases with access to no independent sample, the decision was made to use and analysis the data in different ways.

7.2 Methodology

The crosschecking investigations were divided into 2 groups.

The first focused on using alternative data sets and assessment methods to confirm that test division codes 7, 4, 10 and 1 were the best set of divisions in reducing environmental variance compared with the current classification regions and that their zones had different quality profiles (see Table 26 and associated text on page 104 for description of test divisions and control).

The second investigation aimed at assessing the consistency in which test divisions accounted for environmental variance. That was achieved by comparing the manner in which test divisions accounted for environmental variance based on the analysis of 2 different data samples.

7.2.1 Crosschecking the merits of test division codes 7, 4, 10 and 1

Three approaches were used to try and replicate the identification of the best 4 test divisions. The first 2 approaches focused on the use of different data sets. The first, following a suggestion reported in Chapter 6 was to analyse a more uniformly spread number of environments across years. The second approach, followed another suggestion arising from the research discussed in Chapter 6, and that was to focus on the analysis of only hard-grained lines. However, neither of these approaches will be discussed further because the 4 test divisions considered worthy of discussion in Chapter 6 (test divisions codes 7, 4, 10 and 1) were not shown in the same positive light. The lack of sensitivity and differentiation found in both those analyses contributed to less number of observations used.

The third approach, and focus of discussion in this chapter, was the use of a cluster analysis technique. Henceforth, this investigation has been referred to as the 'cluster' analysis. Grain yield has been the trait most often analysed this way, with few quality examples published (Collaku et al., 2002). Standard procedures rely on the analysis of balanced data. In this instance the available data were unbalanced. However, data were available for testing at linemultiple locations across the wheat-belt for the same line. Clustering was considered an ideal tool from a spatial point of view and so an alternative approach was needed to make use of the available data.

The cluster approach taken was to identify single lines, grown across the entire Australian wheat-belt, and use these independently in correlation based analyses. To progress with analyses, it was assumed that by focusing on a single line the genetic influences on quality were the same, and that the different growing environments would influence the quality expressed. In this way, locations of similar quality performance could be grouped together and compared with the results for the test divisions from the analyses discussed in Chapter 6.

7.2.1.1 Data selection for 'cluster' analysis

The relational database was used to select 6 lines (Table 45). These were not necessarily the most often tested lines (Spear, Rosella, Gutha, Eradu and Molineux had been tested more often) but the selected lines all had been tested across the entire

wheat-belt. In addition, the selected 6 lines meet the selection criterion of having at least 10 observations in 4 of the 5 states – this excluded lines such as Machete, Meering, Halberd, Wilgoyne and Oxley from being selected. Janz had the most observations, and importantly, these represented testing across 148 locations, which was double the number of locations used for testing of the 5 other lines (Table 45). The number of environment observations (location x year combinations) was higher than the number of locations but lower that the total number of observations, indicative that testing of multiple samples had occurred at some locations; this was either replicated testing in the same year or testing across multiple years (Table 45).

Table 45 Lines selected for cluster analysis

Line	Total number of observations	Observations per state					Number of locations	Number of environments observations
		NSW	QLD	SA	VIC	WA		
Janz	487	154	11	177	82	63	148	385
Kite	316	74	13	207	10	12	65	189
Hartog	205	78	48	31	14	34	61	125
Frame	185	22	4	93	55	11	77	174
Chara	135	32	11	28	58	6	72	129
Dollarbird	134	60	6	27	27	14	71	124

7.2.1.2 Statistical analyses for single line cluster analysis

The CINTERACTION procedure in Genstat was used (Payne et al., 2003). Corsten and Denis (1990) described this as a grouping tool based an agglomerative hierarchical clustering of 2 unstructured factors which have an interaction, based on sums of squares. For this study, 2 quality traits considered relatively independent to environmental influence were selected, and these were maximum resistance and dough development time. To create the necessary correlation matrix, REML was used, the model using location as the fixed factor, and environment as the random factor. Year was not used, since classification boundaries need to be fixed from year to year from a management perspective (both for farmers and buyers). Having created the correlation matrix, the CINTERACTION function was applied to that matrix of data. Output was in the form of dendograms. When the dendograms were used to determine which groupings were made of which locations, the dendograms were enlarged between 400-600% times so that the locations could be read. The sums of squares level at which locations were grouped varied for each line. However, for simplicity, the number of groups was restricted to 3 or 4 (Table 46) and that range was consistent with the number of zones of the best test divisions

discussed in Chapter 6. The groupings of locations reflected difference dough strength profiles based on the dough development time and maximum resistance measurements used to create the correlation matrix from which the dendograms were based. The groupings of locations were then mapped for each line. The location Cowra, in the Hartog analysis, was not included in any group as it was considered an outlier due to excessive dough strength properties. The 2 Cowra observations had dough strength values of 910 and 975 BU, with corresponding dough development time values of 3.5 and 6.9 minutes.

Table 46 Group cut-offs of CINTERACTION dendograms of 6 lines

Line	Sums of squares cut-off	Number of groups
Janz	100,000	4
Kite	25,000 and 50,000	4
Hartog	50,000	4
Frame	50,000	4
Chara	100,000	3
Dollarbird	25,000	4

In addition to the analyses conducted on the 6 lines, a single source of data was selected for assessment, because 'source of data' had been previously found to be important in reducing overall variance levels (Chapter 6). The source chosen was #12, since it had assessed a common set of 4 lines grown at 22 locations spread across the wheat-belt [source #12 was the Prime Hard in the South project which was reported in consecutive years at the annual Australian Cereal Chemistry Conference (Oliver et al., 1996, Oliver et al., 1997, Allen et al., 1998, Allen and Pumpa, 1999)]. In addition, to the analysis conducted for dough strength and dough development time, the CINTERACTION procedure was expanded to assess dough strength and thousand-kernel weight, and dough strength and water absorption. The rational here was that these 2 pairs of traits were highly correlated compared with other quality trait pairings in this sub sample.

7.2.2 The assessment of rigid boundaries coping with seasonal variation

An important aspect of divisions used for classification purposes is that they are independent of seasonal variations. To assess the consistency of the manner in which the different test divisions accounted for environmental variance, 2 random data sets were selected and then compared. The selection of 'odd' and 'even' years

followed the logic presented by Chmielewski and Potts (1995) who used 'odd' and 'even' years to develop a statistical model, and then check the validity of that model.

7.2.2.1 Data selection

For this investigation, 5 'odd' and 'even' years with the most locations were selected (Table 47). Within each selection, the number of locations per year was similar, as was the total number of locations per selection (Table 47). Both selections contained both soft and hard-grained cultivars. The total observations per selection were 'odd' – 7,812, and 'even' – 7,410.

Table 47 Summary of locations that were tested in the selected 'odd' and 'even' years

Number of locations in odd years					Total number of locations
1993	**1995**	**1997**	**1999**	**2001**	**Odd years**
62	81	57	53	51	304
Number of locations in even years					
1990	**1994**	**1996**	**1998**	**2000**	**Even years**
51	70	64	53	61	299

Comparison of the 'odd' and 'even' year quality profiles showed the samples were for practical purposes essentially similar (Table 48). However, due to the size of the 'odd' and 'even' samples t-test based comparisons using the mean and standard error actually showed that the only quality trait that was not different between the two samples was grain hardness.

Table 48 Summary of quality trait means for the selected 'odd' and 'even' data

Quality Trait	Odd years		Even years	
	Number of observations	Mean and standard error	Number of observations	Mean and standard error
Test weight	6,362	80.6±0.04	5,980	80.7±0.04
Thousand-kernel weight	5,572	36.2±0.07	4,888	35.4±0.07
Protein	7,812	10.6±0.02	7,410	10.9±0.02
Grain hardness	7,575	18.8±0.07	6,726	18.9±0.07
Flour yield	7,792	74.6±0.03	7,400	74.3±0.03
Water absorption	7,810	61.2±0.05	7,398	61.5±0.05
Dough development time	7,809	4.6±0.03	7,398	4.8±0.03
Extensibility	7,800	20.4±0.03	7,403	20.6±0.03
Maximum resistance	7,812	337±1.38	7,407	345±1.41

7.2.2.2 Statistical analysis

The REML directive in GENSTAT (Payne et al., 2003) was used to run the modified 'environment +' model (incorporating the G×E factor in the residual error) and

estimations were limited to variance components and standard errors. The quality traits analysed were maximum resistance, extensibility, dough development time, water absorption, protein and flour yield. Test weight and thousand-kernel weight were not assessed due to their level of missing observations. Grain hardness was not assessed, because of the influence the line composition had on results. All test divisions, and the control, were assessed to provide a better guide as to any potential differences between the 2 data samples.

7.3 Results and discussion

7.3.1 Single line cluster analysis

The value of the dendograms created from the cluster analyses was how the groupings of locations appeared on a map, and how the spread of locations compared with the 4 test divisions identified in Chapter 6. Collectively, the mapping of location groups by the individual lines showed no discernable patterns that could be matched to the identified test division, or indeed the control. However, an inference can be made as to placement of boundaries based on the Janz analysis because this line had been tested at more locations compared with the other 5 lines, and by that weight of numbers a clearer picture was visible (Figure 42). Conceptually, a boundary separated locations in the northern and eastern portions of the Western Australian wheat-belt from those in the south-western corner of the state. The eastern portion of Western Australia aligned with the western portion of the Eyre Peninsula in South Australia, and the area north of a line running across southern New South Wales through Balranald, Tullibigeal, Temora, Ariah Park and Wallendbeen (Figure 42). That boundary, and its orientation, is similar to that represented by the boundaries of test division codes 7 and 1. The boundary separating locations having stronger dough properties (northern side) to those where weaker properties prevailed (southern side of boundary). However, due to the limited number of locations available for analysis, coupled with the locations representing different years, the placement of the boundary in Figure 42 is not definitive. The lack of discrimination is illustrated by some locations in the high strength group (Group 4) not in geographical proximity to the other sites of that group. For example most of the Group 4 locations are north of the boundary drawn but some occurred in southern Victoria and the lower south-west of Western

Australia. It was assumed that the year these locations were sampled, the environmental conditions that prevailed favoured atypical strong dough properties, perhaps due to high temperatures during grain filling (Wrigley, 2003).

It had been clearly observed during the analyses discussed in Chapter 6 that 'source of data' was an important source of variation when measurements from different test laboratories were assessed together. Therefore, an additional cluster analysis focused on a single data source. The use of a single source of quality data showed that, irrespective of the pair of quality traits assessed, the 22 locations were grouped in the same manner (Table 49). The groupings of locations, and their order within a group, were as listed in Table 49 for the 3 different CINTERACTION analyses. An exception was Group 2, for which the order of locations was different for the dough strength-thousand-kernel weight and dough strength-water absorption analyses. Group 3 was also before Group 2 (as listed in Table 49) for the dough strength-water absorption CINTERACTION analysis.

Table 49 Grouping of 22 locations based on the analysis of maximum resistance and dough development time

Grouping					
1	**2**	**3**	**4**	**5**	**6**
Loxton Salmon Gums Walpeup	Gilgandra Horsham Cryon Moree Young Coonamble Kyalite Nangus	Dalwallinu Minnipa Wunkar	Cowra	Nangari Ariah Park Condobolin Goodlands	Morawa Merredin Varley

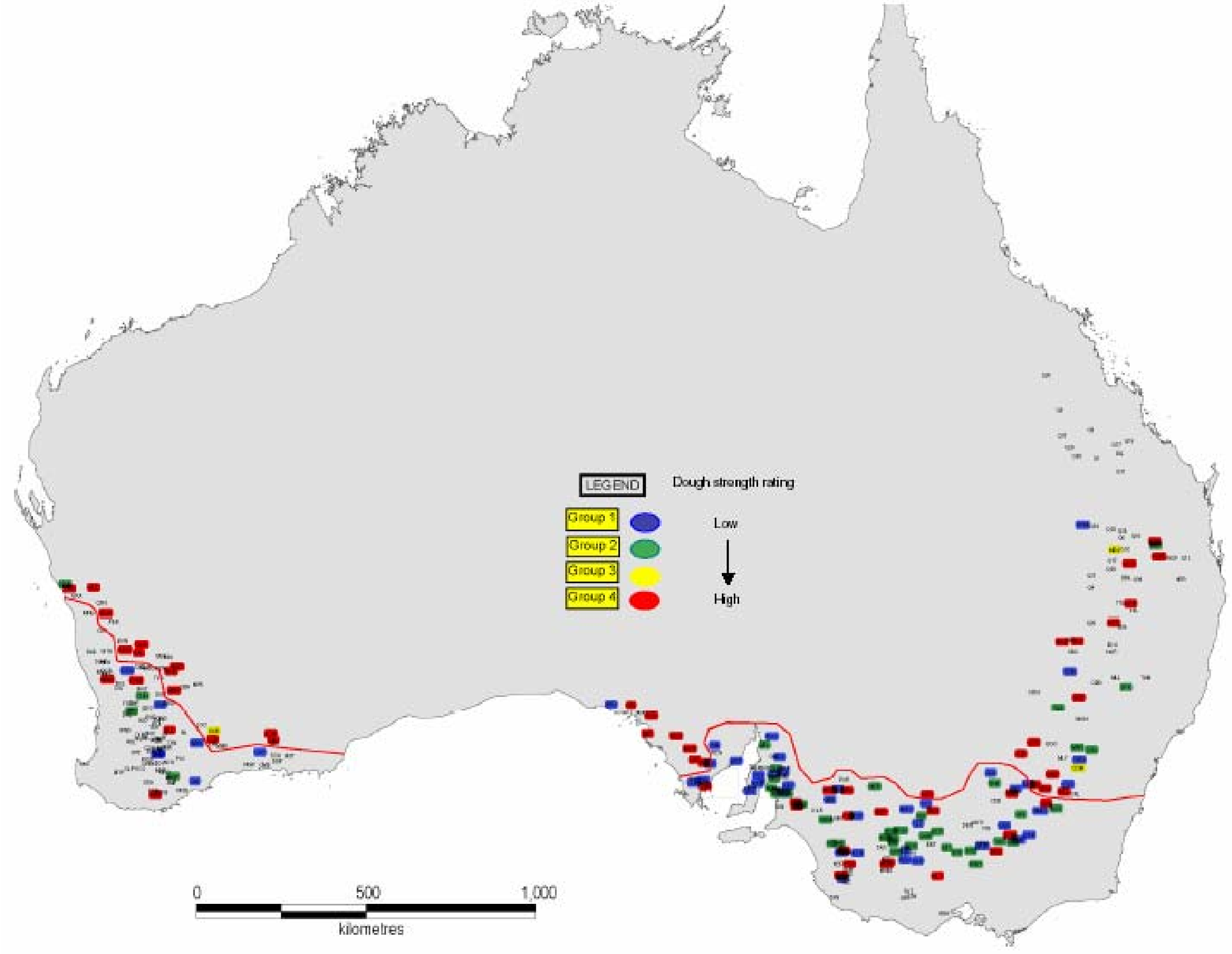


Figure 42 Wheat-belt division based on the quality similarities of Janz tested at different locations

7.3.2 The assessment of rigid boundaries coping with seasonal variation

The 'odd' and 'even' years accounted for the environmental variance differences between test divisions and the control in the same manner for dough strength, water absorption and flour yield (Figure 43, Figure 44 and Figure 45). The trend was that the test divisions were worse at accounting for environmental variance having higher levels compared with the control, with the only exception being test division code 10 for flour yield (Figure 45).

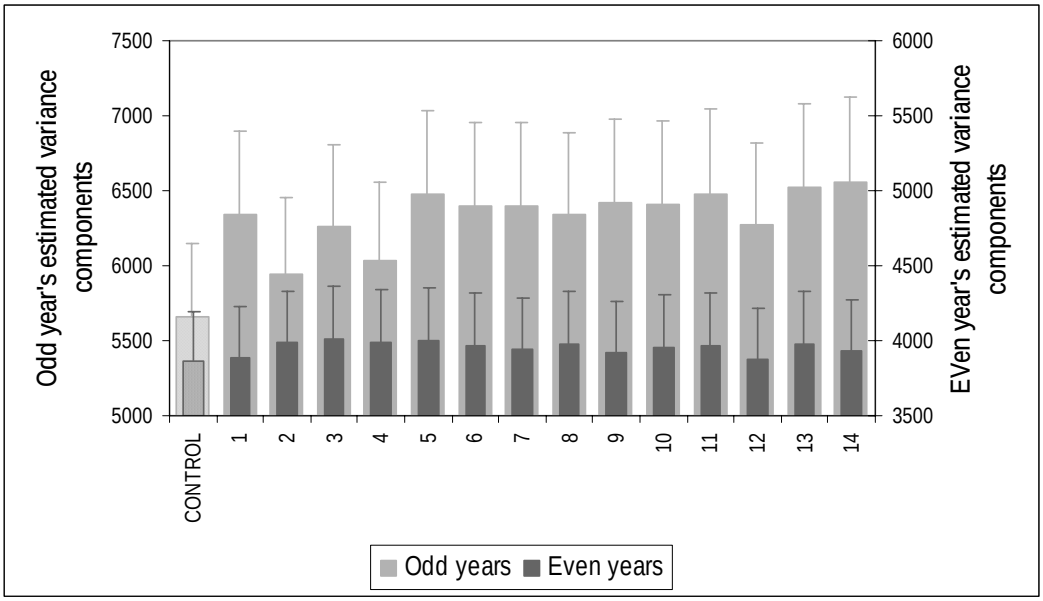


Figure 43 Estimated environmental variance and standard errors of maximum resistance

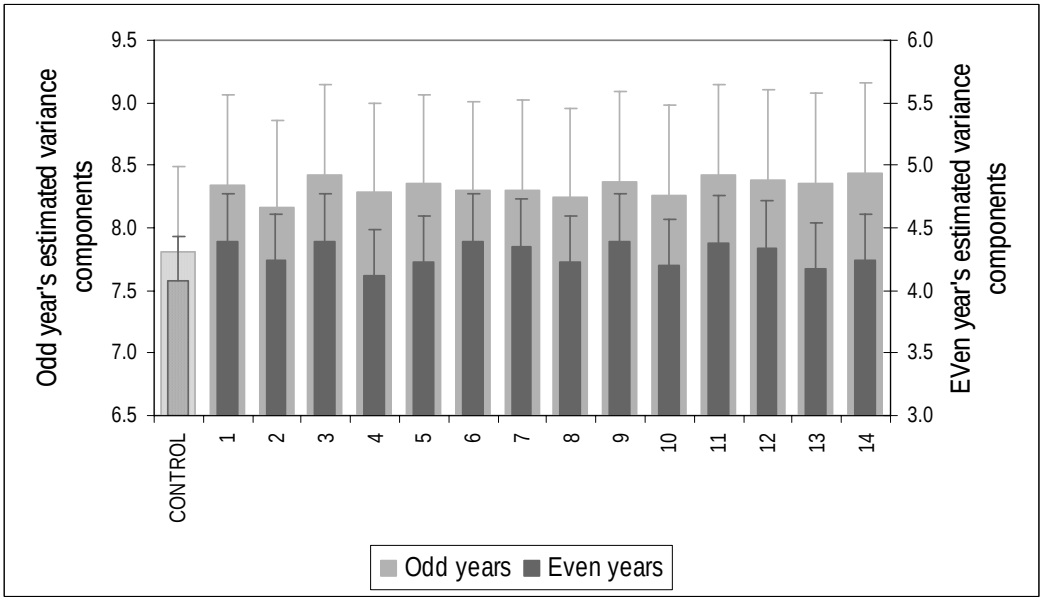


Figure 44 Estimated environmental variance and standard errors of water absorption

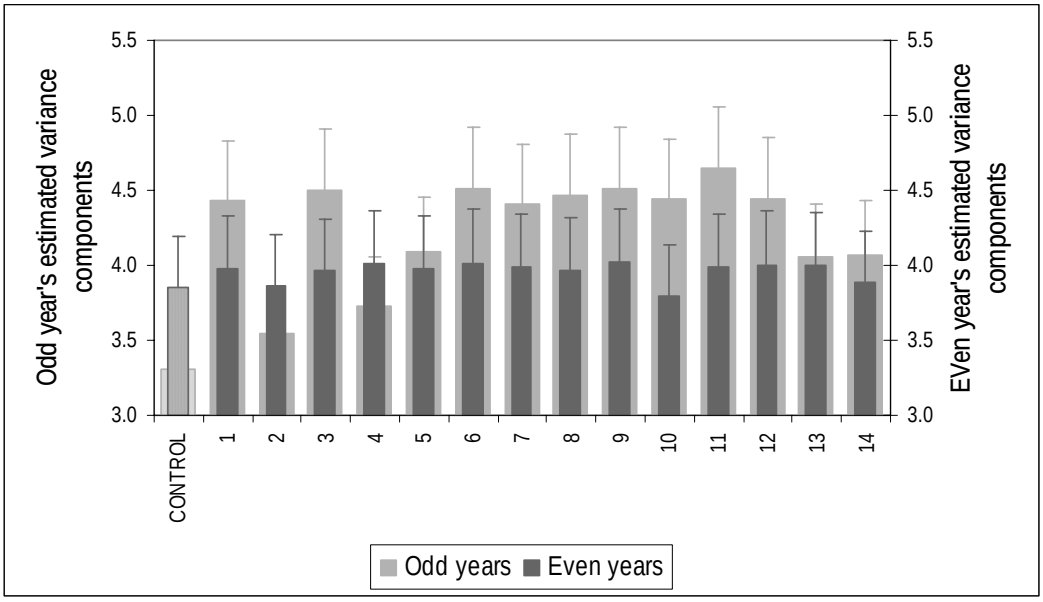


Figure 45 Estimated environmental variance and standard errors of flour yield

In contrast, the ratio of test division and control environmental variances for extensibility, dough development time, and protein, were different for the 'odd' or 'even' year samples analysed (Figure 46, Figure 47 and Figure 48). Such variability between the 'odd' and 'even' was linked different seasonal conditions producing different protein levels.

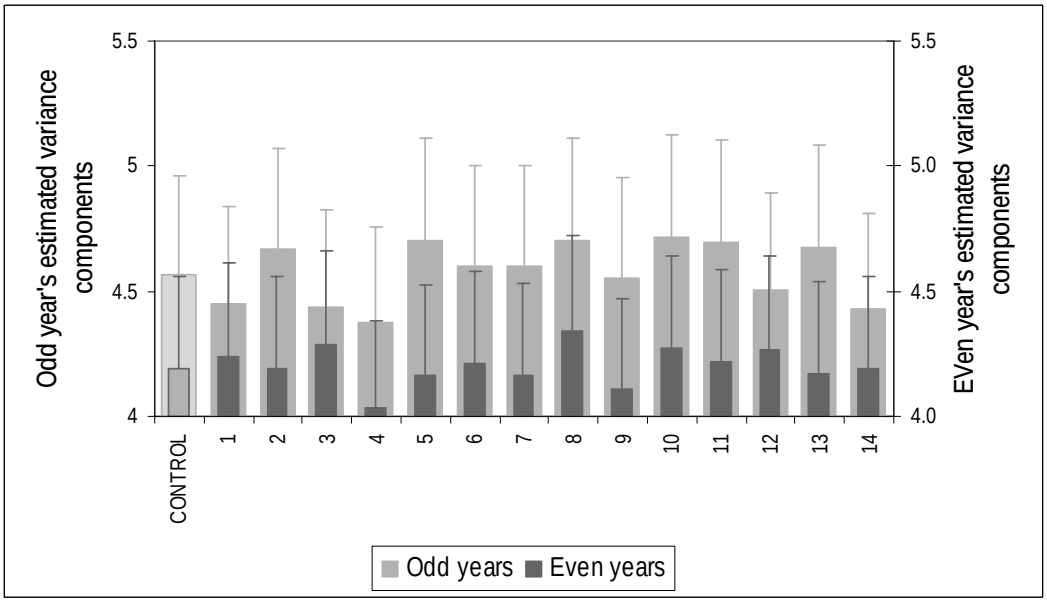


Figure 46 Estimated environmental variance and standard errors of extensibility

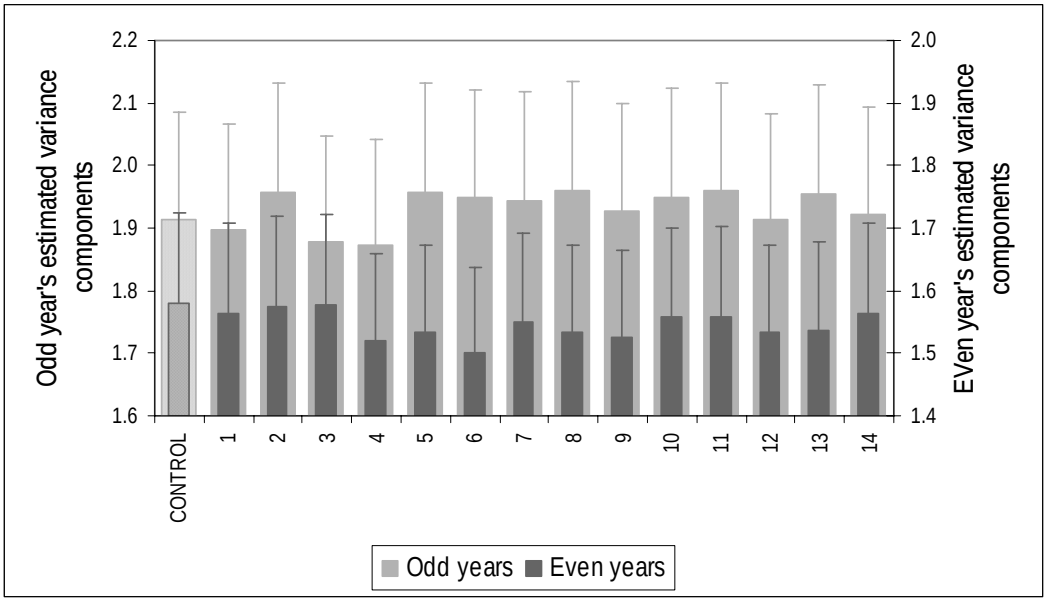


Figure 47 Estimated environmental variance and standard errors of dough development time

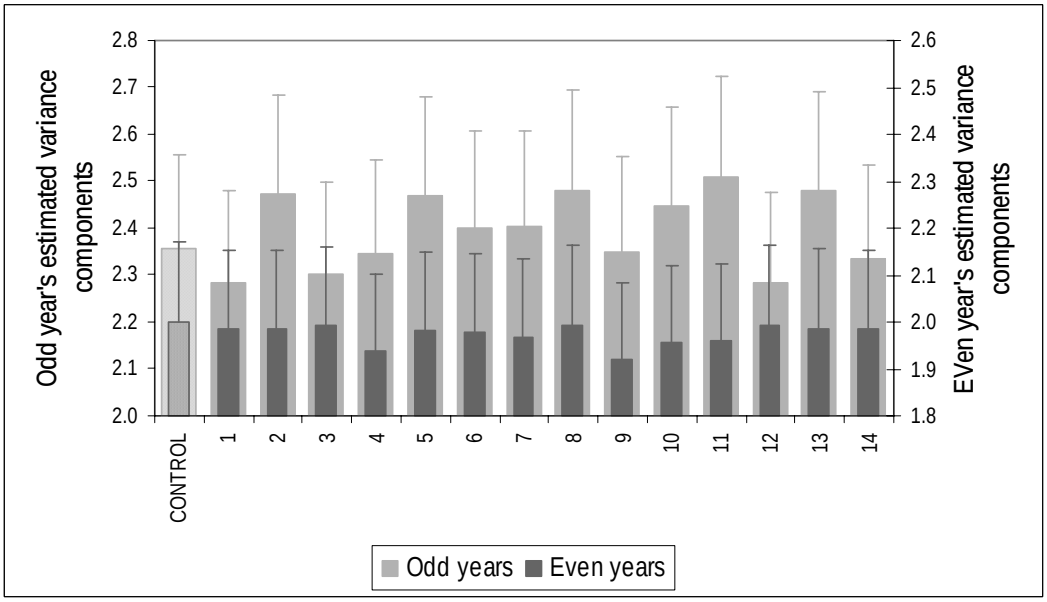


Figure 48 Estimated environmental variance and standard errors of protein

Analysis of the 'odd' and 'even' data samples also showed that quality traits and the manner in which test divisions accounted for environmental variance compared with the control, were influenced by the different combination of years. Such inconsistency suggests that irrespective of the division of the wheat-belt, seasonal influences can alter the manner in which quality is expressed.

Simple comparison of estimated variance components of the 'odd' and 'even' data samples, because no standard statistical test is available, showed differences in the size and manner in which variances were distributed. The sizes of genotype and environment variances were similar for extensibility, protein and flour yield, as were the residual variances, when both data samples were compared (Table 50). However, the size, and distribution between components, of the maximum resistance, dough development time, and water absorption variance were different between the 'odd' and 'even' samples (Table 50). For example, the 'odd' year ratio of environment to genotype variance for maximum resistance was 1.33. In contrast, the same ratio for the 'even' years was 0.58. Similar trends were observed for dough development time and water absorption with the 'odd' year analyses estimated to have a larger environmental variance compared with that of genotype, and the 'even' year analyses estimated to have a greater genotypic variance compared with that of environment (Table 50). It is difficult to say why the differences between the years sampled may have occurred, apart from suggesting that differences in the composition of the lines making up each sample may have reacted differently to the prevailing seasonal conditions.

Table 50 Seasonal influence on mean estimated variance components and standard errors of 6 quality traits

Quality trait	Variance components	Odd Years	Even Years
Maximum resistance	Genotype	4730±231	6859±316
	Environment	6301±546	3949±348
	Residual	2079±37	2038±38
Extensibility	Genotype	1.85±0.11	1.98±0.11
	Environment	4.58±0.40	4.20±0.37
	Residual	2.00±0.04	1.95±0.04
Dough development time	Genotype	1.14±0.07	3.64±0.18
	Environment	1.93±0.17	1.55±0.14
	Residual	1.49±0.03	1.72±0.03
Water absorption	Genotype	6.78±0.32	8.79±0.40
	Environment	8.30±0.71	4.28±0.38
	Residual	2.11±0.04	2.08±0.04
Protein	Genotype	0.25±0.02	0.26±0.02
	Environment	2.39±0.21	1.97±0.17
	Residual	0.52±0.01	0.43±0.01
Flour yield	Genotype	1.47±0.08	1.26±0.07
	Environment	4.21±0.37	3.95±0.35
	Residual	1.28±0.02	1.28±0.02

7.4 Summary of crosschecking investigations

The primary aim of the crosschecking investigations conducted was to assess the validity of the test divisions identified in Chapter 6 as having potential use for classification purposes. The cluster analysis approach, based on the line Janz, was the closest to replicating the potential boundaries discussed in Chapter 6. However, that claim is open to interpretation since the boundary separating the location groups was drawn 'free-hand' between dissimilar groupings of locations, rather than using a statistical approach as was outlined by Smith (2004). Importantly the cluster analysis approach showed the need for a large numbers of location observations, because discrimination of the other 5 line cluster analyses was poor when compared with that of the Janz analysis, a fact contributed to their location numbers being half that of the Janz sample.

The analyses conducted also confirmed that no discrimination was lost when the G×E factor was incorporated with the residual variance in the 'environment +' model. The modification of the model in this way provided the capacity to better predict the quality trait means for comparison purposes.

A secondary focus of the crosschecking investigations was to assess how independent a fixed division might be to seasonal variation. The results showed that year-to-year differences changed the relative influence of genotype and environment on maximum resistance, dough development time and water absorption. Importantly, however, the test divisions accounted for environmental variance of maximum resistance, water absorption, and flour yield, in the same way, irrespective of the year sample assessed. The latter observation a positive feature and supports the use of fixed in time boundaries for use in variety classification of important inherently linked quality traits.

Chapter 8 Conclusions

The use of environmentally based boundaries for wheat variety classification would benefit the Australian wheat industry. Four environmentally based divisions of the wheat-belt have potential for adoption and these were identified by a process of minimising environmental variance while concurrently maximising quality differences. The 4 wheat-belt divisions of choice were, a set of 3 zones based on average October maximum temperature, a set of 4 zones based on the agro-ecological zones described by Williams et al. (2002), a set of 4 zones based on average annual rainfall, and a set of 5 zones based on state Departments of Agriculture variety recommendation zones. The benefits of environmentally based boundaries would be an improved capacity to segregate a consistent quality of wheat due to the minimisation of environmental variance, and process efficiencies since these 4 divisions all have less zones than the current set of 7 classification regions.

G×E was not a significant source of variation when several quality traits were assessed on an individual state basis. The traits assessed were maximum resistance, dough development time, water absorption, grain hardness, flour yield, test weight, grain hardness, thousand-kernel weight, and extensibility. The lack of significant G×E has positive implications for testing regimes because it enables those interested in quality to predict structured genotype and environment performance. Multiple genotype and environmental combinations were used to assess the level of G×E, in contrast to a single experimental window, because of the belief that such an approach provides a higher level of confidence that the sample analysed is truly representative of the population of interest.

The 4 identified divisions have common boundary orientation along an east-west axis. Such boundary orientation is indicative of environmental linkages between the divisions studied, irrespective of whether the basis was temperature, rainfall, humidity, latitude, or agro-climatic-environmental. The crosscheck analyses that were performed provided additional endorsement on the placement and orientation of new boundaries for classification purposes. The identification of maximum spring-time temperature as a division of choice is consistent with the theories of ‘heat shock’ on protein quality.

Geographically separate east and west coast wheat-belt production areas were demonstrated to have the same environmental effect on the expression of wheat quality. The plausibility of investigating alternative divisions for classification purposes across the entire Australian wheat-belt was achieved because for the first time that a sufficiently large enough spatial and temporal data set could be compiled. Previously, the 'environmental' zones developed by the various state Departments of Agriculture in providing recommendations to growers had been used as the basis for wheat variety classification, but this was done using each state separately. The findings of this research were weighted towards several quality traits – maximum resistance, dough development time, water absorption, grain hardness and flour yield. The difficulty in using results from different laboratories was emphasised by the standard flour yield measurements that were used, and how 'source of data', reduced variance levels. However, within each 'source of data' relatively consistent end-product and other additional quality tests were measured. Given the important proof of concept shown in this research, the individual 'source of data' could be analysed to assess the validity of any boundaries within a single state.

The use of historical data in research raises the issues of whether the data reflects prevailing and or future circumstances. Two key variables that were used were climatic conditions and genetic diversity. Therefore any adoption of new boundaries based on the demonstrated proof of concept reported in this dissertation needs to be mindful of future climatic and or parental germplasm changes. If modelling was performed, it would need to consider the sub-sample used, because it is unlikely that such a large spatial and temporal set of data will be available again. Furthermore, a factor that would mask any future assessment is the use of quality results based on composite samples, rather than results from site-by-site testing as were used in this research.

Legal status of a zone is highly desirable for variety classification purposes because it can nullify, to an extent, potential debate from farmers about not having access to a higher paying segregation in their immediate zone as opposed to an adjacent zone. Legal boundaries do not follow environmental gradients but rather shire boundaries that more often than not are straight lines. The choice by industry participants to

adopt one of the 4 identified environmental divisions for classification purposes would require a decision on whether boundaries exclusively reflected environmental gradients or were an alignment of environmental and legal boundaries.

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Chapter 10 Appendices

Appendix 1 Published divisions of the wheat-belt used in this research

Division of the wheat-belt	Zone names	Code
Current classification regions	Zones were QLD, NNSW, CNSW, SNSW, VIC, SA, WA	Control
Aggregated Department of Agriculture zones	Zones were QLD; North, Central and Southern (NSW); A, B, C, D, E, F (VIC); Upper Eyre Peninsula, Central Eyre Peninsula, Lower Eyre Peninsula, Eastern Eyre Peninsula, Yorke Peninsula, Upper North, Mid North, Lower North and Barossa Valley, Central Hills, Lower Murray, Northern Murray Mallee, Southern Murray Mallee, Upper South East, Mid South East, Lower South East (SA); Agzones North West, Central, South West, North East/Central, Lakes/Mallee, South Coast (WA)	1
GRDC management zones	Zones were North, South, West	2
GRDC agro-ecological zones	Zones were QLD Central, NSW NorthWest-QLD SouthWest, NSW NorthEast-QLD South East, NSW Central, NSW VIC Slopes, VIC High Rainfall, SA VIC Bordertown-Wimmera, SA VIC Mallee, SA Midnorth-Lower Yorke Eyre, WA Mallee, WA Sandplain, WA Central, WA Eastern, WA Northern	3
Agro-ecological zones Williams et al. (2002)	The zones as reported by Williams et al. (2002) that were used were codes 7, 8, 13, 15,17, 20, 36, 37,39, 41, 42	4
Bureau of Meteorology Seasonal rainfall	Zones were Summer (S1,S2,S3); Uniform (U1,U2,U3); Winter (W1,W2,W3); WinterDominant (WD1,WD2,WD3), with 1,2,3 equating to a decreasing amount of rainfall	5
Bureau of Meteorology Average November maximum temperature	Zones were divided upon gradient of >=30, >=27, >=24, >=21, >=18, >=15, >=12 degrees Celsius	6
Bureau of Meteorology Average October maximum temperature	Zones were divided upon gradient of >=30, >=27, >=24, >=21, >=18, >=15, >=12 degrees Celsius	7
Bureau of Meteorology Average September maximum temperature	Zones were divided upon gradient of >=30, >=27, >=24, >=21, >=18, >=15, >=12 degrees Celsius	8
Bureau of Meteorology Average August maximum temperature	Zones were divided upon gradient of >=30, >=27, >=24, >=21, >=18, >=15, >=12 degrees Celsius	9
Bureau of Meteorology Annual average rainfall	Zones were divided upon gradient of >=700, >=500, >=400, >=300, <300 mm	10
Bureau of Meteorology Temperature and humidity climate zones	Zones were mild/warm summer and cold winter, warm summer and cool winter, hot dry summer and cold winter	11
Latitude divisions	Zones were <-31 degrees, -31 to <-31 degrees, >=-31 degrees	12
Agro-ecological regions after SCARM (1998)	Applicable zones were 6 (Subtropical slopes and plains), 8 (Wet temperate coast), 9 (Temperate highlands) and 10 (Temperate slopes and plains)	13
Agro-seasonal-soil zones	Zones were West, South, Ex Marine, SouthEast Acid, North	14

Appendix 2 Location latitude and longitude details, and the test division zone each location was allocated for analysis

Notes

Latitude and longitude followed by *, indicate source of data was used instead of GeoScience Australia.

The number of zones per test division is reported in Table 28

The test division codes were

Code number	Test divisions	Code number	Test divisions
1	Aggregated Department of Agriculture zones	8	Average September maximum temperature
2	GRDC management zones	9	Average August maximum temperature
3	GRDC agro-ecological zones	10	Annual average rainfall
4	Agro-ecological zones Williams et al. (2002)	11	Temperature and humidity climate zones
5	Seasonal rainfall	12	Latitude divisions
6	Average November maximum temperature	13	Agro-ecological regions after SCARM (1998)
7	Average October maximum temperature	14	Agro-seasonal-soil zones

Location	**Code**	**State**	**Latitude**	**Longitude**	**Existing classification regions and test division zone allocation**													
					Control	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Aldersyde	1	WA	-32.22	117.16	WA	4	W	2	1	2	3	2	1	2	2	2	B	2	1
Alford	2	SA	-33.49	137.49	SA	4	S	2	2	2	3	2	1	3	3	2	B	2	1
Ameulp	3	WA	-34.15*	118.13*	WA	3	W	2	3	2	2	1	1	2	2	1	B	2	1
Ariah Park	4	NSW	-34.19	147.13	SNSW	4	S	2	2	2	3	1	1	2	1	2	B	2	1
Arthur River	5	WA	-33.20	117.02	WA	3	W	2	1	2	2	1	1	2	1	2	B	2	1
Auburn	6	SA	-34.01	138.41	SA	4	S	2	3	2	3	1	1	2	1	1	B	2	2
Avondale	7	WA	-32.07	116.52	WA	4	W	2	1	1	3	1	1	2	1	2	B	2	1
Badgingarra	8	WA	-30.19	115.32	WA	4	W	2	1	1	3	2	1	3	1	2	A	2	1
Badjerin Rock	9	WA	-30.47*	117.20*	WA	5	W	3	3	2	3	2	1	3	3	2	A	2	1
Balaklava	10	SA	-34.08	138.25	SA	4	S	2	2	2	3	2	1	2	2	2	B	2	1
Ballaying	11	WA	-33.18	117.33	WA	4	W	2	1	2	3	1	1	2	3	2	B	2	1
Balranald	12	NSW	-34.08	143.31	SNSW	4	S	1	2	2	3	3	1	3	4	2	B	2	1
Banyena	13	VIC	-36.34	142.49	VIC	4	S	1	1	2	2	1	1	1	2	1	C	2	2
Barunga	14	SA	-33.49	138.07	SA	4	S	2	2	2	3	2	1	2	2	2	B	2	1
Beacon	15	WA	-30.26	117.52	WA	5	W	3	3	2	3	2	3	3	4	2	A	2	1
Beanbri	16	NSW	-29.57	148.24	NNSW	5	N	3	4	3	4	3	2	3	1	2	A	3	3
Beckom	17	NSW	-34.18	146.58	SNSW	4	S	2	2	2	3	1	1	2	1	2	B	2	1
Bencubbin	18	WA	-30.48	117.51	WA	5	W	3	3	2	4	3	1	3	4	2	A	2	1
Benerembah	19	NSW	-34.16	145.50	SNSW	4	S	2	2	2	3	2	1	2	2	2	B	2	1
Beulah	20	VIC	-35.56	142.25	VIC	3	S	2	2	2	3	1	1	2	3	2	C	2	1
Beverley	21	WA	-32.06	116.55	WA	4	W	2	1	2	3	1	1	2	2	2	B	2	1
Billa Billa	22	QLD	-28.09	150.16	QLD	5	N	3	4	3	4	3	2	3	1	2	A	3	3

Location	Code	State	Latitude	Longitude	Existing classification regions and test division zone allocation													
					Control	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Biloela	-	QLD	-24.24	150.30	QLD	5	N	3	4	3	4	3	2	3	1	2	A	3	3
Biniguy	23	NSW	-29.34	150.08	NNSW	5	N	3	4	3	3	3	2	3	1	2	A	3	3
Blyth	24	SA	-33.50	138.29	SA	4	S	2	2	2	3	2	1	2	1	2	B	2	1
Bogan Gate	25	NSW	-33.05	147.46	CNSW	5	N	2	2	2	3	2	1	2	1	2	B	2	3
Bolgart	26	WA	-31.16	116.30	WA	3	W	2	1	2	3	2	1	3	1	2	B	2	1
Booleroo	28	SA	-32.52	138.21	SA	4	S	2	2	2	3	1	1	2	2	2	B	2	1
Bool Lagoon	27	SA	-37.08	140.43	SA	2	S	1	1	1	2	1	1	2	1	1	C	1	2
Boort	29	VIC	-36.06	143.43	VIC	3	S	1	1	2	3	2	1	2	2	2	C	2	2
Borden	30	WA	-34.04	118.16	WA	3	W	2	3	2	2	1	1	2	2	1	B	2	1
Bordertown	31	SA	-36.18	140.46	SA	3	S	1	2	2	2	1	1	2	1	1	C	2	1
Brim	32	VIC	-36.04	142.25	VIC	3	S	1	1	2	3	1	1	2	3	2	C	2	2
Bruce Rock	33	WA	-31.52	118.08	WA	4	W	2	3	2	3	3	1	3	4	2	B	2	1
Bullaring	34	WA	-32.29	117.44	WA	4	W	2	3	2	3	2	1	2	2	2	B	2	1
Bulyee	35	WA	-32.18	117.31	WA	4	W	2	3	2	3	2	1	2	3	2	B	2	1
Buntine	36	WA	-29.59	116.34	WA	5	W	3	3	2	4	3	3	3	3	2	A	2	1
Cadoux	37	WA	-30.46	117.08	WA	5	W	2	3	2	4	3	1	3	3	2	A	2	1
Canna	38	WA	-28.53	115.51	WA	5	W	3	3	2	4	3	2	3	3	2	A	2	1
Canowindra	39	NSW	-33.34	148.41	SNSW	4	S	2	2	2	3	2	1	1	1	1	B	1	1
Carnamah	40	WA	-29.41	115.53	WA	4	W	3	3	2	3	3	3	3	2	2	A	2	1
Carrabin	41	WA	-31.22	118.40	WA	5	W	3	3	2	3	3	1	3	3	2	B	2	1
Carrolup	42	WA	-33.41	117.22	WA	3	W	2	1	2	2	1	1	2	1	1	B	2	1
Cascades	43	WA	-33.20*	121.11*	WA	4	W	1	3	2	2	1	1	3	2	1	B	2	1
Chapman	44	WA	-28.28*	114.47*	WA	5	W	3	3	2	3	3	2	3	1	2	A	2	1
Circle Valley	45	WA	-33.04	121.40	WA	4	W	3	3	2	3	2	1	3	3	2	B	2	1
Clinton	46	SA	-34.13	138.01	SA	4	S	2	2	2	3	1	1	2	4	1	B	2	1
Coleambally	47	NSW	-34.48	145.53	SNSW	4	S	1	1	2	3	2	1	2	2	2	B	2	1
Colinroobie	48	NSW	-34.26	146.33	SNSW	4	S	2	2	2	3	2	1	2	1	2	B	2	1
Come-by-chance	49	NSW	-30.19	148.28	NNSW	5	N	3	4	3	4	3	2	3	1	2	A	3	3
Condobolin	50	NSW	-33.03	147.09	CNSW	5	N	2	2	2	3	3	1	2	1	2	B	2	3
Coolanilling	51	WA	-33.13*	117.29*	WA	4	W	2	1	2	3	2	1	2	3	2	B	2	1
Coomalbidgup	52	WA	-33.43	121.21	WA	3	W	1	3	1	2	2	1	3	1	1	B	2	1
Coonabarabran	53	NSW	-31.15	149.16	NNSW	5	N	3	2	3	3	2	1	2	1	2	B	2	3
Coonamble	54	NSW	-30.55	148.22	NNSW	5	N	3	4	2	4	3	2	3	1	2	A	3	3
Corack	55	VIC	-36.09	143.02	VIC	3	S	1	1	2	2	1	1	2	2	2	C	2	2
Corrigin	56	WA	-32.19	117.52	WA	4	W	2	3	2	3	2	1	2	3	2	B	2	1
Cowra	57	NSW	-33.49	148.39	SNSW	4	S	2	2	2	3	2	1	1	1	2	B	2	1

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					Control	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Coyrecup	58	WA	-33.40	117.49	WA	4	W	2	1	2	2	1	1	2	1	1	B	2	1
Cranbrook	59	WA	-34.14	117.26	WA	3	W	2	1	1	2	1	1	2	1	1	B	2	1
Cryon	60	NSW	-30.00	148.37	NNSW	5	N	3	4	3	4	3	2	3	1	2	A	3	3
Cuballing	61	WA	-32.49	117.10	WA	3	W	2	1	2	3	1	1	2	1	2	B	2	1
Culham	62	WA	-31.24	116.26	WA	3	W	2	1	1	3	2	1	3	1	2	B	2	1
Cummins	63	SA	-34.15	135.43	SA	4	S	2	3	2	2	1	1	3	1	1	B	2	2
Cunderdin	64	WA	-31.39	117.14	WA	4	W	2	3	2	3	2	1	3	3	2	B	2	1
Dalby	65	QLD	-27.10	151.15	QLD	5	N	3	4	3	4	3	2	3	1	2	A	3	3
Dale	66	WA	-32.13	116.44	WA	3	W	2	1	1	3	2	1	2	1	2	B	2	1
Dalwallinu	67	WA	-30.16	116.39	WA	5	W	3	3	2	3	3	3	3	4	2	A	2	1
Dandaragan	68	WA	-30.37	115.49	WA	4	W	2	1	1	3	2	1	3	1	2	A	2	1
Datatine	69	WA	-33.23	117.48	WA	4	W	2	3	2	2	1	1	2	2	2	B	2	1
Deniliquin	70	NSW	-35.31	144.56	SNSW	4	S	1	1	2	3	2	1	2	2	2	C	2	1
Devenish	71	VIC	-36.19	145.53	VIC	3	S	2	2	1	2	1	1	1	1	2	C	2	2
Diggora	72	VIC	-36.21	144.34	VIC	2	S	1	2	2	2	1	1	1	1	1	C	2	2
Donald	73	VIC	-36.22	142.59	VIC	3	S	1	1	2	3	1	1	1	2	1	C	2	2
Dongolocking	74	WA	-33.24	117.45	WA	4	W	2	3	2	2	1	1	2	2	2	B	2	1
Doodlakine	75	WA	-31.36	117.52	WA	5	W	2	3	2	3	2	1	3	3	2	B	2	1
Dooen	76	VIC	-36.39	142.15	VIC	4	S	1	1	2	2	1	1	1	1	1	C	2	2
Dowerin	77	WA	-31.11	117.02	WA	5	W	2	3	2	3	3	1	3	2	2	B	2	1
Dumbleyung	78	WA	-33.15	117.44	WA	4	W	2	3	2	2	1	1	2	2	2	B	2	1
Edgeroi	79	NSW	-30.06	149.48	NNSW	5	N	3	4	3	3	3	3	3	1	2	A	3	3
Eradu	80	WA	-28.41	115.02	WA	5	W	3	3	2	3	3	2	3	1	2	A	2	1
Esperance Downs	81	WA	-33.36	121.47	WA	3	W	1	3	2	2	1	1	3	1	1	B	2	1
Farrell Flat	82	SA	-33.49	138.47	SA	4	S	2	2	2	3	1	1	1	1	1	B	2	1
Finley	83	NSW	-35.37	145.34	SNSW	4	S	1	2	2	3	2	1	2	1	2	C	2	1
Frances	84	SA	-36.42	140.57	SA	2	S	1	1	1	2	1	1	2	1	1	C	1	2
Gairdner River	85	WA	-34.12*	119.00*	WA	3	W	1	3	2	2	1	1	2	1	1	B	2	1
Galong	86	NSW	-34.35	148.33	SNSW	4	S	2	2	2	2	1	1	1	1	1	B	2	1
Geranium	87	SA	-35.22	140.09	SA	4	S	2	2	2	3	1	1	2	2	1	C	2	1
Gerogery	88	NSW	-35.49	147.00	SNSW	4	S	2	2	1	3	1	1	1	1	2	C	2	1
Gilgandra	89	NSW	-31.42	148.40	NNSW	5	N	3	2	2	3	2	3	3	1	2	B	2	3
Gillingarra	90	WA	-30.54	116.02	WA	4	W	2	1	1	3	2	1	3	1	2	A	2	1
Glenroy	91	SA	-37.13	140.51	SA	1	S	1	1	1	2	1	1	1	1	1	C	1	2
Gnarwarre	92	VIC	-38.10	144.08	VIC	3	S	1	2	1	1	1	1	1	1	1	C	1	2
Gnowangerup	93	WA	-33.56	118.00	WA	3	W	2	3	2	2	1	1	2	3	1	B	2	1

Location	Code	State	Latitude	Longitude	Existing classification regions and test division zone allocation													
					Control	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Goodlands	94	WA	-30.06	117.12	WA	5	W	3	3	2	3	3	3	3	3	2	A	2	1
Goolgowi	95	NSW	-33.57	145.42	SNSW	4	S	1	2	2	3	2	1	3	2	2	B	2	1
Greenhills	96	WA	-31.53	116.57	WA	4	W	2	1	2	3	2	1	3	2	2	B	2	1
Gulnare	97	SA	-33.28	138.26	SA	4	S	2	2	2	3	2	1	2	1	2	B	2	1
Harrismith	98	WA	-32.56	117.51	WA	4	W	2	3	2	3	1	1	2	2	2	B	2	1
Heggaton	99	SA	-33.20*	136.30*	SA	4	S	2	2	2	3	2	1	2	3	1	B	2	1
Hermitage	100	QLD	-28.12	152.06	QLD	5	N	3	4	3	3	2	3	3	1	1	A	3	3
Hopetoun	101	VIC	-35.43	142.21	VIC	4	S	2	2	2	3	2	1	2	3	2	C	2	1
Horsham	102	VIC	-36.42	142.12	VIC	4	S	1	1	2	2	1	1	1	1	1	C	2	2
Howlong	103	NSW	-35.58	146.38	SNSW	4	S	2	2	1	2	1	1	1	1	2	C	2	1
Jitarning	104	WA	-32.47	118.00	WA	4	W	2	3	2	3	1	1	2	3	2	B	2	1
Junee	105	NSW	-34.52	147.34	SNSW	4	S	2	2	1	3	1	1	1	1	2	B	2	1
Kalanbi	106	SA	-31.56	133.40	SA	5	S	2	2	2	3	2	3	3	4	1	B	2	1
Kalannie	107	WA	-30.21	117.07	WA	5	W	3	3	2	3	3	3	3	4	2	A	2	1
Kalkee	108	VIC	-36.32	142.12	VIC	4	S	1	1	2	3	1	1	1	2	1	C	2	2
Kaniva	109	VIC	-36.22	141.14	VIC	3	S	1	2	2	2	1	1	2	1	1	C	2	1
Kapunda	110	SA	-34.20	138.54	SA	4	S	2	3	2	2	1	1	1	1	1	B	2	2
Karoonda	111	SA	-35.05	139.53	SA	5	S	2	2	2	3	1	1	2	3	1	C	2	1
Katanning	112	WA	-33.41	117.35	WA	4	W	2	1	2	2	1	1	2	2	1	B	2	1
Keith	113	SA	-36.05	140.21	SA	3	S	1	2	2	3	1	1	2	1	1	C	2	1
Kendenup	114	WA	-34.29	117.37	WA	3	W	2	1	1	2	1	1	2	1	1	B	2	1
Kenmare	115	VIC	-35.54	142.09	VIC	4	S	1	2	2	3	2	1	2	3	2	C	2	1
Keppoch	116	SA	-36.42	140.35	SA	2	S	1	1	1	2	1	1	2	1	1	C	1	2
Kerang	117	VIC	-35.43	143.55	VIC	3	S	2	1	2	3	1	1	2	2	2	C	2	2
Kimba	118	SA	-33.08	136.25	SA	4	S	2	2	2	3	2	1	3	4	2	B	2	1
Kojonup	119	WA	-33.50	117.09	WA	3	W	2	1	1	2	1	1	2	1	1	B	2	1
Koorda	120	WA	-30.49	117.28	WA	5	W	3	3	2	4	3	1	3	3	2	A	2	1
Koppamurra	121	SA	-37.02	140.53	SA	2	S	1	1	1	2	1	1	2	1	1	C	1	2
Kukerin	122	WA	-33.11	118.05	WA	4	W	2	3	2	3	2	1	2	3	2	B	2	1
Kulin	123	WA	-32.40	118.09	WA	4	W	2	3	2	3	2	1	2	3	2	B	2	1
Kumarl	124	WA	-32.47	121.33	WA	4	W	3	3	2	3	2	1	3	4	2	B	2	1
Kunjin	125	WA	-32.21	117.46	WA	4	W	2	3	2	3	2	1	2	3	2	B	2	1
Kyabram	126	VIC	-36.18	145.02	VIC	3	S	1	2	2	2	1	1	1	1	1	C	2	2
Kyalite	127	NSW	-34.53	143.32	SNSW	4	S	1	2	2	3	2	1	3	3	2	B	2	1
Kybybolite	128	SA	-36.52	140.55	SA	2	S	1	1	1	2	1	1	1	1	1	C	1	2
Lake Bolac	129	VIC	-37.42	142.50	VIC	3	S	1	2	1	1	1	1	1	1	1	C	1	2

Location	Code	State	Latitude	Longitude	Existing classification regions and test division zone allocation													
					Control	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Lake Camm	130	WA	-32.57	119.36	WA	4	W	2	3	2	3	2	1	2	3	2	B	2	1
Lake King	131	WA	-33.05	119.36	WA	4	W	2	3	2	2	1	1	2	3	2	B	2	1
Lake O'Connor	132	WA	-32.31*	119.14*	WA	4	W	2	3	2	3	2	1	2	3	2	B	2	1
Lameroo	133	SA	-35.19	140.31	SA	4	S	2	2	2	3	2	1	2	2	2	C	2	1
Leeton	134	NSW	-34.32	146.24	SNSW	4	S	2	2	2	3	1	1	2	1	2	B	2	1
Litchfield	135	VIC	-36.17	142.50	VIC	3	S	1	1	2	3	1	1	1	2	2	C	2	2
Lock	136	SA	-33.34	135.45	SA	5	S	2	2	2	3	2	1	3	2	1	B	2	1
Lockhart	137	NSW	-35.12	146.43	SNSW	4	S	2	2	2	2	1	1	2	1	2	C	2	1
Lowesdale	138	NSW	-35.49	146.21	SNSW	4	S	2	2	2	3	1	1	1	1	2	C	2	1
Loxton	139	SA	-34.27	140.34	SA	5	S	2	2	2	3	3	1	3	4	2	B	2	1
Magitup	140	WA	-34.07	118.12	WA	3	W	2	3	2	2	1	1	2	2	1	B	2	1
Maitland	141	SA	-34.22	137.40	SA	4	S	2	2	2	3	1	1	2	1	1	B	2	1
Mallala	142	SA	-34.26	138.30	SA	4	S	2	3	2	3	1	1	3	2	1	B	2	1
Mallan	143	NSW	-35.06	143.46	SNSW	4	S	1	1	2	3	2	1	3	3	2	C	2	1
Manangatang	144	VIC	-35.03	142.52	VIC	4	S	2	2	2	3	2	1	3	3	2	C	2	1
Manildra	145	NSW	-33.12	148.37	SNSW	4	S	3	2	2	3	2	1	1	1	2	B	1	1
Mannum	146	SA	-34.54	139.18	SA	4	S	2	2	2	2	1	1	2	3	1	B	2	1
Martinup	147	WA	-33.53*	117.51*	WA	3	W	2	1	2	2	1	1	2	2	1	B	2	1
Mayanup	148	WA	-33.56	116.27	WA	3	W	2	1	1	2	1	1	2	1	1	B	2	1
Mayrung	149	NSW	-35.27	145.17	SNSW	4	S	1	2	2	3	2	1	2	2	2	C	2	1
Meandarra	150	QLD	-27.18	149.52	QLD	5	N	3	4	3	4	3	2	3	1	2	A	3	3
Merinee	151	VIC	-34.22*	141.48*	VIC	4	S	2	2	2	3	2	1	3	4	2	B	2	1
Merredin	152	WA	-31.29	118.17	WA	5	W	3	3	2	3	2	1	3	3	2	B	2	1
Mingenew	153	WA	-29.11	115.26	WA	5	W	3	3	2	3	3	2	3	1	2	A	2	1
Minnipa	154	SA	-32.51	135.09	SA	5	S	2	2	2	3	3	1	3	3	2	B	2	1
Mintaro	155	SA	-33.55	138.43	SA	4	S	2	2	2	3	1	1	2	1	1	B	2	1
Mitchellville	156	SA	-33.36	137.09	SA	4	S	2	2	2	3	2	1	3	4	1	B	2	1
Mitiamo	157	VIC	-36.12	144.13	VIC	3	S	1	1	2	3	2	1	2	2	2	C	2	2
Mogumber	158	WA	-31.00	116.04	WA	4	W	2	1	1	3	2	1	3	1	2	B	2	1
Moolort	159	VIC	-37.03	143.55	VIC	3	S	1	2	1	2	1	1	1	1	1	C	1	2
Moonie	160	QLD	-27.43	150.22	QLD	5	N	3	4	3	4	3	2	3	1	2	A	3	3
Moora	161	WA	-30.38	116.00	WA	4	W	2	1	1	3	2	1	3	1	2	A	2	1
Moorine Rock	162	WA	-31.18	119.07	WA	5	W	3	3	2	3	2	3	3	4	2	B	2	1
Morawa	163	WA	-29.12	116.00	WA	5	W	3	3	2	4	3	2	3	3	2	A	2	1
Moree	164	NSW	-29.27	149.50	NNSW	5	N	3	4	3	3	3	3	3	1	2	A	3	3
Moulyinning	165	WA	-33.13	117.55	WA	4	W	2	3	2	3	1	1	2	3	2	B	2	1

Location	Code	State	Latitude	Longitude	Existing classification regions and test division zone allocation													
					Control	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Mount Barker	166	WA	-34.37	117.40	WA	3	W	2	1	1	2	1	1	2	1	1	B	2	1
Mount Madden	167	WA	-33.09	119.55	WA	4	W	2	3	2	2	1	1	2	2	2	B	2	1
Moyhall	168	SA	-37.02	140.40	SA	2	S	1	1	1	2	1	1	2	1	1	C	1	2
Mudamuckla	169	SA	-32.09	134.02	SA	4	S	2	2	2	3	3	3	3	4	1	B	2	1
Mukinbudin	170	WA	-30.54	118.12	WA	5	W	3	3	2	3	3	3	3	3	2	A	2	1
Mullaley	171	NSW	-31.05	149.55	NNSW	5	N	3	4	3	3	2	3	3	1	2	B	3	3
Mullewa	172	WA	-28.26	115.35	WA	5	W	3	3	2	3	3	3	3	3	2	A	2	1
Mulyandry	173	NSW	-33.31	148.08	SNSW	4	S	2	2	2	3	1	1	2	1	2	B	2	1
Mundulla	174	SA	-36.21	140.41	SA	3	S	1	2	2	2	1	1	2	1	1	C	2	1
Munglinup	175	WA	-33.42	120.51	WA	3	W	1	3	2	2	1	1	3	1	1	B	2	1
Murrayville	176	VIC	-35.15	141.11	VIC	4	S	2	2	2	3	2	1	2	3	2	C	2	1
Nangari	177	SA	-34.29	140.52	SA	5	S	2	2	2	3	2	1	3	4	2	B	2	1
Nangus	178	NSW	-35.02	147.54	SNSW	4	S	2	2	1	2	1	1	1	1	2	C	2	1
Narrabri	179	NSW	-30.19	149.46	NNSW	5	N	3	4	3	3	3	3	3	1	2	A	3	3
Narrogin	180	WA	-32.56	117.10	WA	3	W	2	1	2	3	1	1	2	1	2	B	2	1
Nelshaby	181	SA	-33.07	138.06	SA	4	S	2	2	2	3	2	1	3	3	2	B	2	1
Newdegate	182	WA	-33.04	119.04	WA	4	W	2	3	2	3	2	1	2	2	2	B	2	1
Northampton	183	WA	-28.20	114.38	WA	5	W	3	3	2	3	3	2	3	1	2	A	2	1
Northstar	184	NSW	-28.55	150.25	NNSW	5	N	3	4	3	4	3	2	3	1	2	A	3	3
Norwin	185	QLD	-27.30	151.22	QLD	5	N	3	4	3	3	3	2	3	1	2	A	3	3
Numurkah	186	VIC	-36.05	145.26	VIC	3	S	2	2	2	3	1	1	2	1	2	C	2	2
Nunjikompita	187	SA	-32.15	134.21	SA	5	S	2	2	2	3	2	3	3	4	2	B	2	1
Nyabing	188	WA	-33.38	118.08	WA	3	W	2	3	2	2	1	1	2	2	1	B	2	1
Nyngan	189	NSW	-31.32	147.10	NNSW	5	N	1	2	2	3	3	3	3	1	2	B	2	3
Oaklands	190	NSW	-35.32	146.10	SNSW	4	S	2	2	2	3	1	1	2	1	2	C	2	1
Orange	191	NSW	-33.16	149.06	SNSW	4	S	3	2	2	1	1	1	1	1	1	B	1	1
Palmer	192	SA	-34.51	139.09	SA	4	S	2	2	1	3	1	1	2	2	1	B	2	1
Paringa	193	SA	-34.10	140.47	SA	5	S	2	2	2	3	3	1	3	4	2	B	2	1
Paskeville	194	SA	-34.02	137.54	SA	4	S	2	2	2	3	1	1	2	2	2	B	2	1
Penong	195	SA	-31.55	133.00	SA	5	S	2	3	2	3	2	3	3	4	1	B	2	1
Perenjori	196	WA	-29.25	116.17	WA	5	W	3	3	2	3	3	3	3	3	2	A	2	1
Pingaring	197	WA	-32.45	118.37	WA	4	W	2	3	2	3	1	1	2	3	2	B	2	1
Pingrup	198	WA	-33.32	118.30	WA	4	W	2	3	2	3	2	1	2	3	2	B	2	1
Pinnaroo	199	SA	-35.15	140.54	SA	4	S	2	2	2	3	2	1	2	3	2	C	2	1
Pira	200	VIC	-35.15	143.22	VIC	4	S	2	2	2	3	1	1	2	2	2	C	2	1
Pirrinuan	201	QLD	-27.03	151.13	QLD	5	N	3	4	3	3	3	2	3	1	2	A	3	3

Location	Code	State	Latitude	Longitude	Existing classification regions and test division zone allocation													
					Control	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Qld composite	-	QLD			QLD	5	N	3	4	3	3	3	2	3	1	2	A	3	3
Quairading	202	WA	-32.00	117.24	WA	4	W	2	3	2	3	2	1	3	3	2	B	2	1
Qualeup	203	WA	-33.50	116.48	WA	3	W	2	1	1	3	1	1	2	1	1	B	2	1
Quambatook	204	VIC	-35.51	143.31	VIC	4	S	2	1	2	3	2	1	2	3	2	C	2	2
Quandialla	205	NSW	-34.00	147.47	SNSW	4	S	2	2	2	3	2	1	2	1	2	B	2	1
Redbanks	206	SA	-34.28	138.33	SA	4	S	2	3	2	3	2	1	3	2	1	B	2	2
Regans Ford	207	WA	-30.56	115.51	WA	4	W	2	1	1	3	2	1	3	1	2	A	2	1
Roma	208	QLD	-26.33	148.48	QLD	5	N	3	4	3	4	3	2	3	1	2	A	3	3
Roseworthy	209	SA	-34.32	138.44	SA	4	S	2	3	2	3	1	1	1	1	1	B	2	2
Rudall	210	SA	-33.41	136.16	SA	4	S	2	2	2	3	2	1	3	3	1	B	2	1
Rutherglen	211	VIC	-36.03	146.27	VIC	3	S	2	2	1	3	1	1	1	1	2	C	2	2
Saddleworth	212	SA	-34.05	138.46	SA	4	S	2	3	2	2	1	1	1	1	1	B	2	2
Salmon Gums	213	WA	-32.58	121.38	WA	4	W	3	3	2	3	2	1	3	3	2	B	2	1
Scaddan	214	WA	-33.26	121.43	WA	4	W	1	3	2	2	1	1	3	1	1	B	2	1
Shackleton	215	WA	-31.55	117.50	WA	4	W	2	3	2	3	2	1	3	3	2	B	2	1
Sheephills	216	VIC	-36.20	142.31	VIC	4	S	1	1	2	2	1	1	2	3	2	C	2	2
Sherwood	217	SA	-36.05	140.36	SA	3	S	1	2	2	3	1	1	2	2	1	C	2	1
Spalding	218	SA	-33.29	138.36	SA	4	S	2	2	2	3	1	1	2	1	2	B	2	1
Springridge	219	NSW	-31.23	150.15	NNSW	5	N	3	4	2	3	2	1	3	1	2	B	3	3
St. Arnaud	220	VIC	-36.36	143.15	VIC	4	S	1	1	2	3	1	1	1	1	1	C	2	2
Stow	221	SA	-34.00	138.24	SA	4	S	2	2	2	3	1	1	2	2	2	B	2	1
Streaky Bay	222	SA	-32.47	134.13	SA	5	S	2	2	2	2	1	1	3	3	1	B	2	1
Streatham	223	VIC	-37.40	143.03	VIC	3	S	1	2	1	1	1	1	1	1	1	C	1	2
Struan	224	SA	-37.05	140.47	SA	2	S	1	1	1	2	1	1	2	1	1	C	1	2
Tamworth	225	NSW	-31.05	150.55	NNSW	5	N	3	2	2	3	2	1	2	1	1	B	1	3
Tantanoola	226	SA	-37.41	140.27	SA	1	S	1	1	1	1	1	1	1	1	1	C	1	2
Tarin Rock	227	WA	-33.04	118.15	WA	4	W	2	3	2	3	2	1	2	3	2	B	2	1
Tarranyurk	228	VIC	-36.12	142.02	VIC	3	S	1	2	2	2	1	1	2	2	2	C	2	1
Tatyoon	229	VIC	-37.31	142.56	VIC	3	S	1	2	1	1	1	1	1	1	1	C	1	2
Temora	230	NSW	-34.26	147.32	SNSW	4	S	2	2	2	3	1	1	1	1	2	B	2	1
Tepko	231	SA	-34.58	139.11	SA	4	S	2	2	2	2	1	1	2	2	1	B	2	1
Tickera	232	SA	-33.47	137.42	SA	4	S	2	2	2	3	2	1	3	3	2	B	2	1
Tincurrin	233	WA	-32.59	117.46	WA	4	W	2	3	2	3	1	1	2	2	2	B	2	1
Trangie	234	NSW	-32.01	147.58	NNSW	5	N	3	2	2	3	3	1	3	1	2	B	2	3
Trayning	235	WA	-31.06	117.47	WA	5	W	3	3	2	3	3	1	3	4	2	B	2	1
Tuckey	236	SA	-33.39	136.04	SA	4	S	2	2	2	3	2	1	3	3	1	B	2	1

Location	Code	State	Latitude	Longitude	Existing classification regions and test division zone allocation													
					Control	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Tullibigeal	237	NSW	-33.23	146.43	SNSW	4	S	2	2	2	3	2	1	2	1	2	B	2	3
Tulloona	238	NSW	-28.53	150.05	NNSW	5	N	3	4	3	4	3	2	3	1	2	A	3	1
Tumby	239	SA	-34.22	136.06	SA	4	S	2	2	2	2	1	1	3	3	1	B	2	1
Turretfield	240	SA	-34.33	138.50	SA	4	S	2	3	2	3	1	1	1	1	1	B	2	2
Two Wells	241	SA	-34.35	138.31	SA	4	S	2	2	2	3	2	1	3	2	1	B	2	1
Ultima	242	VIC	-35.28	143.16	VIC	4	S	2	2	2	3	2	1	2	3	2	C	2	1
Ungarra	243	SA	-34.10	136.02	SA	4	S	2	2	2	2	2	1	3	3	1	B	2	1
Urania	244	SA	-34.30	137.36	SA	4	S	2	2	2	2	2	1	2	2	1	B	2	1
Varley	245	WA	-32.42	119.38	WA	4	W	2	3	2	3	2	1	2	3	2	B	2	1
Vasse	246	WA	-33.41	115.17	WA	3	W	2	1	1	2	1	1	3	1	1	B	1	1
Wagga Wagga	247	NSW	-35.06	147.22	SNSW	4	S	2	2	1	3	1	1	1	1	2	C	2	1
Wahring	248	VIC	-36.42	145.12	VIC	3	S	1	2	1	2	1	1	1	1	1	C	1	2
Waite Campus	249	SA	-34.58	138.37	SA	4	S	2	3	1	2	1	1	2	1	1	B	1	2
Walgett	250	NSW	-30.01	148.06	NNSW	5	N	3	4	3	4	3	2	3	1	2	A	3	3
Wallendbeen	251	NSW	-34.31	148.10	SNSW	4	S	2	2	2	2	1	1	1	1	2	B	2	1
Walpeup	252	VIC	-35.08	142.01	VIC	4	S	2	2	2	3	1	1	2	3	2	C	2	1
Wanbi	253	SA	-34.46	140.18	SA	5	S	2	2	2	3	2	1	3	3	2	B	2	1
Wandering	254	WA	-32.40	116.40	WA	3	W	2	1	1	3	1	1	2	1	2	B	2	1
Wannamal	255	WA	-31.09	116.03	WA	4	W	2	1	1	3	2	1	3	1	2	B	2	1
Warramboo	256	SA	-33.14	135.35	SA	5	S	2	2	2	3	2	3	3	3	2	B	2	1
Watercarrin	257	WA	-31.26	117.14	WA	4	W	2	3	2	3	2	1	3	3	2	B	2	1
Watheroo	258	WA	-30.18	116.03	WA	4	W	2	1	2	3	2	3	3	2	2	A	2	1
Wedin	259	WA	-32.58*	117.42*	WA	4	W	2	3	2	3	1	1	2	2	2	B	2	1
Wellcamp	260	QLD	-27.33	151.49	QLD	5	N	3	4	3	3	3	2	3	1	2	A	3	3
Wellstead	261	WA	-34.29	118.36	WA	3	W	2	1	1	2	1	1	2	1	1	B	2	1
Wialki	262	WA	-30.28	118.07	WA	5	W	3	3	2	4	3	2	3	3	2	A	2	1
Wickepin	263	WA	-32.46	117.30	WA	4	W	2	3	2	3	1	1	2	2	2	B	2	1
Wilgoyne	264	WA	-30.46	118.24	WA	5	W	3	3	2	4	3	2	3	3	2	A	2	1
Williams	265	WA	-33.01	116.52	WA	3	W	2	1	1	3	1	1	2	1	2	B	2	1
Windsor	266	SA	-34.25	138.19	SA	4	S	2	2	2	3	2	1	3	4	1	B	2	1
Winulta	267	SA	-34.16	137.52	SA	4	S	2	2	2	3	1	1	2	2	1	B	2	1
Wittenoom Hills	268	WA	-33.27	122.11	WA	4	W	1	3	2	2	2	1	3	1	1	B	2	1
Wolseley	269	SA	-36.21	140.54	SA	3	S	1	2	2	2	1	1	2	1	1	C	2	1
Wongan Hills	270	WA	-30.53	116.43	WA	4	W	2	3	2	3	2	1	3	3	2	A	2	1
Wongarbon	271	NSW	-32.20	148.46	NNSW	5	N	3	2	2	3	2	1	2	1	2	B	2	3
Wonwondah	272	VIC	-36.53	142.12	VIC	4	S	1	1	1	2	1	1	1	1	1	C	2	2

Location	Code	State	Latitude	Longitude	Existing classification regions and test division zone allocation													
					Control	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Woodanilling	273	WA	-33.33	117.25	WA	3	W	2	1	2	3	1	1	2	1	2	B	2	1
Woogenellup	274	WA	-34.32	117.53	WA	3	W	2	1	1	2	1	1	2	1	1	B	2	1
Woomelang	275	VIC	-35.41	142.40	VIC	4	S	2	2	2	3	2	1	2	3	2	C	2	1
Wunghnu	276	VIC	-36.09	145.25	VIC	3	S	2	2	2	2	1	1	2	1	2	C	2	2
Wunkar	277	SA	-34.29	140.18	SA	5	S	2	2	2	3	2	1	3	4	2	B	2	1
Yallaroi	278	NSW	-29.08	150.31	NNSW	5	N	3	4	3	3	3	3	3	1	2	A	3	3
Yanco	279	NSW	-34.35	146.25	SNSW	4	S	2	2	2	3	1	1	2	1	2	B	2	1
Yarrawonga	280	VIC	-36.01	146.00	VIC	3	S	2	2	2	3	1	1	1	1	2	C	2	2
Yealering	281	WA	-32.35	117.37	WA	4	W	2	3	2	3	1	1	2	3	2	B	2	1
Yeelanna	282	SA	-34.08	135.43	SA	4	S	2	3	2	2	1	1	3	1	1	B	2	2
Yilliminning	283	WA	-32.54	117.22	WA	4	W	2	1	2	3	1	1	2	2	2	B	2	1
York	284	WA	-31.52	116.45	WA	3	W	2	1	1	3	2	1	3	2	2	B	2	1
Young	285	NSW	-34.18	148.18	SNSW	4	S	2	2	2	2	1	1	1	1	2	B	2	1

Appendix 3 Simple correlation (r) matrix of quality traits used based on 24,032 observations

Note

Not every observation had a record for each quality trait. Following are the number of missing observations for each trait. TWT-3239, TKW-8764, PSI-1315, FY-31, P-0, WA-14, DDT-19, EXT-29 and RMAX-13

	TWT	TKW	PSI	FY	P	WA	DDT	EXT	RMAX
TWT	1.000								
TKW	0.450	1.000							
PSI	-0.081	0.037	1.000						
FY	0.109	0.170	-0.271	1.000					
P	-0.167	-0.364	-0.209	0.076	1.000				
WA	0.085	-0.045	-0.564	0.137	0.556	1.000			
DDT	-0.106	-0.262	-0.334	0.092	0.622	0.475	1.000		
EXT	-0.131	-0.235	-0.023	0.117	0.630	0.147	0.438	1.000	
RMAX	-0.124	-0.309	-0.406	-0.024	0.434	0.309	0.592	0.228	1.000

TWT=test weight, TKW=thousand kernel weight, PSI=grain hardness, FY=flour yield, P=Protein, WA=water absorption, DDT=dough development time, EXT=extensibility and RMAX=maximum resistance

Appendix 4 Spearman correlation (r) matrix based on full set of quality traits for 10,134 observations

Note

The only pair that did not have a *p-value* <0.05 was PSI and P

	P	PSI	FY	WA	DDT	EXT	RMAX
P	1.000						
PSI	0.000	1.000					
FY	-0.080	0.107	1.000				
WA	0.414	-0.439	-0.027	1.000			
DDT	0.664	-0.214	-0.027	0.406	1.000		
EXT	0.629	0.111	0.093	0.054	0.563	1.000	
RMAX	0.235	-0.190	-0.149	0.046	0.515	0.237	1.000

P=Protein, PSI=grain hardness, FY=flour yield, WA=water absorption, DDT=dough development time, EXT=extensibility and RMAX=maximum resistance