School of Agriculture and Environment

The influence of cultivar, environment and nutrition management on wheat quality in the high rainfall zone of south west, Western 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 acknowledgement has been made.

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

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Abstract

The high rainfall zone (HRZ) of south west Western Australian (WA) has traditionally been dominated by livestock industries. However, a reduction in wool price throughout the 1990's has stimulated a transition to farm systems that contain an increasing proportion of annual cropping enterprises. The HRZ, compared to traditional wheat belt areas of WA, has higher rainfall and a longer, cooler growing season. Potential grain yields as determined by seasonal rainfall are not often achieved because of inadequate nutrition and other constraints such as water-logging and disease. Substantial research has been conducted in the HRZ focusing on increasing grain yield to limits set by seasonal rainfall. Research on wheat grain quality characteristics, however, has been limited. The aim of this research was to examine the influence of cultivar, environment and nutrition management on wheat quality characteristics in the HRZ of south west WA and to examine the stability of cultivar performance in relation to site and season.

A series of experiments was grown at Moora and Williams in 2005, 2006 and 2007. Sites were chosen to represent contrasting environments within the HRZ. Moora, the more northern site typically has higher temperatures and lower rainfall compared to Williams. Eight cultivars were selected, two that are accepted into each of the commercial quality grades (Australian Prime Hard APH, Australian Hard AH, Australian Premium White APW and Durum). Three levels of nutrition management were applied 'control', 'grower' and 'researcher' and were chosen to simulate low, medium and high fertiliser rates likely to be used by growers in the HRZ. Treatments effects were measured for grain yield, physical grain quality characteristics and grain protein quality charactertics as determined by a mixograph.

Environment was responsible for almost 90% of the variation for grain yield, screenings, Hagberg falling number and milling yield. Management of crop nutrition was the principal source of variation for grain protein quantity (48%), dough strength as measured by mixograph area below the curve (52%) and water absorption (46%-52%). It was often the second greatest source of variation for other characteristics measured in

this study. Cultivar was the predominant source of variation for dough strength as measured by mixograph initial build-up (46%) and dough stability (47%), but it had only a small affect on grain yield and grain protein quantity (2%).

The increase in nutrition resulted in a significant increase in water absorption and dough strength and a trend towards increasing dough stability. An increase in gliadin and glutenin proteins is thought to be responsible for this result. The low nutritional status of soils in the HRZ not only restricts grain yield but grain protein quantity and quality. The impact of nutrition management on grain yield and quality characteristics as shown in these experiments should be considered by breeders, agronomists and marketers when interpreting experimental results. Furthermore, the results indicate that the nutritional management of breeding experiments should be based on a sound methodical approach, incorporating a combination of soil test results, grain yield potential and seasonal monitoring for the environment in question and not be simply based on levels that are either 'district practice' or 'non-limiting'.

This study has also identified statistically significant differences between cultivars for stability of grain yield and grain protein quality. Four cultivars (three bread wheat and one durum wheat) were characterised as having dynamic stability, which is described as the ability to respond to an environment in a predictable way. In addition, three cultivars were assessed as having static stability, unchanged performance regardless of any variation in environment for water absorption. This information indicates that assessment of stability of cultivars during the early stages of testing can assist commercial buyers in sourcing suitable grain quality and even that there may be potential to breed cultivars with improved static or dynamic stability.

If it is assumed that the Australian wheat industry cannot compete in a global wheat market based on the relatively small level of production. Then the future of the industry lies in producing the qualities required by specific markets. Realizing the impact of nutrition management on quality characteristics in the HRZ of WA will be a positive step towards a sustainable industry.

Acknowledgements

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Finally to all those eager young minds considering a PhD. It's not easy, but in the face of adversity just remember to dream, aim for the stars, work hard and you will ultimately achieve anything you so choose.

Statement of Contribution of Others

This thesis contains the following manuscripts in preparation for publication, which have been co-authored. Details below.

Chapter 3 Influence of cultivar, environment and nutrition management on grain yield and quality (Manuscript in preparation with Robert Belford, Wal Anderson, Ian Edwards)

Chapter 4 Influence of cultivar, environment and nutrition management on grain protein quantity and quality. (Manuscript in preparation with Robert Belford, Wal Anderson, Ian Edwards)

Chapter 5 Stability of grain yield and grain quality in wheat (Manuscript in preparation with Robert Belford, Wal Anderson, Ian Edwards)

The percentage contribution by the authors is 90% by the candidate, Darren M. Hughes and the remaining 10% by the co-authors in each manuscript.

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Candidate, Darren M. Hughes

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Academic Supervisor, Robert K. Belford

Table of Contents

List of Tables

Chapter 2 **Page**

Chapter 3

Chapter 4

Chapter 5

Chapter 6

List of Figures

Chapter 5

Chapter 6

1. General Introduction

Wheat (Triticum spp) is one of the major staple foods for the human population. It provides over 20% of the calories and protein in human nutrition. It is the staple food in more than 40 countries and for over 75% of the world's population. It is the most widely cultivated food crop; grown from the southern regions of South America and Australia to the northern regions of Canada and China. It can be grown over a wide range of elevations, climatic conditions and soil fertility; furthermore, it is easily transported and safely stored over long periods (Bushuk 1998).

Wheat is ranked third in global production behind maize and rice, with 625 million tonnes (Mt) grown in 2004-05 (ABARE 2005). World production between 2001 and 2009 has varied between 566 Mt (2002-03) and 625 Mt (2004-05). In 2006-07 the European Union was the world biggest producer of wheat (125 Mt), followed by China (105 Mt), India (70 Mt) United States (49 Mt) and Russia (45 Mt). The world biggest importers of wheat in 2006-07 were Brazil (7.5 Mt), Egypt (6.8 Mt) and India (6.7 Mt) (ABARE 2007). World wheat consumption in 2004 was 614 Mt, with the majority shared between human consumption (433 Mt) and stock feed (106 Mt) (ABARE 2005).

Wheat production in Australia is in the order of 20 Mt per annum. By global standards Australia is a small producer, with approximately 4% of global production. However, Australian wheat exports account for about 18% of global trade (AWB 2005), signifying Australia's position as an important producer for the global wheat market. By 2050 the world's population is forecast to exceed 10 billion people (Bhalla 2006) and to meet future demand, grain production must increase at an annual rate of 2% on an area of land similar to that currently utilised (Gill *et al.* 2004). Australia is going to play a significant role in feeding the world's population with wheat in the decades ahead.

Global wheat production by overseas competitors is likely to increase due to improved scientific knowledge and technological advances, which will place pressure on existing and future markets for Australian wheat. In addition, some international customers believe certain grades of Australian wheat are deficient in quality characteristics including protein content, milling extraction, dough strength and dough extensibility. There is little published information detailing the deficiencies of Australian wheat because of the commercial sensitivity surrounding such information, but it is widely recognised in both marketing and breeding organisations that there is a problem (Ian Edwards – Edstar Genetics, Ken Quail – Bread Research Institute and Chris Moore – InterGrain *pers comm*). Given future global pressures the Australian wheat industry cannot afford to be a producer of "bulk" wheat. Growers, researchers and marketers must work together to develop "product differentiation" in the global market and to provide consumers with a consistent, high quality product.

Panozzo and Eagles (1998) defined wheat quality as the ability of the grain to meet the requirements of the processor. This will depend upon both the cultivar and environment in which it is grown. There are also many examples detailing the effects of crop management on wheat quality both in Australia (Anderson *et al.* 2005; Mason *et al.* 2006; Shackley 2000) and internationally (Craven *et al.* 2007; Kindred *et al.* 2004; Lopez-Bellido *et al.* 1998). Perhaps cultivar by environment studies should be cultivar by environment by management studies, especially where farming systems are heavily reliant on successful management for profitability.

This thesis focuses on wheat quality in the High Rainfall Zone (HRZ) in Western Australia (WA). Typically, wheat in WA is grown in low to medium rainfall areas where annual rainfall is between 300-450mm, however, it has been demonstrated that there is potential for annual crop production in the HRZ where annual rainfall is between 450 and 800 mm per year (Poole *et al.* 2002). The HRZ is characterised as having higher rainfall, longer and cooler growing seasons and a longer period of frost risk compared to traditional wheat growing areas (Zhang *et al.* 2006). In recent years a large research effort has focussed on increasing grain yield in the HRZ (Hill and Wallwork 2002; Hill *et al.* 2005; Hill *et al.* 2007; Riffkin *et al.* 2003, Simpson *et al.* 2006; Zhang *et al.* 2004a), with a relatively small focus on quality by comparison.

In the book "Wheat Products Guide" (Germaine *et al.* 2004) the foreword by Peter Reading and Sarah Scales says;

'To continue to build and strengthen a differentiated position for Australian wheat, sustained efforts to deepen our understanding of the quality requirements of our customers will be required. Knowledge of critical wheat quality factors can be used to support the marketing of Australian wheat to obtain higher prices. It can also be used to assist the development of new wheat varieties to better meet current and future market requirements.'

This thesis builds on the knowledge of critical wheat quality factors required to drive the wheat industry forward. Quantification of the effects of cultivar, environment and management with special reference to the HRZ of WA may help increase the quality of WA wheat and increase production in an area which has typically been dominated by livestock enterprises.

1.1 Thesis Hypothesis and Aims

1.1.1 Hypothesis

That management per se has a significant impact on grain quality of wheat grown in the south west of Western Australia.

1.1.2 Study Aims

1. To examine physical grain and protein quality characteristics of selected wheat cultivars grown in the HRZ of WA.
2. To examine increasing levels of nutrition and their impact on physical and dough characteristics of wheat grown in the HRZ of WA.
3. To determine the relative impact of cultivar, environment and management on physical and dough quality traits of wheat.
4. To determine if cultivars vary in stability for grain yield and grain quality characteristics when grown in the HRZ of WA.

Chapter 2

Literature Review

2. Literature Review

2.1 Cultivar by Environment by Management

Cultivar, environment and their interactions in wheat present a complex problem to wheat producing nations worldwide. Studies are conducted to determine the level of cultivar by environment interactions relative to the main effects (Williams *et al.* 2008). Effects have been recorded and well documented, among others, in Australia (Basford and Cooper 1998, Panozzo and Eagles 1998, Williams *et al.* 2008), North America (Busch *et al.* 1969, Lukow and McVetty 1991, Peterson *et. al.* 1992), Europe (Mladenov *et al.* 2001) and China (Zhang *et al.* 2004b).

A comprehensive review conducted by Basford and Cooper (1998) into the effect of cultivar by environment interactions on Australian grain production concluded that there is a clear understanding of the effects of cultivar and environment on grain yield and a number of traits that contribute to grain yield. However, their effects on grain quality are less clear, largely because less effort has been invested to determine their importance. More recently, a review by Williams *et al.* (2008) on cultivar by environment effects on wheat quality characteristics in Australia concluded that protein quality is influenced more by cultivar than environment.

Unfortunately, in traditional cultivar by environment studies the influence of crop management is often overlooked, because it is part of the environment term and is often standardised across experimental sites as a means of reducing its effect on the interaction. This practice, however, hides the influence of both management and the possible interaction between cultivar and management (Anderson *et al.* 2005). For example, Rao *et al.* (1993) in North America, indicated that the most important environmental factors that affect protein content are rate and timing of nitrogen fertilisation application; and Shackley (2000) under WA conditions reported that both nitrogen rate and timing are management factors used to improve wheat quality. Cooper *et al.* (2001) concluded that “It is likely that a large component of the previously documented G x E interaction for grain yield in wheat … are in part a result of G x M interactions". By ignoring the effects of management, we may be ignoring the factor which makes the greatest contribution to variance.

In farming systems heavily dependant upon management for profitability, typical of WA farms, the potential gains from breeding, allied with agronomic research, may therefore be restricted. Figure 2.1 indicates traditional thinking of cultivar and environment on wheat quality. The single effects of cultivar and environment, which generally contribute greatest to variance, are indicated by the lightly shaded areas of the circles. Cultivars by environment interactions, which generally contribute less to variance, are indicated by the heavily shaded area of the circles.

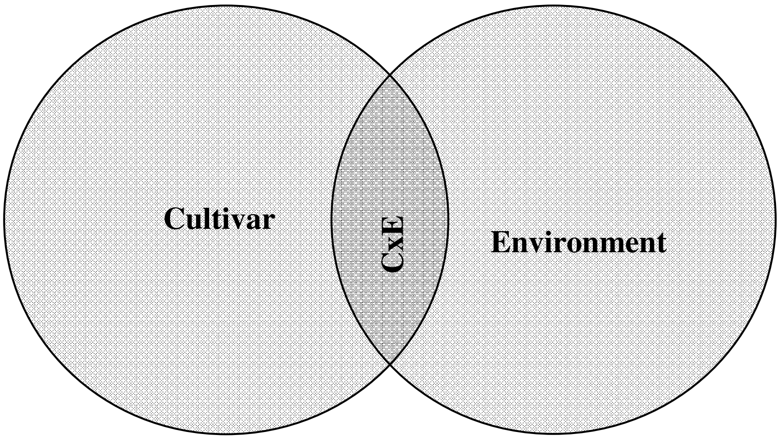

Figure 2.1. Traditional cultivar, environment and interaction effects in wheat.

Cultivar refers to the set of genes possessed by individuals that are important for the expression of the trait(s) under investigation (Basford and Cooper 1998). Cultivar has been considered the major source of variation for many quality traits in wheat (Morris *et al.* 1997; Pomeranz *et al.* 1985; Souza *et al.* 2004; Yong *et al.* 2004; Zhang *et al.* 2004b). Environment can be defined as a set of biophysical factors (water, temperature, soil type) that influence growth and development of plants and thereby influence the expression of the trait(s) (Basford and Cooper 1998). Environment has also been reported as having a significant contribution to variance of grain quality characteristics (Graybosch *et al.* 1995; Guttieri *et al.* 2002; Lukow and McVetty 1991; Souza *et al.* 2004; Yong *et al.* 2004). Williams *et al.* (2008) indicates that variation in the relative contributions of cultivar, environment and cultivar by environment is often dependent on the cultivar and environment sampled. This is an important point because it explains the reason why the contribution to variance often apportioned to cultivar, environment and interactions can vary considerably in the published literature.

In addition there is potential for the E x M interaction to not have been fully recognised. Allard and Bradshaw (1964) attempt to partition environmental variation into two categories: unpredictable and predictable components (Cooper *et al.* 2001 called it repeatable rather than predictable) (also commonly referred to as random and fixed effects). Unpredictable components include fluctuations in weather i.e. amount and distribution of rainfall, and other factors such as established density of the crop. Predictable components include permanent characters of the environment i.e. climate and soil type and those characters which vary steadily throughout the season i.e. day length. Moreover, Allard and Bradshaw (1964) included ‘‘those aspects of environment that are determined by man’’ or which can otherwise be termed ‘management’ and included variables such as planting date, sowing density, methods of harvest and other agronomic practices as predictable components.

Allard and Bradshaw (1964) recognise the confusion that can arise in the partitioning of unpredictable and predictable components by their comment ‘distinction between the two categories is not always clear’. The partitioning of environmental variation into predictable and unpredictable components is therefore difficult due to confusion over the definition of environment. A clear definition for management is required to clearly define gains in grain yield and quality between E and M.

Management can be defined as practices, techniques or options reasonably available to growers to influence growth and development of the plant and thereby influence the expression of trait(s). Shackley (2000) indicated that once a suitable cultivar has been selected, the most important factor for producers of high quality wheat is to employ management practices that will maximise the probability of achieving the required level of grain protein. Management would therefore include, but not be limited to, factors such as time of sowing (Sadras *et al.* 2002), nutrition (Long and Sherbakoff 1951; Reuter and Dyson 1990; Saint Pierre *et al.* 2008; Tea *et al.* 2007), weed and disease control (Palta and Peltzer 2001; Shackley 2000) and rotations (Anderson *et al.* 1995). These are all management factors which research has identified as having an effect on grain quality. Therefore, do the combined effects of management have a greater influence on grain quality than either cultivar or environment?

The following is a review of the literature examining the effects of cultivar and environment and outlining the effects of management on grain quality in wheat. The review looks to understand grain quality in Australia with special reference to the HRZ of WA, the focus of the experiments later described in this thesis.

2.2 Cultivar

Wheat shares a remarkable evolutionary history with humans. It has adapted to the temperate climates, in contrast to maize and rice which are best suited to more tropical conditions (Bushuk 1998). Wheat is grown all over the world, except the hottest tropical regions (Posner and Hibbs 1997) and cooler arctic regions. In the equatorial regions of central Africa and the Andean region of Latin America wheat is grown up to 3000 metres above sea level, while in the Netherlands it is grown on polders several metres below sea level (Pingali 1999). Wheat was first grown as a food crop about 10,000 years ago, however, there is much debate among researchers about its botanical origin. There is evidence that cultivated *Triticum monococcum* (einkorn - an ancestor to modern day wheat) developed from a wild grass which was native to the arid lands of Asia minor (Orth and Shellenberger 1988). The common wheat genus *Triticum* is believed to have originated in Asia and parts of Africa in an area that stretches from Syria to Kashmir and southwards to Ethiopia (Belderok 2000).

Triticum, depending upon species, is a combination of A, B and D genomes. The A genome comes from *Triticum monococcum,* a diploid wheat which contains two sets of seven chromosomes. The B genome originated from a cross between *Triticum monococcum* and an unknown wild grass species to form a tetraploid sometime before 8000 BC. Aegilops squarrosa (*Triticum tauschii*) is responsible for the D genome in hexaploid wheat and is a significant contributor to the bread making properties of wheat (Belderok 2000).

The *Triticum* genus consists of a number of species which can be divided into three groups depending on the number of chromosomes present in vegetative wheat plant cells: diploid (14 chromosomes), tetraploid (28 chromosomes) and hexaploid (42 chromosomes). There are approximately 30 species and over 40,000 cultivars of wheat worldwide (Setter 2000).

Three species of wheat are commercially important; *Triticum aestivum, Triticum compactum* and *Triticum turgidum L. var. durum. Triticum aestivum* and *Triticum compactum* are both hexaploid wheats and mainly used in the production of bread and cake flour (Setter 2000). Hexaploid wheat (2n=6x=42, AABBDD) is composed of A, B and D genomes and has the largest genome of the three major agricultural cereal crops – 16000 Mb - which is approximately eightfold larger than maize and forty times larger than rice (Arumuganathan and Earle 1991). *Triticum turgidum L. var. durum* (AABB) is a tetraploid wheat. Semolina produced from durum holds together well due to the high gluten content and is used mainly for pasta and couscous (Bushuk 1998; Setter 2000). The characteristics required for pasta making are highly heritable and therefore can be manipulated by breeding (Bushuk 1998).

2.2.1 Cultivar Classification

In Australia a wide array of wheat cultivars are grown, with varying degrees of grain quality. Traditionally, cultivar classification has been conducted by the Australian Wheat Board (AWB) and based on test results received from breeding companies and independent testing. The AWB classified Australian bread wheat into six major grades based on unique quality characteristics that suited the AWB marketing strategy. Quality assessments are often based on composite samples from several locations, which unfortunately provides no measurements of environmental influences or stability of the cultivar being considered. The Australian wheat industry has recently been through substantial changes with the deregulation of the export bulk wheat market, previously held as a monopoly by the AWB. This has led to changes in the agency responsible for the classification of wheat in Australia. In 2009 it was announced that BRI Research, previously the Bread Research Institute, will be responsible for the classification of new cultivars.

Australian Prime Hard (APH) is Australia's top quality, high protein milling wheat. APH is mainly grown in northern Australia where specially selected white, hard-grained wheat cultivars produce exceptional milling quality. Flour from APH wheat is used to produce high quality Chinese style yellow alkaline noodles and Japanese Ramen noodles and is often blended with lower protein wheat to produce flours suitable for a range of baked products (Cracknell and Williams 2001). Market requirements are for a hard grain with strong extensible dough properties and flour protein levels between 10.0 and 13.0%. Starch quality is less critical due to the influence of alkali on starch swelling, with colour stability particularly important for yellow alkaline noodles sold in a fresh form (Crosbie *et al.* 1998). APH wheat has traditionally been grown in Queensland and northern New South Wales on soils with high natural fertility. However, continuous cropping has depleted much of this natural fertility. Therefore, nutrition management is critical in achieving minimum grain protein required for APH (Wheat Nutrition 2008). In WA there is currently no segregation for APH cultivars; therefore they must be delivered to the Australian Hard grade. Perhaps if nutritional management techniques to achieve the minimum grain protein and quality parameters required for APH are known, segregation can be developed in WA.

Australian Hard (AH) is comprised of specific hard, white wheat cultivars segregated at a minimum protein of 11.5%. Flour extracted from Australian Hard is used in the production of Middle Eastern flat breads, Chinese steamed noodles and pan breads (Cracknell and Williams 2001). Australian Hard is a segregation accepted in all grain growing regions of Australia.

Australian Premium White (APW) is a blend of white, hard grained wheat cultivars, which have a minimum protein level of 10%. APW is used for the production of Asian noodles, Middle Eastern and Indian style breads and Chinese steamed breads (Cracknell and Williams 2001). APW is used to make two different styles of steamed bread in China. Northern China prefers steamed bread that has a very cohesive, elastic and dense texture, compared to southern China, which prefers a more open and softer texture. Northern style steamed breads require flour protein between 10.0-12.0%, with medium to strong dough properties and moderately high to high flour paste viscosity. Southern style steamed bread requires flour protein between 9.5-11.0% and medium strength. General flour requirements for all types of steamed bread include a low level of amylase activity, white colour and a low level of damaged starch (Crosbie *et al.* 1998).

Australian Premium Durum (APD) is the classification for durum; it has a minimum protein content of 13%, although various grades below this are segregated on the basis of protein, hectolitre weight, screenings and colour. Durum wheat has the hardest kernels of all wheat and because of market specifications generally has higher grain protein content than bread wheat. The semolina produced from durum exhibits high levels of stable yellow pigment and high water absorption, which makes it suited to the production of high quality wet and dry pasta products (Cracknell and Williams 2001).

Several other major quality grades exist for Australian wheat, such as Australian Soft, Australian Standard White and Australian Noodle; they not been discussed because they have not been examined in the experiments discussed later.

2.3 Environment

The Australian wheat belt can be classified largely into two regions based on rainfall distribution. The winter rainfall region is the biggest area and encompasses Western Australia, South Australia, Victoria and southern New South Wales and accounts for about 70% of Australia's cereal production. These areas typically receive between 60 to 70% (up to 85% in the northern wheat belt of Western Australia,) of their rainfall during the cool winter growing season (May-October). The second dominant grain growing area is the northern region which is characterised by summer dominant rainfall and extends from central New South Wales to Queensland and accounts for about 25% of production. Approximately 5% of Australia's wheat is grown in a region which receives evenly distributed rainfall throughout the year (Foster 2000). Figure 2.2 outlines the agro-ecological zones of Australia, which define the wheat growing areas based on a combination of rainfall distribution and amount, temperature and soil type.

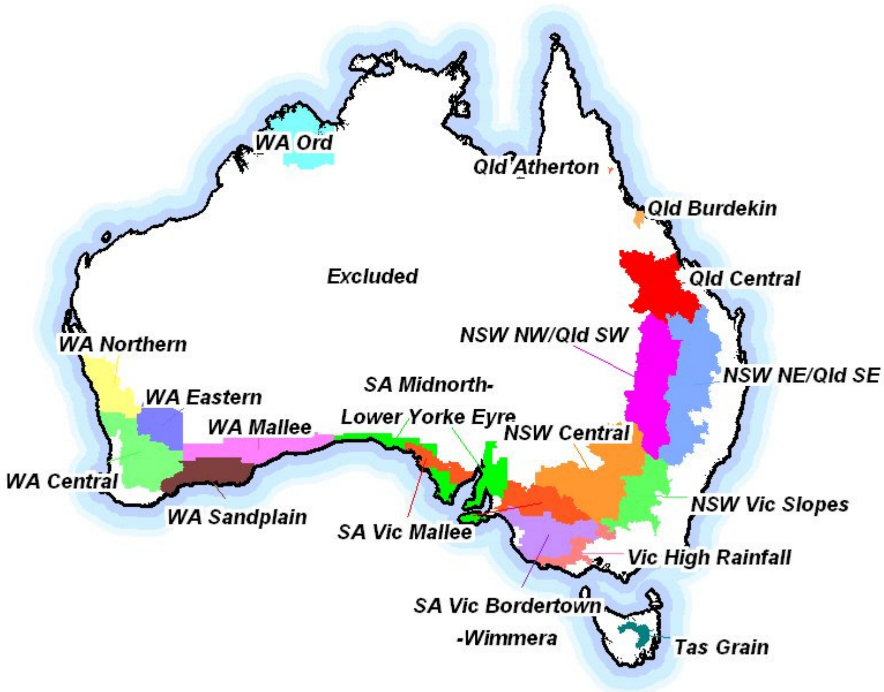

Figure 2.2. Agro-ecological zones of Australia.

Source: GRDC (http://www.grdc.com.au/uploads/documents/grall.jpg)

The Western Australian wheat belt is situated in a Mediterranean-type climate with hot, dry summers and cool, wet winters. Traditionally in Western Australia wheat grown in the northern and eastern regions of the wheat belt has higher grain protein. These regions have a warm, dry finish to the season, which limits carbohydrate deposition in the grain, increasing grain protein percentage. Southern and western regions of the wheat belt have cooler and moister conditions during grain fill, which increases carbohydrate deposition and dilutes protein in the grain (Shackley 2000).

It is forecast that environmental conditions in the south west of WA will change due to the growing impact of climate change. Western Australia is expected to become warmer and drier than present. By 2030 annual temperatures are expected to rise between 0.4 - 2^{o}C. In south west WA rainfall is forecast to decline by 20% (relative to 1990 values) (Foster 2007). In general, the northern and eastern regions of the WA wheat belt are expected to be adversely affected due to a decline in rainfall. Western and southern regions, including the HRZ zone, are expected to benefit from the decline in rainfall and a subsequent reduction in the incidence of water-logging, which Zhang *et al.* (2006) has identified as a major constraint to production. Therefore, there is potential for the main wheat producing region of WA to move into what is now the HRZ due to the impact of climate change.

Environmental conditions are rarely optimal and often limit the yield and quality of wheat (Mladenov *et al.* 2001). Numerous authors have identified environmental conditions affecting grain quality (Table 2.1) and grain quality characteristics affected by the environment (Table 2.2). Growers should attempt to minimise susceptibility to adverse environmental conditions in order to reduce year to year variation in grain quality and deliver customers a consistent quality product.

Table 2.1. Selected references relating to environmental conditions affecting wheat quality.

Environmental Condition	Author
Growing season temperatures	Johnson *et al.* 1972
Temperature during grain fill/duration of grain fill	Randall and Moss 1990 Johnson and Mattern 1987
Distribution of rainfall	Faridi and Finley 1989
Late season frosts	Lookhart and Finney 1984; Shackley 2000

Table 2.2. Selected references relating to quality characteristics influenced by environment.

Quality Characteristic	Author
Grain protein, soundness, maturity, plumpness, milling yield, moisture content, content of shrivelled, dry green or frosted grains.	Simmons 1989
Protein content and protein related quality parameters; mixograph peak time	Fowler and de la Roche 1975
Flour protein, gliadin, loaf volume, dough development time, dough breakdown, extensibility and Rmax	Panozzo and Eagles 2000

2.3.1 Rainfall

Australia receives less rainfall than any other continent (except Antarctica) and the rainfall patterns are highly seasonal. More than 80% of Australia has an annual average rainfall of less than 600 mm per year. Figure 2.3 shows Australia’s 30 year (1961-1990) annual average rainfall.

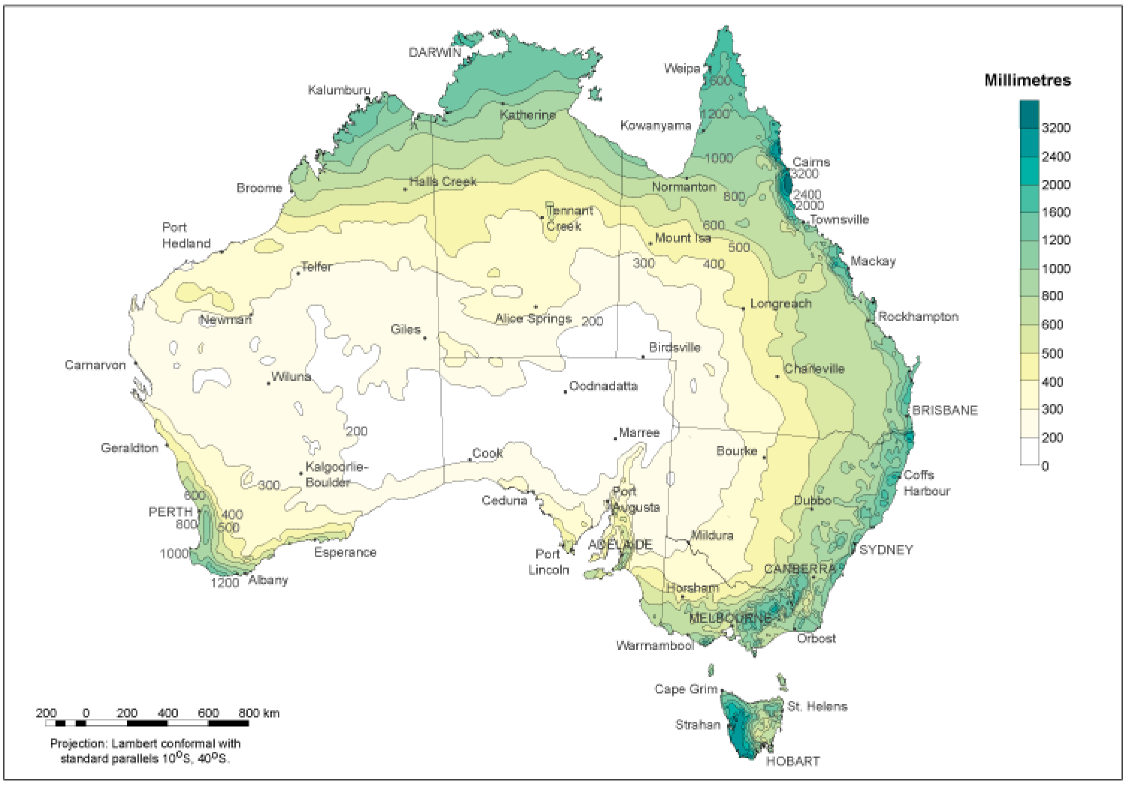

Figure 2.3. Australia's 30 year (1961-1990) average annual rainfall. Source: Australian Bureau of Meteorology (www.bom.gov.au/jsp/ncc/climate_averages/rainfall/index.jsp)

Most of Western Australia's wheat is currently produced in areas with less than 500 mm annual rainfall, with over 40% of the production coming from areas receiving 325 mm or less (Foster 2000). The Western Australian wheat belt extends from about 28^0S (Geraldton) to about 34^0S (Mt. Barker, Esperance) across average annual rainfall zones from about 300 mm (Merredin) up to about 750 mm (Mt. Barker). The HRZ in WA is defined as cropping areas where annual rainfall is between 450 and 800 mm even though there is very little wheat produced at annual rainfall amounts exceeding 600 mm. This contrasts with the definition in south-eastern Australia where the HRZ extends from annual rainfall of 500 to 900 mm per year and where growing season length ranges between 7 and 10 months (Zhang *et al.* 2006).

The HRZ of WA is influenced by largely winter dominant rainfall, compared to south west Victoria and the slopes of New South Wales where distribution is more uniform. The variability of rainfall in the HRZ of WA from May to October expressed as a coefficient of variation around the mean is between 20-25%, compared to traditional wheat belt areas which vary between 25-35%. This lower variability in rainfall during the growing season indicates that rainfall is more reliable in the HRZ than in the traditional wheat belt areas (Zhang *et al.* 2006).

Water-logging has been identified as a major constraint to increasing crop production in the HRZ (Zhang *et al.* 2006). Excessive rainfall during the growing season combined with subsoils of low permeability can lead to widespread water-logging, which reduces the rate of crop growth and the availability and uptake of soil nitrogen. French and Schultz (1984) indicated that water-logging can reduce grain protein levels in wheat, however, its influence is thought to be dependent upon the duration of water-logging in relation to the stage of plant development and demand for nutrients, particularly nitrogen.

2.3.2 High temperature

Temperature is a major environmental factor affecting grain quality in wheat (Wrigley 1994). The Australian wheat belt is often subject to lengthy periods of above-optimal, chronic high temperatures (daily maxima above 30^{o}C) and short periods of heat shock (3-5 days of temperatures between 33-40^{o}C) during grain fill.

High temperatures during grain fill (>30^{o}C) can significantly increase grain protein quantity but decrease protein quality. As the temperature rises during grain fill there is a tendency for grain protein quantity to increase; this can result in an increase in grain quality, as measured by dough strength. However, as the temperature rises above 30^{o}C the relationship between grain protein quality and dough strength breaks down (Satorre and Slafer 1999). High temperatures prolong gliadin synthesis and reduce glutenin synthesis, which can produce a higher gliadin:glutenin ratio in mature grain and consequently result in weaker dough properties (Blumenthal *et al.* 1993).

From a series of experiments conducted throughout the Australian wheat belt, Randal and Moss (1990) determined that air temperatures up to 30^{o} C increased dough strength but above 30^{o} C dough strength was reduced. Similarly, Borghi *et al.(1995)* from data collected from experiments conducted in the Mediterranean climate of southern Europe, reported that a long period of temperatures in the range of 30-35^{o}C had a dough 'strengthening' effect, while frequent episodes of daily maximum temperatures above 35^{o}C led to a dough 'weakening' effect.

2.3.3 Frost

Radiation frosts in spring are an irregular occurrence over much of the wheat growing areas of Australia. However, in the mid to late 1990's there were widespread crop losses from frost perhaps due to improvements in cropping technology such as a greater emphasis on continuous cropping, release and widespread adoption of early flowering wheat varieties, emphasis on early sowing of cereals to maximise yield potential, and improved technical ability to sow early (Shackley 2000).

Frost damage in wheat is a result of interactions between the environment and the plant. Factors such as soil type, soil moisture content, cloud cover, daytime temperature, wind speed, humidity, position in the landscape, crop species, crop nutrition, crop density and crop moisture status, all influence the occurrence and resulting frost injury (Shackley 2000). However, the stage of development when the frost occurs governs the severity of the damage. A frost event during flowering can cause partial sterility in spikes although the surviving grain can be larger and have higher protein levels (Jenner *et al.* 1991).

In a study by Allen *et al.* (2001) grain samples from APH cultivar Janz were taken from unfrosted, lightly frosted, and severely frosted areas of the Riverina district in New South Wales and tested for grain quality. The study concluded that as the degree of frost damage increased, grain size, flour extraction, baking quality and falling number decreased, flour ash, dough strength and amylase activity increased, while flour colour deteriorated. The study also determined that after removing frosted grains from a sample the remaining grains showed desired APH characteristics, which potentially identifies techniques growers can use to better manage the effect of frost damage on grain. Advances in commercial grain screening technology has allowed growers to screen grain at harvest, removing frosted grain and allowing wheat to be delivered into the premium grades.

2.3.4 Soil Type

In this review the effect of soil type has been considered under environment. However, the impact of soil type on crop performance depends on the interactions between physical fertility (soil texture, density etc) and chemical and biological fertility; these factors can, be influenced by management (e.g. the application of lime, gypsum and clay). This highlights the need for accurate definitions of environment and management (page 5 and 6) thereby avoiding confusion between the two terms and allowing researchers to more accurately partition the effects of environment and management.

A number of soils that occur in the wheat belt of WA are morphologically and chemically similar to the soils found in Eastern Australia and areas overseas, but WA soils are generally more highly weathered and have lower capacity to hold water and nutrients for plant growth. The soils which support agricultural production in WA are some of the oldest and most stable land surfaces on earth. Due to the lack of tectonic, volcanic and glacial activity there is minimal soil renewal (Moore 1998). The soils of the Western Australia wheat belt can be broadly classified into three groups; sandy duplex (sodosols and chromosols), deep sands (rudosols, tenosols and podosols) and loamy earths (kandosols, calcarosols, sodosols, and dermosols) (Isbell 2002; Moore 1998). The choice and management of soil type can have a large bearing on the probability of the desired grain protein percentage being achieved and the appropriate premiums for quality being received as a result (Shackley 2000).

Sandy duplex soils are characterised as acid sands over neutral to alkaline clays or loams at <30cm and are naturally deficient in N, P, S, K, Zn and occasionally Cu, Mn, and Mo. Boron can become toxic if the subsoil pH is >9, and Al if the surface pH is <4.5. They have low soil water storage and are susceptible to water-logging, wind and water erosion and water repellence (Moore 1998).

The most common soils of the HRZ in WA are yellow duplex soils with a distinct texture contrast between the A and B horizons. These soils have sandy textured surfaces with low available water holding capacity and clay subsoils with low permeability. The sandy surfaces typically have available water storage capacity of 20-50 mm for medium sand to 90-120 mm for loamy sand although water holding capacity varies from 20-100 mm/m in soils with sodic B horizons to 120-230 mm/m in non-sodic B horizons (Zhang *et al.* 2006).

Deep sands are characterised as having sand >80 cm deep and can be white, grey and yellow in colour. They are deficient in N, P, K, S, Cu, Zn, and Mn and occasionally deficient in Mo and Fe. Aluminium can become toxic if the pH is below 4.5. These soils typically have very low soil water storage, are susceptible to wind erosion and subsurface compaction, and can become water repellent. Deep sands occur mainly on the West Coast, West Midlands, South Coast and Central and Eastern wheat belt areas (Moore 1998). The yellow and white sands of the northern wheat belt have produced crops with low yields and protein levels due to their naturally low level of fertility. However, the introduction of longer pasture phases, stubble retention and reduced tillage has increased the organic matter and nitrogen reserves, leading to higher grain protein levels in wheat (Shackley 2000).

Loamy earths consist of uniform loams, loams grading to clay loams and clays which can vary in colour from red to red/brown or yellow. Loamy earths are deficient in P, N and occasionally Zn. They are susceptible to high alkalinity, wind erosion, water erosion and hard or crusting surface. Loamy earths are found throughout the eastern wheat belt, northern wheat belt, Avon valley and in the east of the Great Southern (Moore 1998). Loamy earths are naturally high in organic matter and nitrogen and have consistently produced high yields and protein, particularly in the warmer and drier locations. However, if these soils have been continuously cropped with wheat using little nitrogen fertiliser and heavily cultivated in the past, the natural fertility of the soil has declined and can result in low grain yields and protein (Mason 1987; Mason 1994; Shackley 2000).

In general, fine texture soils tend to have higher organic matter and thus are likely to mineralize more organic N, which tends to lead to grain with higher protein quantity, however, these soils are generally heavily cropped and can be low in nutrition. By contrast, coarse textured soils have lower nutrition and tend to produce lower grain protein quantity, although when these soils have been well managed, for example with longer pasture phases, they can produce grain with high grain protein quantity (Shackley 2000).

2.4 Management

Management refers to the techniques growers use to influence growth, development and yield of the crop in the target environment and to modify the expression of grain quality traits. The effects of management were examined in multi-environment wheat breeding trials in Queensland, Australia by Cooper *et al.* (2001). A diverse set of 272 advanced breeding lines were grown at 3 sites over 2 years. Management regimes were generated at each site as separate trials and included variables such as planting time, N fertilizer application rate, cropping history and irrigation. Cultivar by management interactions were found to be the largest source of variation for both grain yield and protein; in both cases C x M variation was larger than genotypic variance alone. It was also noted that a large proportion of the previously documented G x E interactions for grain yield of wheat in the northern regions are in part due to G x M interactions and that the influence of management on cultivar performance warrants more consideration in the conduct of wheat breeding trials in the northern grain region.

Similarly, Souza *et al.* (2004) examined the influence of cultivar, environment and nitrogen management on spring wheat quality in North America. Seven spring wheat cultivars were grown under irrigation at three sites and in moisture limited conditions at three sites between 1998 and 2000. The study concluded that N influenced Chinese noodle colour in irrigated environments and test weight, flour ash, loaf volume and bake absorption in moisture limited environments and that the response to N management was not usually cultivar specific.

Management includes a number of factors such as nutrition, weed and disease control, and time of sowing. The most important factor for producers of high quality wheat is to employ management practices that will maximise the probability of achieving the required level of grain protein (Shackley 2000).

2.4.1 Nutrition

Nutrition has been identified as one of the major factors limiting production in the HRZ of Western Australia. A review by Hill *et al.* (2007) into the nutrition of wheat crops grown in the HRZ of WA determined that average use of N was 56 kg/ha, P 17 kg/ha, K 16 kg/ha and S 9 kg/ha. These are well below the amounts required to achieve rainfall limited potential grain yields of 5-8 t/ha that can be produced in the HRZ of Western Australia (Zhang *et al.* 2006). In order to achieve grain yields over 5 t/ha in the HRZ it has been recommended that growers apply 150 kg/ha N, 50 kg/ha P, 50 kg/ha K and 23 kg/ha S (Bolland 2000).

If growers are to increase grain quality, increasing nutrition is one tool available to growers. Increasing the use of artificial fertiliser is perhaps the easiest option, nonetheless expensive. Perhaps a combination of artificial fertilisers and holistic farm management (for example including clover pastures or leguminous crops in the farm system) would be a more cost effective way to increase nitrogen nutrition. Emphasis in this section will be given to nitrogen and sulphur, nutrients that have a major impact on grain protein quantity and quality for bread-making.

Nitrogen

Nitrogen (N) is an important element in many plant compounds such as amino acids and proteins; it is a key component of chlorophyll and plays a vital role in photosynthesis.

All WA soils are potentially deficient in N, particularly the coarse textured soils (sands and sandy surfaced duplex soils). The fine textured soils tend to have higher organic nitrogen, although this natural fertility has been depleted over the years from intensive cropping with non-leguminous plants (Mason 1998b).

The average application of nitrogen fertiliser to wheat in Western Australia in the early 1990's was 22 kg N ha^{-1}. By 1996 it had increased to 30 kg N ha^{-1} (Anderson and Hoyle 1999), and by 2000 this had increased again to 35 kg N ha^{-1}. At average wheat yield of 2 t/ha and 10% average protein, up to 35 kg N ha^{-1} can be expected to be removed from the soil (Shackley 2000). The remainder must come from the soil (Anderson and Hoyle 1999) in the form of residual organic nitrogen (RON) or stable organic nitrogen (SON).

Nitrogen is a mobile nutrient and is prone to losses through leaching, volatilisation and immobilisation. Recovery of nitrogen fertiliser by the crop is only about 40-50% of that applied, however, this can vary between 20 and 56% in dryland wheat crops in Australia (Anderson and Hoyle 1999). The uptake of N varies between cultivars and is a function of the size and activity of the root system (Goodman 1979). Any improvement in uptake efficiency of applied nitrogen could have a major impact on the profitability of fertilizer application and the translocation of N to grain in wheat.

The general response to additional nitrogen is greener plants, due to increased chlorophyll production, which can lead to increased vegetative growth, photosynthetic area and grain yield. The increase in grain yield under Western Australian conditions has been attributed largely to the increase in the number of ears (Bestow 1992; Feyter and Cossen 1977) however, it can also be attributed to an increase in the number of kernels per ear (Darwinkel 1983) if N supply is sufficient during the time of spike development. Once the requirements for growth and yield have been fulfilled the additional nitrogen can result in an increase in grain protein (Mason 1998b).

Nitrogen is absorbed from the soil mainly as nitrate and transported to the leaves where it is reduced to glutamate in the chloroplast. As the older leaves and tillers die the nitrogen in protein is mobilised and utilised for protein synthesis in the younger leaves and surviving tillers. Mobilisation of nitrogen in the older leaves and deposition in the grain may simply be the final stage in a process that began before ear emergence (Satorre and Slafer 1999). The leaves and the stems are the most important reserves of nitrogen, each contributing up to 30% of the nitrogen in protein deposited in the grain. The roots can contribute up to 10% and the glumes around 15%. More importantly, the glumes appear to act as a temporary deposit for nitrogen early in grain fill and as a site for the transfer of nitrogen from xylem to phloem (Jenner *et al.* 1991).

The traditional approach to nitrogen application to field crops was to apply a fixed amount at a specific time, however, more recent recommendations are for a flexible approach based on site, season, cultivar, end-use and likely nitrogen demand. Mason (1998b) recommended in deep coarse-textured soils in high rainfall areas N application should be delayed three to four weeks until the crop has an effective root system. Work conducted by Simpson *et al.* (2006) in the HRZ of south west Western Australia found applying nitrogen tactically after major rainfall and water-logging events increased grain yields by up to 60% over current practices. Poole (2005) recommended that nitrogen application strategies in the Australian HRZ wheat belt should be based on canopy management principles, i.e. matching peak nitrogen supply with peak demand, based on European and New Zealand nitrogen management practice.

Nitrogen application strategies may vary for three reasons. Firstly, small differences in rainfall, temperature and soil conditions may result in different strategies being more appropriate for certain areas and seasons. Secondly, as understanding of crop phenology and N remobilization improves, new ideas on N application are likely to be developed. Thirdly, the development of new fertilisers which control the release of N thereby closely matching crop nutrition with crop demand. Given that N is an important and costly nutrient it is foreseeable that research will continue to develop diverse strategies to improve the efficiency of N to increase grain yield and quality.

Research has shown that timing of application of N fertiliser has an effect on the uptake and utilisation of nitrogen in wheat under a range of field conditions. Early applications of N promote leaf and tiller growth, increase the number of fertile florets per spike and improve subsequent grain set (Shackley 2000). Late application of nitrogen increases grain protein quantity (Long and Sherbakoff 1951) and quality (Langer and Liew 1973; Mason 1998b; Pushman and Bingham 1976).

Nitrogen application has also been shown to influence grain protein components. Wieser and Seilmeier (1998) in Germany demonstrated that albumins and globulins were barely influenced by different nitrogen fertilization, however, gluten was strongly influenced; effects were more pronounced on gliadins than glutenins. It affected not only the quantity but also the proportion of gluten proteins; u-gliadins and HMW glutenins increased as N levels increased while c-gliadins and LMW glutenins decreased. Tea *et al.* (2007) in France, studied the effects of N applied at Zadoks growth stages 25, 31 and 39 on bread making quality and concluded that increasing N increased dough strength. It has been demonstrated that additional N can influence protein fractions, therefore, it may be possible to suggest that in the HRZ of WA where natural soil N is low and where extra N must be applied to grow a profitable crop, management of N may positively influence dough rheology.

The typical crop response to added nitrogen is represented in Figure 2.5. Zone A shows that when soil nitrogen levels are low, a small amount of added nitrogen results in a large increase in yield, but grain protein quantity either remains unchanged or decreases. Zone B is representative of a normal nitrogen supply, yield increases more slowly with additional nitrogen and protein begins to increase. In zone C yield begins to plateau and the additional nitrogen is being channelled into grain protein, so protein content rises rapidly (Shackley 2000).

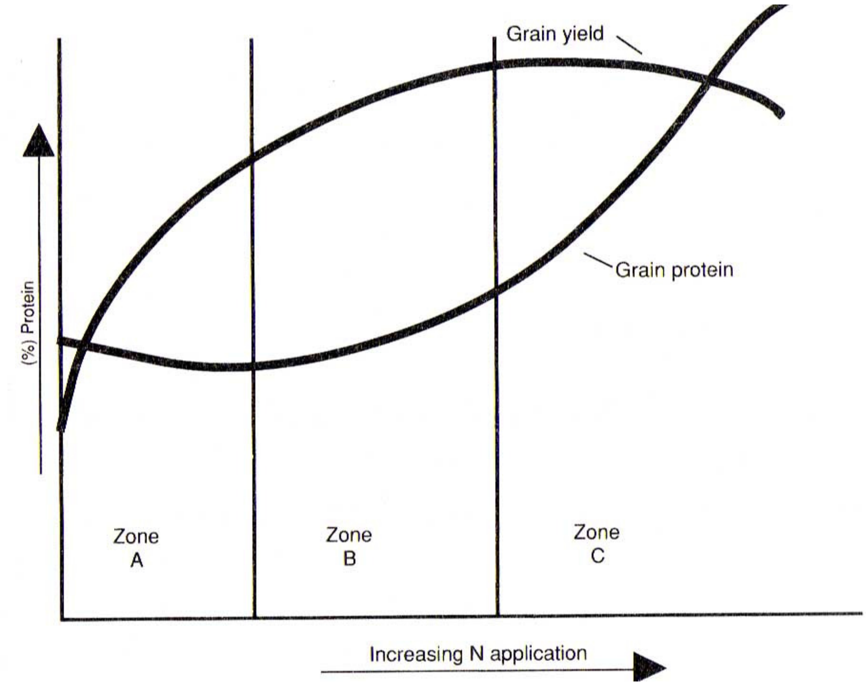

Figure 2.4. Response of yield and protein to nitrogen fertiliser. Source: Shackley 2000

Studies have also shown that nitrogen can also have an effect on alpha amylase activity in the grain which is measured using the Hagberg falling number method. Work by Kindred *et al.* (2004) in the United Kingdom concluded that applying nitrogen can reduce alpha amylase activity by two mechanisms. Firstly, more complete grain filling which can increase the size of the grain cavity and reduce the likelihood of disruption between the endosperm and the testa. Secondly, applying nitrogen seems to delay crop maturity and increase dormancy, this increases the risk of incipient or actual post maturity sprouting

Sulphur

Sulphur (S) is an essential element for plants and an important component of the amino acids methionine, cystine and cysteine, which are essential components of most proteins. Plants obtain most of their sulphur requirements from the soil, however, in areas close to industry there can be a significant input from the atmosphere. Sulphur deficiency rarely occurs in cereal crops in Western Australia, due to the use of single superphosphate as a source of phosphorus for crops and pastures (Mason 1998a).

Sulphur is responsible for producing good quality protein in the grain. If sulphur deficiency affects the production of sulphur-containing amino acids, it will reduce the quality of the protein which in turn reduces the quality of flour for bread making (Mason 1998a). Moss *et al* (1981) grew wheat cultivar Olympic under a combination of sulphur and nitrogen fertiliser treatments in the field, and concluded that low sulphur grain was harder (higher pearling resistance) and produced dough with a greater resistance to extension and lower extensibility compared to high sulphur grain. The study also determined that a restricted supply of sulphur produced dough that had high resistance to mixing due to a decrease in the proportion of albumins.

MacRitchie and Gupta (1993) used samples from the experiment described above, and concluded that grain low in sulphur led to a rise in the proportion of HMW to LMW glutenin subunits, adversely affecting dough properties. This happens because LMW glutenins are richer in sulphur than HMW glutenins, due to differences in the number of cysteine residues per molecule.

Other examples of sulphur affecting grain quality have been reported by Yoshino and McCalla (1966), who collected data from field experiments in Canada and found an increased proportion of non-gluten nitrogen in low sulphur grains and suggested that this was likely to reduce the baking quality of grain from sulphur deficient plants. Furthermore, from a glasshouse sand culture experiment Archer (1974) reported that grain quality for baking is seriously reduced or entirely lost in grain from sulphur deficient plants. Wrigley *et al.* (1980), using the same method as Archer (1974), determined that sulphur deficiency markedly alters the proportion of the protein in each of the classes of grain protein, and as a consequence changes the nutritional quality due to a major reduction in the proportion of all essential amino acids except lysine.

2.4.2 Disease

Under different conditions, disease can either increase or decrease grain protein levels (Anderson 1991). Crop diseases can reduce water uptake by plants, which tends to result in pinched grain and higher levels of grain protein quantity and screenings. Root disease can also reduce nitrogen uptake, which leads to lower grain protein concentrations (Dimmock and Gooding 2002). Disease can be further refined into two sub-classes; leaf disease and root disease.

Leaf diseases are caused by a wide variety of fungi, viruses, and bacteria. They reduce grain yield by damaging the green leaves and preventing them from producing the sugars and proteins needed for growth. Viruses and bacteria block or damage the plants internal transport system, reducing the movement of water and sugars throughout the plant (Wallwork 1992). Leaf diseases affect nitrogen uptake which commonly increases during the latter stages of grain filling so premature and disrupted ripening may effect a reduction in protein concentration particularly in hot dry conditions, thereby affecting grain quality (Dimmock and Gooding 2002). O'Brien *et al.* (1990) demonstrated that stripe rust (*Puccinia striiformis)* can reduce flour yield and dough strength, shorten development time, and produce dough which has less mixing tolerance and reduced extensograph heights.

Common leaf diseases of wheat include stem rust (*Puccinia graminis*), stripe rust (*Puccinia striiformis*), leaf rust (*Puccinia recondita*) (Wallwork 1992), powdery mildew (*Blumeria graminis* f.sp. *tritici*) and septoria nodorum (*Phaeosphaeria Stagonospora nodorum*).

Leaf diseases are controlled through either genetic resistance or fungicides. Improving the genetic resistance of wheat to disease is one of the primary aims of a wheat breeder; however, research has shown particular genes responsible for resistance to leaf disease can have an effect on grain quality (Table 2.5). The use of fungicide to control leaf diseases helps to maintain green leaf area and photosynthetic capacity, and thus support grain filling and consequently reduce the severity of grain shrivelling. Fungicides are known to have contrasting effects on grain protein. Their use to control rust and powdery mildew either increased or had no significant effect on grain protein, however, control of septoria often resulted in reduced grain protein (Dimmock and Gooding 2002). Dimmock and Gooding (2002) gave no explanation why these contrasting results occur. Significant research is still required to fill the knowledge gaps on the effects of crop disease on grain protein quantity and quality.

Table 2.3. Genetic resistance and effect on grain quality in wheat.

Gene	Disease controlled	Effect on Quality
Lr19	Leaf rust	Discolours flour, reduces value of grain, reduced mixing tolerance and dough stickiness (Marais 1992).
Lr28	Leaf rust	Linked to a slight reduction in dough development time (Kumar and Raghavaiah 2004).
Lr34	Leaf rust	Causes lower 1000 grain weight, reduced flour yield, SDS-sedimentation volume, dough strength, water absorption and baking strength index (Drijepondt *et al.* 1990).
Lr41	Leaf rust	Associated with reduced baked-mixing time and water absorption (Cox *et al.* 1997).

There are large gaps in the knowledge of the effects of root diseases on grain protein. The limited evidence available suggests that the effects are relatively small and probably inconsistent. Root diseases can severely stunt early growth of root systems or ‘prune’ plant roots which can impair root function during reproductive development. Root diseases can thus reduce the water and nutrient uptake of plants, which can lead to reduced supply of starch and thus pinched grain and higher protein levels. Reduced nitrogen uptake can lead to lower protein concentrations and yields (Schoeny *et al.* 2003). Thus the timing of the disease in relation to grain fill is important (Reuter and Dyson 1990).

Common root diseases of the Western Australian wheat belt are take-all (*Gaeumannomyces graminis*) and rhizoctonia (*Rhizoctonia solani*). Rotations offer growers the most effective form of control for root diseases, with resistant cultivars and chemicals offering some degree of control for certain diseases (Hollaway 2007).

2.4.3 Weeds

Weeds have the ability to reduce both vegetative dry matter yield and grain yield of wheat through competition for light, water and nutrients, but their effect on grain protein is varied. This competition may reduce the uptake of nitrogen by the crop and may reduce grain protein. However, competition for soil moisture during grain fill tends to increase grain protein by limiting the time available for carbohydrate deposition in the grain (Mason and Madin 1996). Herbicide resistance is an increasing problem for wheat production systems in WA; weeds may therefore play an ever increasing role in influencing quality characteristics. This would be difficult to quantify at an industry level, however, growers must be aware of the problem and manage the farm system accordingly.

The absolute effect of weeds on grain protein depends on the magnitude of the competition for nitrogen and moisture (Bestow 1992; Shackley 2000). Controlling weeds in the year preceding the crop also has the potential to increase grain protein, by raising legume content of pasture and N content in soil and reducing grass weeds burdens of the subsequent crop (Palta and Peltzer 2001). Shackley *et al.* (2000) expands this further to say that the increase in grain protein is attributed to better root disease control following the removal of grasses in the preceding crop or pasture. Table 2.6 indicates the effect of weed control in the year before cropping on subsequent grain protein.

Grass weeds such as ryegrass (*Lolium spp*.), barley grass (*Hordeum leporinum*) and brome grass (*Bromus spp*.) have the potential to have the biggest effect on protein, largely attributable to their vigorous root systems and their high demand for nitrogen. Grasses have large fibrous root systems, which enable them to seek out moisture and to capture more of the mobile nutrients such as nitrogen. Grasses tend to compete for nutrients and will reduce the potential yield of the crop due to competition for nitrogen in the tillering phase and the grain protein due to competition for nitrogen during grain filling (Anderson *et al.* 1995). Table 2.7 shows the impact of grass weeds on grain protein in wheat at two levels of N. Broadleaf weeds such as wild radish (*Raphanus raphanistrum*) have a smaller effect on grain protein, but many broadleaf weeds have a taproot allowing them to access moisture and nutrients deep in the soil profile late in the season. This extra moisture would otherwise allow the grain to continue filling and take up more nutrients.

Table 2.4. Weed control in the year before cropping and its effect on grain protein.

Treatment on clover pasture in previous year	Wheat protein (%)
Nil	12.1
Broadleaf herbicide	12.1
Grass herbicide	13.4
Both herbicides	13.8

Source: Shackley 2000

Table 2.7. The effect of grass weeds on grain protein at two levels of N.

N applied (kg/ha)	Grain protein (%)
	Grass-free sites (3)
0	10
40	10.5
	Grassy sites (3)
0	8.9
40	9.3

Source: Anderson and Impiglia 2002

2.4.4 Time of Sowing

Under the Mediterranean climate of Western Australia time of sowing is dependant upon opening seasonal rains and can vary widely from year to year. The optimum time of sowing for a wheat cultivar is dependent upon maturity with the aim to have the cultivar flowering during the ‘flowering window’, the period between the time of last frost and the onset of terminal drought. Investment in sowing machinery has allowed farmers to shift the average sowing date from mid June in the late 1980's to mid May by the late 1990's. The influence of time of sowing on grain protein is discussed in further detail in Section 2.5 'Measures of Grain Quality' under management.

Time of sowing is recognised as having a significant effect on the yield and quality of wheat. Delays in sowing beyond certain critical dates can result in grain yields reducing at 50 kg/ha/day (Anderson *et al.* 1996), while grain protein can increase at 0.027%/day (Sadras *et al.* 2002). Anderson *et al.* (1995) concluded that from experiments with long season wheats in the central wheat belt of Western Australia that it is generally uneconomic to delay sowing purely to increase grain protein. A study by Flood *et al.* (1996) conducted in north-west Victoria determined that time of sowing had a significant effect on grain protein, particle size index, milling yield and test weight, however, the level of response varied. Sowing crops over an extended period appears to have little or no detrimental effect on grain quality with respect to baking properties, although there may be substantial increases in grain protein in later sown crops associated with lower yields.

2.4.5 Crop Rotations

Crop rotation is the practice of growing different crops in sequence to improve nutrient supply and soil structure and to reduce the effects of pests and disease. Wheat grown after legumes can have grain protein that exceeds that of continuous wheat by at least 2% and by as much as 5% depending on the season (Shackley 2000). By comparison, factors such as delayed sowing, applied nitrogen, cultivar and grass control may increase grain protein levels by 1-2% (Anderson *et al.* 1997). Anderson *et al*. (1995) found that wheat following a medic or field pea rotation on clay loam soils produced grain of more than 13% protein without the addition of extra nitrogen.

Short-term (1 year) legume rotations are likely to result in yield increases because of increased contribution of soil nitrogen and the disease break for the following wheat crop; however, they are unlikely to result in an increase in protein (Rowland and Perry

2000). Grain protein levels are likely to increase following long term (3 year) legume rotations because soil nitrogen levels are built up far higher than required to supply the needs of the crop and the excess nitrogen may result in higher grain protein levels (Sadras *et al.* 2002). Table 2.3 shows the contribution of various crops and pastures to N in the soil. Table 2.4 illustrates the impact of different rotations on grain protein in wheat in WA.

Table 2.6. The average contribution of various crops and pastures to N in the soil

Crop/Pasture	N
Medic	120 kg N/ha
Clover	91 kg N/ha
Field peas	98 kg N/ha
Beans	119 kg N/ha
Vetch	70 kg N/ha
Grain legume stubbles	30-50 kg N/ha
Grazed Pastures	12 kg N/t legume dry matter, 4 kg N/t grass dry matter
Green Manure	16 kg N/t legume dry matter
Cereal Stubbles	Low N content and temporary tie-up of mineral N

Source: Reuter and Dyson 1990 and Wurst and Johnson 1999

Table 2.7. The effect of different rotations on grain protein levels in wheat in WA.

Rotation	Grain Protein (%)
Medics (*Medicago* spp.)	
Continuous wheat	9.1
1 year medic: 1 year wheat	10.9
3 years medic: 1 year wheat	11.9
Field peas (*Pisum sativum*)	
Continuous wheat	8.7
Wheat: peas	10.8
Lupins (*Lupins angustifolium*)	
Continuous wheat	9.5
Wheat: lupins	10.6

Source: Mason 1987

2.5 Measures of Grain Quality

There are many measures of grain quality in wheat, this section describes those relevant to the end-uses of wheat used in the experiments in this thesis.

2.5.1 Grain Protein

Grain protein is the most important characteristic determining the market value of wheat. It is the protein contained in the flour, which, in combination with water forms a continuous network of gluten; it is the gluten which provides structure to a loaf of bread. Considerable research, discussed below, has been conducted into the variables influencing grain protein, nonetheless, substantial research is still required to understand the interactions between influencing variables.

Grain protein can be considered as both quantity (otherwise referred to as content or concentration) and quality. Grain protein *quantity* is the percentage by weight of protein in the grain, and varies between 8% and 18% of total grain dry matter. High protein is usually regarded as an indicator of high quality for bread-making. Nevertheless, quantity can be a flawed predictor of bread making ability. For example, drought conditions can stress the plant and produce grain of high protein, however, flour from this wheat can produce poor quality bread. The difference is a reflection of protein *quality* and relates primarily to variation in the relative amounts and composition of gluten proteins (Payne 1987). Different levels of protein are desirable for other wheat products such as white, salted noodles (9.5 – 11.5%) and cakes (less than 9%).

Wheat contains a number of different proteins, each of which appears at different times and in different concentrations in the development of the grain. The protein contained in an average grain of wheat is between 4-10 mg and the rate of deposition is thought to be between 0.15-0.20 mg per day (Satorre and Slafer 1999). The rate and duration of protein deposition in the grain are governed by factors of supply external to the grain (Jenner *et al.* 1991). Proteins first appear in the grain about 10 days after anthesis and are located within membrane-bound spherical bodies. Towards the end of grain filling the proteins begin to fuse, forming a continuous, highly compressed protein matrix in which the starch granules are embedded (Jenner *et al.* 1991).

Grain Protein of wheat is classified according to extractability and solubility in various solvents. The extraction of ground wheat grains results in the following protein fractions (Belderok 2000);

Albumins - which are soluble in water

Globulins - insoluble in pure water but soluble in dilute NaCl solutions, and insoluble at high NaCl concentrations

Gliadins - soluble in 70% ethyl alcohol

Glutenins - soluble in dilute acid or sodium hydroxide solutions.

Metabolic proteins (albumins and globulins) are the first to appear and constitute about 90% of the total grain protein in the first ten days of grain growth. The proportion of metabolic protein declines during grain filling and makes up 20-30% of the protein at maturity (Satorre and Slafer 1999). They are responsible for the metabolism and structure of the endosperm cells. They have little effect on the extensibility and elasticity characteristics of gluten and wheat flour dough (Simmons 1989).

Glutenins and gliadins have a significant effect on dough rheology and baking quality (Payne 1987, Weegels et al 1996). Gliadins make their first appearance 5-10 days after anthesis. Glutenins are the final protein to appear and may not appear in measurable amounts until 20 days after anthesis. At maturity gliadin and glutenin proteins represent between 60-80% of total protein (Satorre and Slafer 1999). They are storage proteins, located in the mealy endosperm and responsible for retaining gas necessary for the production of spongy baked goods (Belderok 2000). Gliadins are smaller monomeric proteins compared to glutenins. (Payne 1987; Shewry *et al.* 1992).

Glutenins are made up of about 20 polypeptide units linked by disulfide bonds and contribute significantly to the visco-elastic properties of doughs (Weegels *et al.* 1996). Glutenins form about 50% of the flour protein and can be divided into low-molecular-weight (LMW) glutenins which amount to 40% of the total, and high-molecular-weight (HMW) glutenins which make up the remaining 10% (Simmons 1989).

Low molecular weight glutenins belong to a heterogeneous group of proteins and range in molecular weights between 30 000 and 80 000 KD. They are alcohol, urea or detergent-soluble and comprise a significant part of the endosperm protein bodies. Genes controlling synthesis of LMW glutenins are located on short arms of chromosomes 1A, 1B and 1D (Simmons 1989). The number of low molecular weight sub-units present in cultivars of common wheat has not been determined (Bushuk 1998).

High molecular weight glutenins are important for dough strength and baking quality (Weegels *et al.* 1996). Their molecular weights range from 500 000 to several million KD and are due to the presence of unreduced disulfide bonds occurring between peptide chains. Genes controlling synthesis of HMW glutenins are located at three loci, one each on the long arms of chromosomes 1A, 1B and 1D (Simmons 1989). More than 30 different high molecular weight sub-units have been identified in the world wheat collection (Bushuk 1998). HMW glutenin subunits 5 + 10 and 2 + 12 in combination have been reported to be strongly correlated with superior bread-making properties (Dong *et al.* 1991; Schofield 1994) compared to other HMW glutenins.

Traditional breeding for higher grain yield and higher grain protein simultaneously is difficult due to the proposed negative relationship between the two traits (Borghi *et al.* 1997; Peterson 1992). A survey of wheat crops in South Australia, Victoria and New South Wales by Sadras *et al.* (2002) found that grain protein in wheat decreased as grain yield increased at a rate of ~1%/t.ha. However, Mesfin *et al.* (2000) examined the grain yields of 12 high protein and 12 low protein lines and although there were no significant differences they indicated that it may be possible to combine high grain protein and high grain yields in commercial lines.

Protein quality for milling is measured through effects on water absorption, strength, extensibility and stability of the dough. Water absorption is determined by the protein content of flour, the amount of damaged starch it contains and the presence of non-starch carbohydrates. It is important because flour used in bread making should have high water absorption at normal working consistencies so the yield of dough into bread is relatively high (Simmons 1989). Dough strength is an expression of gluten and depends on how much gliadin and glutenin proteins are present to form gluten. Strength measures the extensibility and toughness of dough (Cornish *et al.* 2006; Edwards *et al.* 2001). The dough strength required varies depending on end-product use; higher strength is essential for pasta (Feillet and Dexter 1996) and bread dough and lower strength for biscuit dough (Cornish *et al.* 2006). Dough stability is a measure of the dough to over mixing; it is important as it allows a long window of opportunity for bread making (Nash *et al.* 2006). Moreover, it often indicates the most appropriate end-use for wheat (Tian *et al.* 2007).

Protein quality is measured by a number of instruments; in Australia the farinograph and extensograph are used widely, France and parts of Africa use an alveograph while the mixograph is commonly used in North America (Williams 2006). The mixograph was the instrument used in the experimental stage of this study to measure protein quality. It was developed in the United States of America in 1939 as a means of studying the action of high speed commercial mixers. It measures the resistance of dough to mixing after the addition of water to flour and is a very useful tool for estimating important physical dough properties in early wheat genotypes in many breeding programs (Finney and Shogren 1972). The mixograph is capable of differentiating amongst wheats differing in strength characteristics including 'extra strong' types, from wheats of more usual dough strength for bread making purposes (Khatkar *et al.* 1996). It is also useful in testing rheological properties and predicting *al dente* quality of durum (Kovacs *et al.* 1997). Figure 2.4 is an example of the mixograms of strong, good, weak and extremely weak dough characteristics.

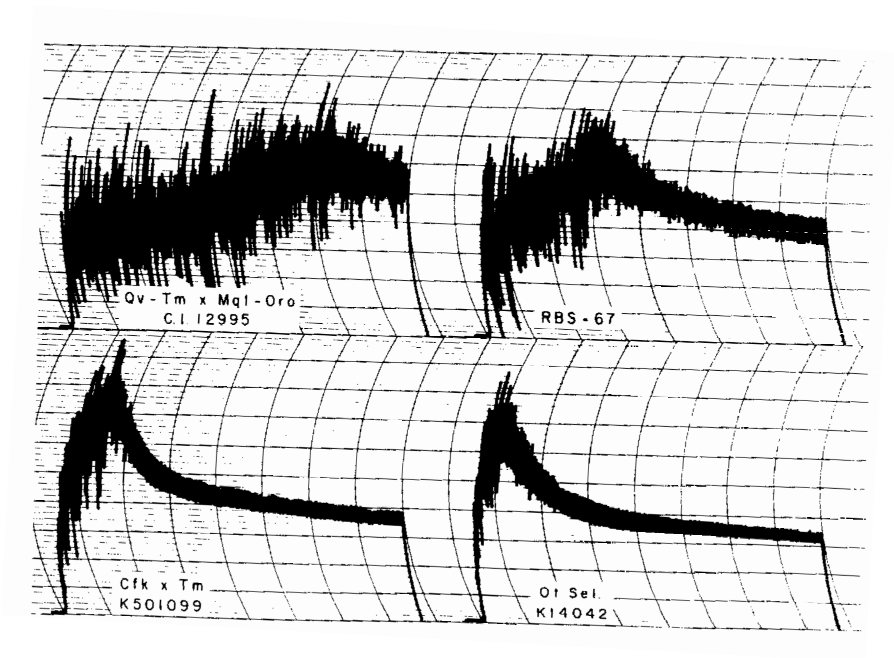

Figure 2.5. Mixograms of a hard wheat showing strong (top left), good (top right), weak (bottom left) and extremely weak (bottom right) dough characteristics. Source: Atwell 2001

2.5.2 Milling Yield

Milling yield is the most important technical and economic factor of milling and can play a major role in the buying decisions of flour mills. Milling yield is the amount of extractable flour in grain and is influenced by the percentage of starchy endosperm. Commercial milling yield varies between 72-82% by weight of grain, the remaining 18-28% consists of germ, husk, seed coat and aleurone. Measurements such as hectolitre weight and 1000 kernel weight provide some indication of endosperm content and potential milling yield (Simmons 1989). Table 2.8 indicates the factors which can influence milling yield.

Table 2.8. Factors which can influence milling yield in wheat.

• Grain size and shape	• Proportion of endosperm in the matured grain
• Embryo size	• Grain hardness
• Depth and shape of the grain crease	• Bulk density
• Thickness and density of the seed coat	• Ease and degree at which the endosperm can be separated
• Cell wall thickness in the sub-aleurone endosperm	

Source: Marshall *et al.* 1986

Cultivar effects which influence milling yield are size distribution of the starch granules (Edwards *et al.* 2001) and allele *Pinb-D1b* (Chena *et al.* 2007). Moreover, Cane *et al.* (2004) examining puroindoline genes and their effects on grain quality traits in southern Australian wheat cultivars determined that cultivars which have *Pina-D1b* have lower milling yield than cultivars which contain *Pinb-D1b*. More recently, Cane *et al.* (2008) identified that the serpin null allele located on chromosome 5B significantly reduced milling yield by approximately 0.4g of flour per 100g of grain milled across a range of different germplasm sources and flour protein levels.

Environmental conditions such as cool, moist conditions during grain fill can affect milling yield due to variations in endosperm content, shape of the grain and thickness of the bran coat. Periods of hot dry conditions during grain fill tend to produce grain which is shrivelled thus reducing milling yield (Simmons 1989). Reference material is limited, however, it may be possible that those management factors which affect hectolitre weight will also affect milling yield.

2.5.3 Alpha-Amylase Activity

Increased alpha-amylase activity causes problems in bread production from crumb discolouration to mechanical handling breakdowns (Lunn *et al.* 2001). Hagberg falling number is the grain quality measure used to assess alpha-amylase activity in wheat. A minimum falling number of 300 seconds is required for milling wheat in Australia. The technique measures changes in the viscosity of a heated suspension of flour in water that are attributable to the degree to which starch has been broken down into glucose and maltose by enzyme activity (Chamberlain *et al.* 1982; Gooding and Davies 1997). A comprehensive review by Mares and Mrva (2008) into late maturing α-amylase in wheat indicated that it is often restricted to specific cultivars and further reduced in the presence of dwarfing genes *Rht1*, *Rht2* and *Rht3.* Furthermore, its expression appears to be controlled by 1 or 2 recessive genes acting alone or in combination.

There are four types of alpha-amylase that are known to affect wheat; pre and post maturity sprouting, pre-maturity alpha-amylase and retained pericarp alpha-amylase in grains that remain green at harvest. Of these the ones which most frequently give problems are post-maturity sprouting and pre-maturity alpha-amylase activity (Kindred *et al.* 2004).

Post-maturity sprouting has a large effect on falling number. It results from grain dormancy followed by germination and occurs frequently in wet summers when harvest is delayed and the grains sprout. Similar effects are seen if wet conditions develop around the ears of lodged crops (Kindred *et al.* 2004). Pre-maturity alpha-amylase shows no visible external symptoms. It occurs mainly in the crease region of the grain, emanating from the aleurone layer around the end cavity. It appears to be triggered by temperature shock, but only if it occurs in a period of sensitivity around 25-30 days post anthesis (Mares and Mrva 2008). The causes are poorly understood but have been linked to low temperatures during grain development, slow grain drying rate, large grain size, morphology and grain cavity characteristics (Evers *et al.* 1995). Gale *et al.* (1983) suggested that alpha-amylase in non-sprouted grain was greatest when grain drying rate during grain maturation had been slowed.

Fungicides can affect alpha-amylase activity in non-sprouted grain. When fungicides extend grain filling, they can reduce the drying rate. Furthermore, it is also possible that grain temperature may also affect alpha-amylase activity by affecting seed dormancy levels. Crop temperature may be influenced by fungicides if, for example, there are different evapo-transpiration rates from diseased and non-diseased canopies (Kindred *et al.* 2004).

2.5.4 Hectolitre Weight

Hectolitre weight is one of the most widely used measures of grain quality. It is highly correlated with flour yield in milling wheats and semolina yield in durum (Sutton *et al.* 1992). Grain with higher hectolitre weight tends to have higher milling yield, however, packing characteristics and moisture content of the grain can also have an effect (Simmons 1989). Grains with low hectolitre weight due to frost, immaturity or heat stress are likely to have low milling yield and poor end-product quality.

Anderson and Sawkins (1997) from experiments conducted in Western Australia observed lighter hectolitre weight from Australian soft cultivars compared to Australian Standard White cultivars, however, no explanations were given as to why this occurred. Leaf diseases such as stripe and stem rust tend to reduce hectolitre weight (Loughman *et al.* 2005; O'Brien *et al.* 1990), however, the degree of influence depends upon the level of disease severity. Management factors such as nitrogen (Anderson and Smith 1990) and time of sowing (Anderson *et al.* 1996; Anderson and Sawkins 1997) can similarly either increase or decrease hectolitre weights.

2.5.1 Screenings

Wheat grains that pass through a 2mm slotted screen are called screenings, and their proportion in each delivery load determines payments to the growers in the Australian marketing system for wheat (Sharma and Anderson 2004). High screenings are an indicator of poor flour yield not only due to the quantity of grain removed during cleaning before milling, but are also indicative of smaller grains and lower flour yield throughout the sample (Anderson *et al.* 1997). A maximum of 5% screenings is allowed for milling wheat in Australia.

Grain size variation among cultivars has been shown to influence screenings in wheat (Anderson *et al.* 1995; Anderson *et al.* 1997). Environmental conditions such as hot, dry conditions during grain fill can reduce grain size and increase screenings in wheat (Sharma and Anderson 2004; Sofield *et al.* 1977). Management factors such as delayed time of sowing in combination with high N fertiliser rates and high plant populations can increase small grain screenings (Cranstoun and Garstang 1993). Growth regulators that promote tillering (Hashem and Wilkins 2002), high weed burden (Anderson *et al.* 1992) and potassium deficiency (Anderson *et al.* 1995) are also known to increase the levels of small grain in wheat. Increasing sowing rate has been shown not to increase screenings levels in Western Australia (Anderson and Sawkins 1997; Shackley 2000).

2.6 Stability of Grain yield and Quality

Stability of grain yield (Heinrich *et al.* 1983) and quality (Lemelin *et al.* 2005) has been defined as the ability of the cultivar to avoid large fluctuations in yield/quality over a range of environments and denotes consistency in rank relative to other cultivars in a given set of environments (Yue *et al.* 1997). Instability is commonly caused by differential expression of traits across environments or genotype-environment interactions (Romagosa and Fox 1993). Stability across a wide range of environments is important for growers, marketers and processors. Growers want stable grain yield, their biggest determinant of profit, from one year to the next. Marketers want stable grain quality thereby delivering a constant product to processors. Stability of quality for processors guarantees constant procedures and minimises losses during processing (Grausgruber et *al.* 2000). An extensive review into stability analysis in plant breeding was conducted by Becker and Léon (1988) covering a range of topics such as concepts of stability, statistical measures, estimating stability in breeding material and selection for improved stability.

There are two concepts of stability; static and dynamic. A cultivar that has static stability is defined as having an unchanged performance regardless of any variation in environmental conditions (Becker and Léon 1988). Static stability is considered desirable for quality characteristics by the milling and baking industries (Grausgruber *et al.* 2000). However, breadmaking quality of a cultivar usually reacts to favourable and unfavourable environmental conditions; therefore it is unrealistic to expect the same level of performance across all environments (Grausgruber *et al.* 2000). Dynamic (Becker and Léon 1988) or agronomic (Becker 1981) stability means that the performance of a cultivar may change from environment to environment but in a predictable way. Growers would consider dynamic stability important for management of crops for grain yield. Both concepts of stability are considered valuable but their application depends on the characteristics under investigation (Becker and Léon 1988).

Many statistical methods have been developed to measure grain yield and quality stability in wheat. These include stability variance (Shukla 1972), non-parametric variance of ranks based on corrected values (Huehn 1990) and principal components of an additive main effects and multiplicative interaction (AMMI) analysis (Gauch 1992). Greater discussion on statistical methods used to measure stability in wheat can be found in a review looking at the influence of cultivar and environment on wheat quality by Williams *et al.* (2008). One of the more widely used statistical techniques for assessing stability is regression analysis. Regression analysis was used in this study to assess cultivar stability for grain yield and quality characteristics, therefore this review will focus discussion around this method.

Regression analysis has been used since about the 1930's (Stringfield and Salter 1934; Yates and Cochran 1938) to measure the response of cultivars to varying environments and was further developed in the 1960's (Eberhart and Russell 1966; Findlay and Wilkinson 1963). The paper by Findlay and Wilkinson (1963) is one of the most cited papers describing the use of regression analysis to assess stability. Since then regression analysis has been widely used (Lukow and McVetty 1991; Peterson *et al.* 1992; Tesemma *et al.* 1998) as a means of measuring the stability of cultivars for grain yield and quality characteristics in wheat.

Outputs of regression analysis to predict adaptability of cultivars can be expressed graphically. When the individual cultivar characteristic is plotted against the average of all cultivars, the regression co-efficient (*b*-value) illustrates phenotypic stability or responsiveness of the cultivar to a range of environments. Cultivars which record b=1 display dynamic stability (Eberhart and Russell 1966). Values of b significantly >1 describe cultivars which have increasing responsiveness to environmental change (below average stability). Cultivars with b values significantly <1 display greater resistance to environmental change (above average stability) (Findlay and Wilkinson 1963). Cultivars with b=0 can be considered to have static stability (Findlay and Wilkinson 1963).

Regression analysis is commonly used in conjunction with standard deviation in cultivars means and deviations from regression. However, Peterson *et al.* (1992) assessed genotype by environment effects on quality characteristics of hard red winter wheat in the USA and concluded “genotypic differences in *b*-values were significant and regression analysis was considered effective in documenting relative stability of genotypes. The relative magnitude of standard deviations in genotype means and deviations from regression were of lesser value in characterizing stability”. This comment therefore indicates regression analysis, without being used in conjunction with standard deviation in cultivars means and deviations from regression, is a sufficiently rigorous analysis to characterise the stability of cultivars.

Regression analysis has an advantage over other statistical techniques in terms of its simplicity which allows meaningful interpretation of results, nonetheless it also has some disadvantages. These include:

1. The environmental index is not independent of data analyses because it is extracted from the whole set of data (Freeman and Perkins 1971).
2. Regression coefficients are biased because the assumption of that the independent variable, in this case the environmental mean, is measured without error could not be met (Sprent 1969).
3. Error variance found in the analysis of replicated experiments are not homogenous between sites (Skrøppa 1984).
4. Poor repeatability of *b* and the large number of environments needed for a reliable estimate (Becker and Léon 1988).

There is no correct statistical method to use when assessing stability in wheat. The concluding comments of Becker and Léon (1988) state that various multivariate methods have been develop to allow detailed analysis of cultivar by environment interactions but they will not replace the regression approach. Moreover, the sophistication of other methods, which is often regarded as their main advantage, can fail to provide any simple measure of stability which allows a ranking of cultivars.

It is foreseeable that increasing stability of grain yield and quality will become increasingly important in WA. A keynote address by Edwards (1997) to the International Wheat Quality Conference highlighted areas of change in the market requirements of wheat. One of these changes was that stability of quality will assume increased importance; not only must it be a quality product but it must be consistent quality. Furthermore, the growing impact of climate change in south west WA could possibly create even greater variability in grain yields and quality than already experienced. Therefore improving stability will help growers, marketers and processors alike by reducing large variations in yield and quality often experienced in the variable Mediterranean-type climate of south west WA.

2.7 Summary

Cultivar by environment interaction in wheat is a complex problem. Significant resources have been invested to determine the effects of this interaction on grain quality; nonetheless, reports are often conflicting. Genetic factors such as protein fractions (in particular the high and low molecular weight glutenins), disease resistance and size distribution of starch granules have been shown to affect grain quality. Similarly, environmental factors such as high temperatures and moisture conditions during grain fill have also been reported as affecting quality. However, the effects of management are often overlooked, thereby possibly leading to the conflicting reports.

This review has described many management practices which have an influence on quality. Perhaps the greatest influence is the impact of nutrition on grain protein, the single most important quality characteristic in wheat. It is likely that a grower in WA who fails to apply adequate nutrition will not achieve the minimum grain protein standards required for premium wheat classifications. Future cultivar by environment studies should therefore consider management as a main effect and not simply discount its effect on results.

Chapter 3

Influence of cultivar, environment and nutrition management on grain yield and quality in wheat.

This thesis chapter has been prepared as a manuscript to be submitted to Crop and Pasture Science

3. Chapter 3

3.1 Abstract.

Wheat production in the high rainfall zone (HRZ) of Western Australia (WA), a traditional grazing area, has expanded since the fall in wool prices that occurred in the early 1990's. The yield of the grain produced has not approached the levels that can be expected on the basis of average rainfall and the grain quality has often fallen below the standard required for milling. The aim of this research was to examine the extent to which it is possible to raise the yield of wheat to the level set by the seasonal rainfall each year at the level of grain protein that will attract a price premium. A series of identical experiments were conducted between 2005 and 2007 in the HRZ of the WA wheat belt to examine the influence of cultivar, environment and nutrition management on grain yield and quality in wheat. Eight cultivars of wheat, six bread (Triticum aestivum) and two durum (T. turgidum var durum), were grown at three levels of increasing nutrition; 'control', 'grower' and 'researcher', chosen to simulate low, medium and high fertilizer rates that growers use in the HRZ in WA. The main effects of cultivar, environment and management were statistically significant for all variables measured; interactions were significant but relatively small in magnitude.

The WA wheat belt is influenced by a variable Mediterranean-type climate and consists of soils which are old, low in nutrients and have low water holding capacity. This study reports that environment (site.year) was the largest source of variation for grain yield and all quality traits except grain protein. Management (i.e. nutrition) was the greatest source of variation for grain protein and was the second greatest source of variation for grain yield and other quality traits. By contrast, cultivar was responsible for only a small amount of the variation for grain yield and physical grain quality characteristics. This study has also demonstrated that provided the appropriate nutrition management is adopted the minimum grain protein for premium paying grades of wheat can be successfully achieved in the HRZ of WA.

Additional keywords: genotype x environment x management, wheat quality, high rainfall zone

3.2 Introduction (as per literature review)

Wheat in WA is typically grown under a Mediterranean-type environment with cool, wet winters and hot, dry summers, on soils that are old, highly weathered, with low exchangeable nutrients and poor plant available water-holding capacity (Anderson et al. 2005). Traditionally wheat in WA has been grown in low to medium rainfall areas with annual rainfall between 300-450 mm. However, it has been recognized that there is considerable potential for annual crop production in the HRZ of WA where annual rainfall varies between 450 and 800mm (Poole et al. 2002). In addition to higher rainfall the HRZ has longer and cooler growing seasons and a longer period of frost risk compared to more traditional wheat belt areas (Zhang et al. 2006). Significant research has been undertaken in the HRZ of WA in an effort to increase grain yield (Anderson and Smith 1990; Hill and Wallwork 2002; Zhang et al. 2004a). Limited research has been conducted to investigate the effects of cultivar, environment and nutrition management on grain quality characteristics in the HRZ.

Panozzo and Eagles (1998) defined quality as the ability of the grain to meet the requirements of the processor; achieving necessary quality requirements depends upon the cultivar and the environment in which it is grown. Cultivar x environment interaction in wheat is a complex problem, in which wheat breeding organisations have invested heavily. A review conducted by Basford and Cooper (1998) into the effect of cultivar x environment interactions within the Australian wheat industry concluded that there is a clear understanding of the contribution to grain yield of a number of traits. More recently a review by Williams et al. (2008) on the effects of cultivar by environment on wheat quality concluded that in Australia, cultivar and environment have similar rankings across the country for protein quality, dough rheology and starch quality, while there was a relative lack of cultivar by environment interaction.

Cultivar refers to the set of genes possessed by individual genotypes that are important for the expression of the trait(s) under investigation (Basford and Cooper 1998). Cultivar is commonly described as the single most important determinant of most traits that contribute to grain quality (Souza et al. 2004) in rainfed wheat. Environment can be defined as a set of biophysical factors (e.g. water and temperature) that influence growth and development of the individuals thereby influencing the expression of the trait(s) (Basford and Cooper 1998). Environmental conditions such as growing season temperature (Johnson et al. 1972), temperature during grain fill (Randall and Moss 1990), distribution of precipitation (Faridi and Finley 1989), late season frosts (Lookhart and Finney 1984) and duration of grain fill (Johnson and

Mattern 1987) are all known to influence wheat quality. Lukow and McVetty (1991) in Canada considered environment to be the most important factor influencing wheat quality characteristics.

Unfortunately, the effects of management are often overlooked in cultivar by environment studies due to it being included as part of the environment term and standardized across experiments. This practice hides the influence of management and the possible interaction of cultivar and management (Anderson *et al.* 2005). Management can be defined as practices, techniques or options available to growers to influence the growth and development of the crop and the expression of the quality trait(s). Management techniques such as the rate and timing of nitrogen applications (Shackley 2000), rotation (Evans *et al*. 2003), weeds (Shackley 2000), disease control (Reuter and Dyson 1990) and time of sowing (Sadras *et al.* 2002) have all been shown to influence grain protein, the single most important quality characteristic in wheat.

This paper analyses the contributions of cultivar, environment and nutrition management to variance of grain yield and selected grain quality characteristics; the aim is to evaluate the potential to achieve the dual goals of both yield and quality improvement in the HRZ of WA. Unlike many other studies management has been assessed independently of environment. Other chapters explore the influence of cultivar, environment and nutrition management on milling yield and protein quality (Chapter 4) and the stability of grain yield and grain quality in relation to site and season in the HRZ of WA (Chapter 5).

3.3 Materials and methods

3.3.1 Experimental sites

Identical field experiments were conducted at two sites close to the towns of Moora and Williams, in 2005, 2006 and 2007 in the HRZ of the WA wheat belt (Figure 3.1). Moora and Williams were chosen as contrasting rainfall and temperature environments within the HRZ of the WA wheat belt; typically higher temperature and lower rainfall are recorded in Moora. Rainfall and temperature data were used from nearby town sites (Table 3.1 and Figure 3.2). Soil samples (0-10 cm) were collected prior to sowing at each site and year and analysed for macro-nutrients, organic carbon and pH (Table 3.1); the soils at Moora are classified as kandosols while those at Williams are chromosols (Isbell 2002). The Moora site (30°59′S, 115°08′E) was located on the same property in 2006 and 2007, which is approximately 15 km south of the 2005 site. The site was moved due to the dry start to the growing season in 2006 (Figure 3.2). The Williams experimental site (33°01′S, 116°52′E) was located on the same property over the life of the study. Experiments were located in paddocks which had a leguminous pasture (*Trifolium subterraneum L.*) or crop (*Lupinus angustifolius L.*) the previous year.

Trial sites within a paddock were chosen on the advice of the grower. Trials were located in areas of the paddock which had a uniform soil type, were free from sub-soil constraints and were unlikely to have had undue influence from the effects of paddock management e.g. headlands which may have received extra nutrition or have higher weed burdens. The range of natural fertility across paddocks was not sampled due to financial constraints, however, paddocks which were chosen had soil types typical of the environment and have been used for commercial crop production. Soil fertility at each trial site in each year was sampled using a variation of the procedure described in “Australian Soil Fertility Manual’ (2006 p81). Individual soil cores (15-20) were taken in a W formation across the trial site with a composite then sent for analysis. Further information on trial management, design and layout are detailed in the Appendices.

Table 3.1. Plot size, sowing date, rainfall, temperature and soil analysis for the experimental sites at Moora and Williams in 2005, 2006 and 2007.

			Plot Sizes			Rainfall*		Temperature**		Soil Properties					
Location	Year	Environment Code	Length	Width	Sowing Date	GSR[a]	TR[b]	GSMIN[c]	GSMAX[d]	N[e]	P[f]	K[f]	S	OC[g]	pH
			m			mm		℃		mg/kg				%	$CaCl_2$
Moora	2005	M05	18	2.5	14 June 2005	465	501	7.1	19.8	23	13	26	3.3	0.81	5.2
	2006	M06	18	1.6	29 June 2006	178	407	8.1	21.6	33	30	31	4.6	1.06	6.7
	2007	M07	22	1.6	13 June 2007	246	406	8.8	20.2	33	38	40	35	1.78	5.4
Moora Long Term Average						367	460	8.1	19.9						
Williams	2005	W05	18	2.5	12 June 2005	416	510	6.6	17	49	55	72	11	3.08	5.3
	2006	W06	18	1.6	9 June 2006	201	342	6.1	18.8	33	33	79	10	3.46	5.0
	2007	W07	18	1.6	12 June 2007	361	463	5.5	18.1	20	69	114	7.7	4.01	5.0
Williams Long Term Average						432	540	6.8	17.2						

[a]Growing Season (May-October) Rainfall, [b]Total Yearly Rainfall, [c]Mean Growing Season Minimum Temperature, [d]Mean Growing Season Maximum Temperature, [e]Nitrate+Ammonium, [f]Measured using the Colwell method (Colwell 1963), [g]Organic Carbon, *Rainfall records taken from the towns of Moora and Williams, **Temperature records taken from the towns of Badgingarra and Wandering

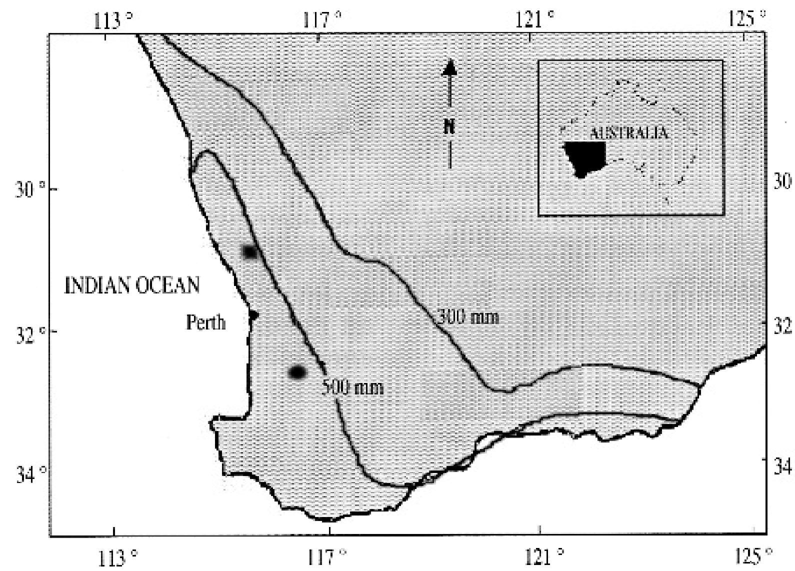

Figure 3.1. Location of experimental sites Moora (■) and Williams (●) in the HRZ of south west Western Australia in 2005, 2006 and 2007. Adapted from Gunasekera *et al.* 2006.

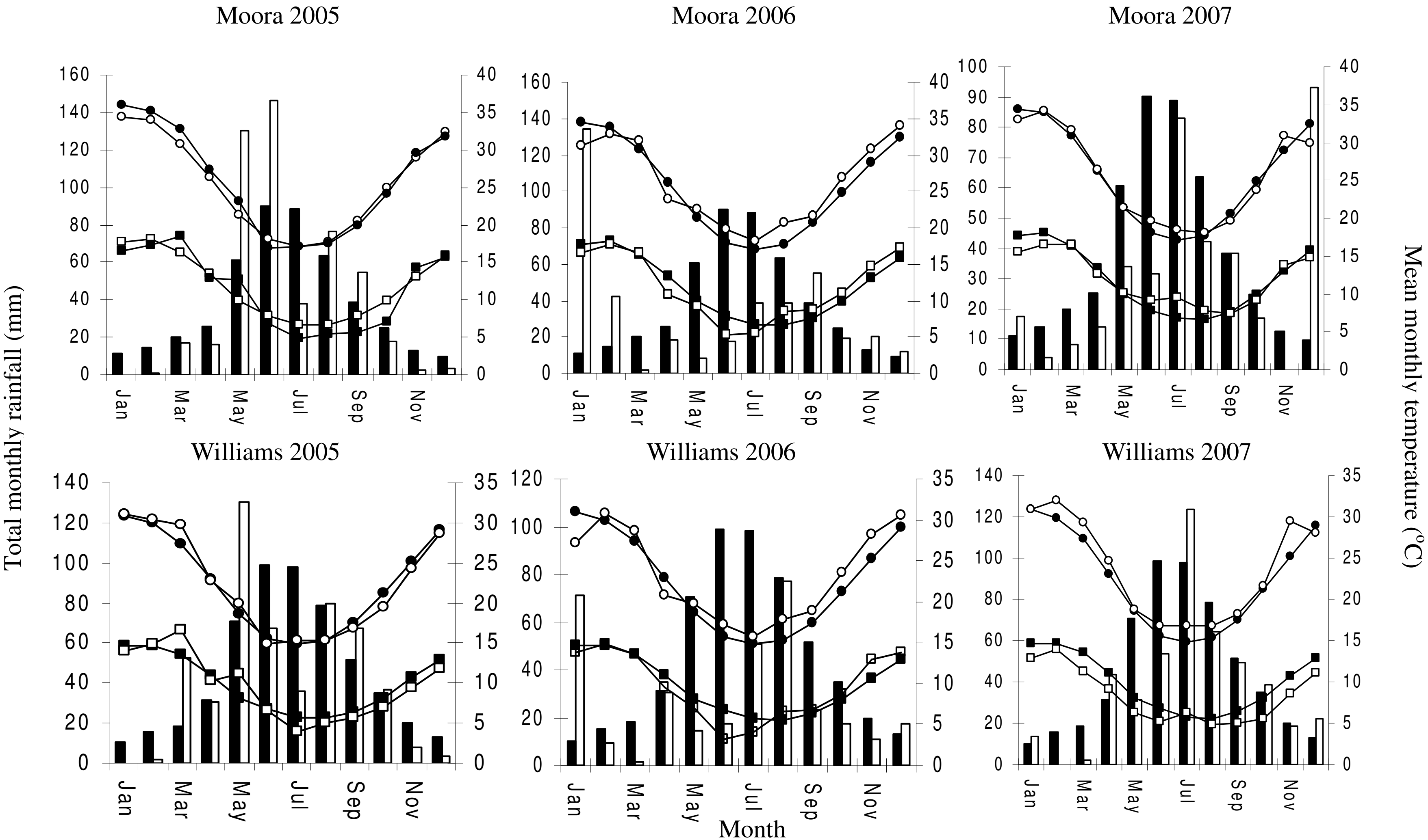

Figure 3.2. Total monthly rainfall (open histogram), long-term average total monthly rainfall (solid histogram), mean monthly maximum temperature (○), long-term mean maximum temperature (●), mean monthly minimum temperature (■) and long-term mean minimum temperature (□) at Moora and Williams in 2005, 2006 and 2007.

3.3.2 Cultivars and seed

Eight wheat cultivars, six bread and two durum, were used. Cultivars were selected based on commercial quality classification, pedigree and breeding organisation in an effort to achieve genetic diversity within the commercially available range in Australia. Despite this, three of the cultivars Lang, Sunvale and GBA Sapphire have many genes in common because they are from the same family. The cultivars, quality classification, year of registration, origin and pedigree, are outlined in Table 3.2. Bread wheat cultivars were sown at 75 kg/ha and durum wheat 100 kg/ha; in 2006 and 2007 sowing rate for durum cultivars was increased to 110 kg/ha. Seed rates were adjusted to account for differences in seed size between bread and durum wheat cultivars.

3.3.3 Management

Nutrition treatments were based on three regimes: 'control', 'grower' and 'researcher' (Table 3.3). Treatments were chosen to simulate low, medium and high fertiliser rates that growers in the HRZ use (Hill *et al*. 2007). Basal fertiliser was superphosphate with added copper, zinc and molybdenum (P 9.0, S 10.1, Ca 19.0, Cu 0.60, Zn 0.30, Mo 0.06 w/w %) which was drilled approximately 2 cm below the seed at sowing. Nitrogen (Urea N 46 w/w %) was applied at three strategic times; immediately before sowing (IBS), four weeks after sowing (4WAS) (approximately growth stage Z13-14, Zadoks *et al.* 1974) and eight weeks after sowing (8WAS Z30-31). Muriate of Potash (K 49.5 w/w %) was top dressed IBS at 100 kg/ha. Weeds, insects and diseases were controlled throughout the growing season as required.

Table 3.2. Cultivar, quality classification, year of registration, origin and pedigree of the cultivars used in experiments at Moora and Williams in 2005, 2006 and 2007.

Cultivar	Quality Classification	Year of Registration	Origin	Pedigree
Lang[e]	APH[a]	1999	LRC[1]	QT3765/Sunco
Sunvale[e]	APH	1996	SU[2]	Cook*2/VPM1//3*Cook
Carnamah	AH[b]	1996	WADA[3]	Bolsena/1CH//77W:660
GBA Sapphire[f]	AH	2003	GBA[4]	Janz/AUS24133//2*Janz
Wyalkatchem	APW[c]	2001	WADA	Machete/84W129-504
Stiletto	APW	1993	RAC[5]	Veranopolis/3*Spear/3/Dagger
Kalka	APDR[d]	2003	AGT[6]	Wollaroi*(Linghzi*Yallaroi#)*RH88000
Wollaroi	APDR	1993	NSW DPI[7]	Guillemont Seln No.3/Kamilaroi Sib

[a]APH - Australian Prime Hard- used for the production of Chinese style yellow noodles and Japanese Ramen noodles and is often blended with lower protein wheat to produce flours suitable for a range of baked products, [b]AH - Australian Hard - Middle Eastern flat breads and Chinese steamed noodles, [c]APW - Australian Premium White - Asian Noodles, Middle Eastern and Indian style bread and Chinese steamed breads, [d]APDR - Australian Premium Durum - wet and dry pasta products, [e]Western Australia does not have an APH classification, these cultivars must be delivered to AH, [f]GBA Sapphire has an APH classification in Queensland and New South Wales. [1]LRC- Leslie Research Centre, Queensland; [2]SU- Sydney University; [3]DAFWA- Department of Agriculture and Food Western Australia; [4]GBA- Grain Biotech Australia; [5]RAC- Roseworthy Agricultural College, [6]AGT- Australian Grain Technologies, [7]NSW DPI – New South Wales Department of Primary Industries.

Table 3.3. Amount of basal fertiliser (kg/ha) and amount and timing of nitrogen (kg N/ha) per management regime at Moora and Williams in 2005, 2006 and 2007.

Basal Fertilizer	Control	Grower Average			Researcher		
Super Cu, Zn, Mo	100	150			200		
		Timing and Rate of N					
Protein Target (%)		*IBS*[a]	*4 WAS*[b]	*8 WAS*[c]	*IBS*	*4 WAS*	*8 WAS*
APH[dgij]	0	25	25	25	50	50	75
AH[ehij]	0	25	50		50	50	75
APW[fhij]	0	25	50		50	50	50
APDR[dhij]	0	25	25	25	50	50	75

[a]Immediately Before Sowing, [b]4 Weeks After Sowing, [c]8 Weeks After Sowing, [d]Minimum grain protein content 13%, [e]Minimum grain protein content 11.5%, [f]Minimum grain protein content 10.5%, [g]Minimum Hagberg falling number 350 seconds, [h]Minimum Hagberg falling number 300 seconds, [i]Maximum screenings 5%, [j]Minimum test weight 74 kg/hl.

3.3.4 Experimental design and Statistical Analysis

A randomised block design with three replicates (the Williams experiment in 2006 had four replicates) was used in all experiments. Plot sizes are shown in Table 3.1. A combined analysis of variance (ANOVA) was performed across sites and years. Least significant differences values were calculated at the 95% probability level. All analyses were conducted using the GENSTAT (version 9) (VSN International, Herts, UK) statistical software package. The contribution to variance as a percentage was estimated by dividing the sum of squares for each variance component by the total sum of squares.

3.3.5 Measurements

At maturity the grain was harvested with a plot harvester, weighed and 2 kg was retained for quality analysis. Grain protein percentage (grain % N x 5.7) at 11% moisture was determined by near infrared reflectance spectroscopy. Screenings were determined by shaking 0.5 L of grain from each plot for 40 shakes using a mechanical shaker fitted with a 2 mm slotted screen. The screenings were visually separated into whole and broken grains and % screenings calculated on the basis of whole grain only. Prior to further measurements being taken the entire sample retained at harvest was cleaned using a Carter Day Dockage Tester (Kenkel and Anderson 2004) to remove unmillable material (whiteheads, chaff and weed seeds). Thousand seed weight (g) was determined from a 200-grain sample. Test weight (kg/hl) was obtained using a chondrometer. Hagberg falling number was measured according to method AACC 56-81B (American Association of Cereal Chemists 2000).

3.4 Results

3.4.1 Climate and soil characteristics

The six environments tested in these experiments produced a range of growing conditions as shown in Table 3.1 and Figure 3.2. 2005 was the only year where above average rainfall was recorded at both sites. At Moora 130 mm was recorded in May and 146mm in June compared to the long-term average of 61 mm and 90 mm, respectively. At Williams 130 mm was recorded in May compared to the long-term average of 71 mm. Well above average rainfall during May for both sites resulted in delayed sowing past the optimal time for the cultivars tested in this study. At both sites in 2006 well below average rainfall was recorded during vegetative growth stage; Moora recorded above average rainfall during grain fill. Moora recorded 134 mm in January, well above the long-term average of 11 mm. Sowing at the Moora site in 2006 was delayed due to the exceptionally dry start to the growing season. 2007 was also a relatively dry year; both sites recorded below average rainfall during vegetative growth.

Growing season minimum and maximum temperatures were calculated for Moora and Williams. The temperatures during the growing season were considerably warmer at Moora compared to Williams and this range is considered representative of the warmer and cooler parts of the HRZ in WA. In the 2006 growing season the maximum temperature during grain fill was slightly elevated above average at both sites. Despite the best efforts to choose sites of similar nutrition, the sites at Williams tended to have higher levels of nutrition compared to the sites at Moora (Table 3.1).

3.4.2 Contribution to Variance

Cultivar, environment and management all had significant effects on the variables measured in this study; interactions were statistically significant but the percentage contribution to variance was small compared to the main effects (Table 3.4). The combination of year, site and environment (year.site) was the most important determinant of grain yield and quality traits, except grain protein. The total contribution of year, site and environment (year.site) varied from 45% for grain protein up to 90% for grain yield, screenings and Hagberg falling number. Of these, site was the predominant component of environmental variability for grain yield (50%), 1000 seed weight (63%), screenings (65%), test weight (70%) and Hagberg falling number (76%). Management was largely responsible for the variation in grain protein (48%) and was consistently the second most important source of variance for grain yield (6%) and other quality traits. Cultivar was responsible for only 2% of the total variation for grain yield and grain protein and up to 6% for 1000 seed weight (Table 3.4).

3.4.3 Environment

The effects of year, site and environment (year.site) across all cultivars and management practices are shown in Table 3.5. Grain yield was higher at Williams but grain protein was higher at Moora. Year and site both had highly significant effects on grain yield. For 1000 seed weight, screenings, test weight and Hagberg falling number a similar trend showed differences between sites were larger than differences between years at each site. Differences between years and sites for grain protein were similar.

3.4.4 Management

The effects of nutrition management across cultivars, years, sites and environment (year.site) are shown in Table 3.6. Grain yield and quality traits all showed a response to increasing levels of nutrition. At the ‘researcher’ level average grain yield was 2.6 t/ha and grain protein was 12.9%.

As management increased from ‘control’ to ‘grower’ a large increase in both grain yield (23%) and grain protein (14%) was recorded. As management increased from ‘grower’ to ‘researcher’ grain yields began to plateau (6% increase) and the extra nutrition continued to contribute to an increase in grain protein (14%). Figure 3.3 represents the generalised response of grain yield and grain protein to nutrition management. However, the magnitude of these responses to management was influenced by cultivar (Table 3.7). For example, the grain yield of GBA Sapphire and Wyalkatchem increased most and their protein percentage increased less than the other cultivars.

Table 3.4. Significance (sig) and percentage of total variance for each source of variation (%) for grain yield, grain protein, 1000 seed weight, screenings, specific weight and Hagberg falling number for experiments grown at Moora and Williams in 2005, 2006 and 2007.

Source of variation	d.f.	Grain Yield sig	Grain Yield %	Grain Protein sig	Grain Protein %	1000 Seed Weight sig	1000 Seed Weight %	Screenings sig	Screenings %	Test Weight sig	Test Weight %	Hagberg Falling Number sig	Hagberg Falling Number %
C	7	***	2	***	2	***	6	***	1	***	1	***	2
M	2	***	6	***	48	***	4	***	3	***	7	***	4
Y	2	***	14	***	11	***	16	***	8	***	8	***	6
S	1	***	50	***	26	***	63	***	65	***	70	***	76
E	2	***	25	***	8	***	7	***	17	***	9	***	8
C x M	14	**	0	***	0	NS	0	*	0	NS	0	***	0
C x Y	14	***	0	***	0	***	1	***	0	***	1	***	1
C x S	7	***	0	**	0	***	0	***	2	***	1	***	1
C x E	14	*	0	***	0	***	0	***	0	***	0	***	1
M x Y	4	***	1	***	3	NS	0	***	0	***	1	NS	0
M x S	2	***	0	***	0	NS	0	***	2	***	1	*	0
M x E	4	***	0	***	1	***	1	***	1	**	0	NS	0
C x M x Y	28	*	0	***	0	NS	0	*	0	NS	0	*	0
C x M x S	14	NS	0	*	0	*	0	NS	0	NS	0	NS	0
C x M x E	28	NS	0	*	0	NS	0	*	0	NS	0	NS	0
Y x S x R	13	***	0	*	0	*	0	***	0	***	0	**	0
Residual	299		0		0		0		0		0		0
Total	455												

*,**,*** Significant at P = 0.05, P = 0.01 and P = 0.001, respectively. C=Cultivar; M=Management; S=Site; Y=Year; E=Environment (site.year) R=Replicate

Table 3.5. Effect of year, site and environment on grain yield, grain protein, 1000 seed weight, screenings, test weight and Hagberg falling number in wheat grown at Moora and Williams in 2005, 2006 and 2007.

	Grain Yield[A]	Grain Protein[B]	1000 Seed Weight[C]	Screenings[B]	Test Weight[D]	Hagberg Falling Number[E]
2005	2.2	11.6	33.6	3.8	79.4	429
2006	2.0	12.0	35.3	5.4	81.0	408
2007	2.9	10.6	39.0	2.2	81.0	412
l.s.d	0.1	0.1	0.5	0.3	0.1	4
Moora	1.8	12.1	32.7	6.7	78.7	439
Williams	2.8	10.8	38.8	1.3	82.1	395
l.s.d	0.0	0.1	0.4	0.2	0.1	3
M05	1.4	12.1	31.0	6.2	78.7	441
M06	2.2	13.3	29.6	11.0	77.9	448
M07	1.9	10.7	37.6	2.5	79.5	430
W05	3.0	11.1	36.3	1.4	80.0	417
W06	1.9	10.9	39.5	1.1	83.4	378
W07	3.8	10.6	40.4	1.8	82.5	395
l.s.d*	0.1	0.1	0.7	0.4	0.4	5

*l.s.d P = 0.05, [A]=t/ha, [B]=%, [C]=g, [D]=kg/hl, [E]=seconds

Table 3.6. Effect of management on mean grain yield, grain protein, 1000 seed weight, screenings, test weight and Hagberg falling number in wheat grown at Moora and Williams in 2005, 2006 and 2007.

	Grain Yield^{A}	Grain Protein^{B}	1000 Seed Weight^{C}	Screenings^{B}	Test Weight^{D}	Hagberg Falling Number^{E}
Control	2.0	10.0	37.3	3.0	81.4	407
Grower	2.4	11.4	35.8	3.7	80.6	418
Researcher	2.6	12.9	34.7	4.9	79.6	424
l.s.d*	0.1	0.1	0.5	0.3	0.3	4

*l.s.d P = 0.05, ^{A}=t/ha, ^{B}=%, ^{C}=g, ^{D}=kg/hl, ^{E}=seconds

Table 3.7. Mean cultivar x management response for grain yield, grain protein, 1000 seed weight, screenings, test weight and Hagberg falling number at Moora and Williams in 2005, 2006 and 2007.

	Management	Grain Yield[A]	Grain Protein[B]	1000 Seed Weight[C]	Screenings[B]	Test Weight[D]	Hagberg Falling Number[E]
Lang	**Control**	1.90	10.3	33.8	3.8	81.9	412
	Grower	2.50	11.6	32.6	4.6	80.9	423
	Researcher	2.55	13.3	30.2	6.5	79.9	428
Sunvale	**Control**	1.85	10.2	33.9	3.3	81.8	419
	Grower	2.25	11.6	33.0	4.4	80.6	430
	Researcher	2.46	13.2	32.2	5.1	79.8	433
Carnamah	**Control**	2.28	9.5	38.5	2.9	80.9	413
	Grower	2.81	10.7	36.7	3.0	79.9	422
	Researcher	2.76	12.7	35.4	4.5	78.4	424
Sapphire	**Control**	2.08	9.8	34.4	3.8	82.3	405
	Grower	2.48	11.1	33.9	5.1	80.9	419
	Researcher	2.82	12.4	32.8	6.6	80.4	430
Stiletto	**Control**	2.28	9.5	41.0	2.8	80.5	381
	Grower	2.66	11.0	38.2	3.9	80.6	409
	Researcher	2.86	12.6	37.4	4.8	79.5	425
Wyalkatchem	**Control**	2.21	9.7	41.2	1.5	82.2	411
	Grower	2.76	10.8	39.3	1.6	81.5	418
	Researcher	3.04	11.9	38.6	1.9	80.8	424
Kalka	**Control**	1.69	10.2	38.5	2.8	81.1	397
	Grower	2.00	12.1	36.2	3.8	79.8	398
	Researcher	2.08	13.9	35.5	4.6	78.9	396
Wollaroi	**Control**	1.65	10.5	37.4	2.9	80.5	416
	Grower	2.07	12.1	36.3	3.5	80.2	422
	Researcher	2.18	13.5	35.4	5.0	78.6	427
l.s.d		0.16	0.2	1.5	0.8	0.8	10

*l.s.d P = 0.05, [A]=t/ha, [B]=%, [C]=g, [D]=kg/hl, [E]=seconds

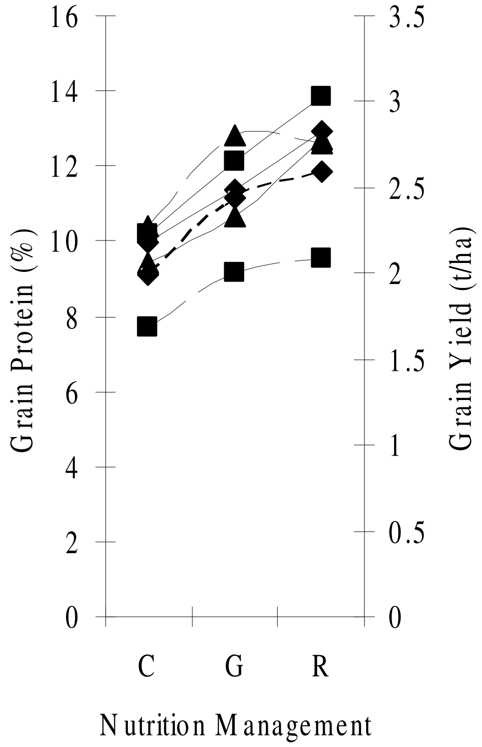

Figure 3.3. Average response of Carnamah (▲), Kalka (■) and the average of all eight cultivars (♦) for grain yield (---) and grain protein (—) at three levels of management; control (C), grower (G) and researcher (R) at Moora and Williams in 2005, 2006 and 2007.

It was also clear that as nutrition was increased screenings and Hagberg falling number also increased, while 1000 seed weight and test weight decreased. The magnitude of the response to management was also influenced by cultivar (Table 3.7) with the increase in screenings of Wyalkatchem being relatively small for example, and the decrease in test weight of Stiletto being relatively large at the higher level of nutrition. The response of cultivars to management also indicates that provided the appropriate level of nutrition is adopted minimum grain protein levels for premium-paying grades can be achieved in the HRZ of WA. Both APH and durum cultivars, at the 'researcher' level of nutrition achieved grain protein in excess of 13%. Similarly, regardless of the level of management all cultivars met the minimum commercial classification specifications for test weight and Hagberg falling number. The level of screenings for some cultivars at the 'researcher' level was above the maximum 5% permitted (Table 3.7).

3.4.5 Environment x Management

Actual grain yields were compared to the potential grain yield calculated by the empirical method of French and Schultz (1984) (Table 3.8). These calculations used an average water loss of 110 mm and a water use efficiency of 20 kg/ha.mm of rainfall in the growing season. In 2005 when the seasonal rainfall exceeded 400 mm, actual grain yield results were between 14-23% of potential. This probably indicates that losses of water were greater than 110 mm in 2005 and were probably in the vicinity of 150 mm as indicated by Zhang *et al.* (2004a). Water losses were perhaps higher due to higher leaching as a result of well above average May and June rainfall (Figure 3.2).

In the driest year of 2006 the actual grain yields were greater than the calculated potential, possibly indicating that water losses were less than the model average of 110 mm. At Moora in 2006 actual grain yields were 155-180% of potential depending upon management regime. Growing season rainfall at Moora in 2006 was well below average, however, total rainfall approached the long term average (Table 3.1); of this, January rainfall (Figure 3.2) was well above average and stored soil moisture probably made a significant contribution to grain yield and distorted the French and Schultz (1984) potential yield calculation.

As the level of nutrition increased the actual grain yield was closer to the potential yield (Table 3.8). For bread wheat cultivars alone, the gap between actual and potential grain yield was further reduced; over the six environments, bread wheat cultivars at the ‘researcher’ level achieved 91% of potential. Further analysis of the results using two cultivars with specific adaptation to the WA environment, Carnamah and Wyalkatchem, indicated that with locally adapted cultivars and adequate levels of nutrition, the grain yield was close to the theoretical potential. Wyalkatchem at the ‘researcher’ level achieved 103% of potential or 20.6 kg of grain per effective mm of growing season rainfall. Similarly, Carnamah at the ‘grower’ level, achieved grain yields which were 94% of potential or 18.8 kg of grain per effective mm of rainfall (Table 3.9).

Table 3.8. Growing season rainfall (GSR), potential grain yield (PY) based on French and Schultz (1984), actual grain yield and actual grain yield as a percentage of potential yield for bread wheat cultivars only (% PY B) for each level of management at Moora and Williams in 2005, 2006 and 2007.

Environment	GSR	PY (t/ha)	Control (t/ha)	% PY B	Grower (t/ha)	% PY B	Researcher (t/ha)	% PY B
Moora 2005	465	7.1	0.99	15	1.51	23	1.66	25
Moora 2006	178	1.4	2.03	155	2.33	180	2.16	168
Moora 2007	246	2.7	1.60	61	2.02	78	2.14	83
Williams 2005	416	6.1	2.86	50	3.01	52	3.23	57
Williams 2006	201	1.8	1.53	88	1.80	105	2.04	119
Williams 2007	361	5.0	3.06	64	4.08	86	4.39	91
Mean	311	4.0	2.01	72	2.46	87	2.60	91

Table 3.9. Percentage (%) of actual grain yield measured against potential grain yield for Carnamah and Wyalkatchem at control, grower and researcher levels of management.

		Williams	Moora	Mean
Carnamah	Control	71	86	78
	Grower	81	108	94
	Researcher	85	91	88
Wyalkatchem	Control	69	89	79
	Grower	88	99	93
	Researcher	96	110	103

3.5 Discussion

3.5.1 Production in the HRZ

A review by Zhang *et al.* (2006) into crop production in the HRZ of southern Australia concluded that average potential grain yield for wheat at Kojonup (approximately 100 km south of Williams) in WA is 5.7 t/ha. In this study, the maximum grain yield achieved by a single treatment was 5.06 t/ha by GBA Sapphire at the 'researcher' level, at the Williams site in 2007. Hill *et al.* (2007) estimated that in order to achieve grain yields over 5 t/ha growers need to apply 150 kg/ha N, 50 kg/ha P, 50 kg/ha K and 23 kg/ha S. In this study under the 'researcher' regime, nutrition levels were between 150-175 kg/ha N, 18 kg/ha P, 20.1 kg/ha S and 49.5 kg/ha K. With the exception of P, nutrition levels in this study were close to the levels anticipated for high production.

Hill *et al*. (2007) used experimental sites further south in the HRZ of WA and concluded that in environments with up to 350 mm GSR, extra nutrition could lift grain yields to potential levels. However, in wetter environments (>500mm GSR) extra nutrition by itself was not sufficient to reach water limited potential yields. Hill *et al.* (2007) indicated that further research is still needed to clarify factors limiting production when GSR is >500 mm. Nonetheless factors such as water-logging, nitrogen leaching or rainfall at inappropriate times to optimise grain yield may be restricting yield when GSR is >500 mm. The results of this study are similar; in environments which received 350 mm GSR or less, under the 'researcher' regime, two of the three environments recorded grain yield >88% of potential yield as assessed by the criteria of French and Schultz (1984) (Table 3.8).

All the cultivars achieved targeted grain protein levels when 'researcher' levels of nutrition were supplied (Table 3.7). Similarly, test weight and Hagberg falling number were above the minimum required for targeted quality grades. Screenings results were mixed; at the 'researcher' level screenings levels for all cultivars other than Wyalkatchem came close to or exceeded the maximum commercial limit of 5%. Grain can be graded for a small cost prior to delivery to reduce screenings levels but the impact of increased nutrition on screenings must be considered when targeting premium quality classifications in the HRZ.

3.5.2 Cultivar x Environment x Management

This study has demonstrated that it is possible to approach the rainfall-limited grain yield of wheat in the HRZ of WA by appropriate nutrition management and choice of cultivar for the environment. Environment (year, site and year.site) was the predominant source of variation for grain yield and all quality characteristics except grain protein. Sharma *et al.* (2008) also demonstrated that environment (70%) was the principal source of variation in grain yield in a study of cultivar by environment by management. Similarly, Fox *et al.* (1981) in a study of genotype by environment in WA concluded that environment was responsible for 81% to 96% of variation for grain yield. Ma *et al.* (2004) in Canada and Souza *et al.* (2004) in the USA in cultivar by environment by nutrition management studies have also highlighted the significant contribution of environment to variation in grain yield.

A recent study by Anderson *et al.* (pers comm. – manuscript is under review by Crop and Pasture Science) examined the variability of cultivar response to nitrogen and seed rates in Western Australia. Twenty-two field experiments were conducted over three years to determine the response of current and recently released cultivars to seed rate (SR) and N fertilizer (N). Three cultivars were common between this study and Anderson *et al.* (pers comm.) Carnamah, GBA Sapphire and Wyalkatchem. A cross-site analysis was used to determine variance components where E (site.year) was considered as a random effect and G, N and SR were treated as fixed effects.

The results showed that E accounted for 89% of the variation in grain yield across the 22 sites. Fixed effects G, N and SR accounted for 2%, 2% and 1%, respectively. Nitrogen and SR, which could be considered as M, accounted for 3% of the variation. The results from this study determined that E (year + site + year.site) also accounted for 89% of the variation. Similarities in the contribution to variance by G were also recorded in both studies. The contribution of M in this study was 6% compared to 3% in Anderson *et al.* (pers comm.). The soils in south-west Western Australia are old and highly weathered and have low capacity to hold nutrients for plant growth. It is possible that in the HRZ of WA that plant nutrition has a greater influence on grain yield compared to seed rate or N fertiliser.

Similarities in the contribution of E and G to variance were recorded in this study and Anderson *et al.* (pers comm.) using two different statistical approaches. The contribution to variance of M was quite different between the two studies and a potential explanation for this result has been given. There are other statistical models which could have been used to analyse the data from this study, nonetheless comparison of the results from this study with that of Anderson *et al.* (pers comm.) indicates similarities and helps to validate the statistical method used to analyse the results in this study.

In this study site was the single most important contributor to environment as a source of variance for grain yield (50%), similar to the findings of Sharma *et al.* (2008). This trend indicates that future research efforts need to address additional local constraints to production. For example, the low K, S and organic carbon measured at the Moora site, although compensated through fertilizer additions in this study, may still complicate interpretation of the results. This research and that of Hill *et al.* (2007), suggests that appropriate combinations of cultivars and fertilizer practices can increase grain yield. However, overcoming seasonal variability at specific sites is likely to have the biggest effect.

Management was the principal source of variation for grain protein and was consistently the second greatest source of variation for all other characteristics. This result contrasts with the results of Souza *et al.* (2004) who recorded a non significant response from nitrogen on grain protein. Some international customers believe certain Australian grades of wheat are deficient in protein content, dough strength and dough extensibility

(Ian Edwards, pers comm.). This study has demonstrated that increasing nutrition management will increase grain protein content to the levels required for premium-paying grades such as APH and durum in the HRZ of WA. The impact of management on protein quality is considered later.

3.5.3 Conclusion

While confirming the conclusions of Hill *et al.* (2007) this study has shown the importance of growing locally adapted cultivars, matched with adequate nutrition if potential yields are to be achieved at levels of grain protein appropriate to the premium-paying grades. The major wheat production areas in WA are in the medium and low rainfall zones where seasonal rainfall is mostly less than 350 mm. Recent increases in wheat production in the HRZ have shown the relevance of understanding requirements in respect of both cultivar and management where seasonal rainfall often exceeds 350 mm. In addition to demonstrating that nutrition management can achieve the minimum grain protein for the premium-paying grades the possible establishment of an APH grade in the HRZ of WA will require assessment of bread making and milling quality of locally produced grain. These aspects are examined in subsequent chapters - bread making and milling quality of wheat (Chapter 4) and the stability of grain yield, grain protein quantity and grain protein quality characteristics of wheat grown in the HRZ of WA (Chapter 5).

This study has also demonstrated it is important to account for the possible effects of management when the aim is to distinguish differences in yield potential of cultivars. This has clear implications for cultivar x environment studies in plant breeding programmes and for traditional cultivar experiments that aim to deliver comparative yield information to farmers. Thus nutrition should ideally be based on a combination of soil test results, grain yield potential and seasonal monitoring for the specific environment used for cultivar evaluation and not simply on levels that are either ‘district practice’ or ‘non-limiting’.

3.5.4 Acknowledgments

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Chapter 4

Influence of cultivar, environment and nutrition management on milling yield, protein quantity and protein quality in wheat.

This thesis chapter has been prepared as a manuscript to be submitted to Crop and Pasture Science

4. Chapter 4

4.1 Abstract.

The influence of cultivar, environment and nutrition management on milling yield, grain protein quantity and quality were examined in a series of identical experiments conducted between 2005 and 2007 at two locations in the high rainfall zone (HRZ) of Western Australian (WA). Eight cultivars (six bread wheat and two durum wheat), were grown at three levels of nutrition; ‘control’, ‘grower’ and ‘researcher’ to simulate low, medium and high fertilizer rates that growers in the HRZ use. Nitrogen was applied at three strategic times; immediately before sowing, four weeks after sowing and eight weeks after sowing. Nitrogen rate and timing were matched to achieve the minimum grain protein required for each commercial quality classification.

The main effects of cultivar and management (i.e. nutrition) were statistically significant for all variables measured and accounted for the largest portion of variability; environment and interaction effects (i.e. site, year and site.year) were usually significant but accounted for much less of the observed variability. Cultivar was the predominant source of variation for dough strength (as measured by mixograph peak time) and dough stability (mixograph breakdown). Bread wheat cultivars Lang and Sunvale, classified as suitable for the Australian Prime Hard (APH) grade, had higher water absorption (mixograph peak height and initial build up) and stronger dough strength (area below mixograph curve) compared to bread wheat cultivars with Australian Hard (AH) and Australian Premium White (APW) classification criteria. Comparing the durum cultivars, Kalka had slightly higher grain protein, while Wollaroi had better water absorption, dough strength and dough stability. Increasing the level of nutrition was principally responsible for increasing dough strength and water absorption. There was also a trend towards improved dough stability as nutrient management increased. Environment accounted for most of the variance in milling yield while the effects on other protein quality traits were mixed.

This study concluded that, with appropriate nutrition management, bread wheat grown in the HRZ of WA can achieve protein quality characteristics comparable to those from hard wheat grown in North America and meet the standards required by customers for Australian wheat. However, durum quality was below that which is required in the most quality-conscious markets. Protein quality was similar at both Moora and Williams despite significantly different protein quantity. This study suggests that in the Western Australian grain growing environment where the soils are extremely old, highly weathered, and nutrient deficient, the nutrition management of plant breeding experiments is critical if reliable results for grain quality are to be obtained when assessing potential new cultivars.

Additional Keywords: genotype x environment, protein quality, milling yield, genotype x environment x management.

4.2 Introduction (as per literature review)

Wheat (Triticum spp.) in Western Australia is typically grown in areas where annual rainfall is between 300-450 mm. However, it has been recognized that there is potential for good quality wheat to be grown in the high rainfall zone (HRZ) where annual rainfall varies between 450 and 800mm (Poole *et al*. 2002). A significant level of research has been done in the HRZ focusing on increasing grain yield (Anderson and Smith 1990; Hill and Wallwork 2002; Zhang *et al.* 2004a) and more recently on grain yield and quality (Chapter 3). However, research on milling yield and protein quality in the HRZ is limited. Milling yield is defined as the amount of flour that can be extracted from a given amount of grain (Simmons 1989); protein quality is responsible for water absorption, strength, extensibility and stability of the dough.

Protein quality is measured by a number of instruments; in Australia the farinograph and extensograph are used extensively, France and parts of Africa use an alveograph while the mixograph is commonly used in North America (Williams 2006). The mixograph was developed in the United States of America in 1939 as a means of studying the action of high speed commercial mixers. It measures the resistance of dough to mixing after the addition of water to flour and is a very useful tool for estimating important physical dough properties in early wheat genotypes in many breeding programs (Finney and Shogren 1972). The mixograph is capable of differentiating wheats for differences in strength characteristics, including ‘extra strong’ types from wheats of more usual dough strength for bread making purposes (Khatkar *et al.* 1996).

It is also useful in testing rheological properties and predicting al dente or firmness quality of durum (Kovacs *et al.* 1997).

Cultivar, environment and cultivar x environment interactions have long been known to have effects on milling yield and protein quality. Definition of cultivar and environment can be found in Basford and Cooper (1998). Effects such as size and shape of the grain (Simmons 1989), size distribution of the starch granules (Edwards *et al*. 2001) and variation in the amount and composition of gluten protein (Payne 1987) are genetic factors known to influence milling yield and protein quality. Moreover, environmental factors such as hot dry conditions during grain fill can reduce milling yield due to reduced endosperm content and a deep crease in the grain. Conversely cool, moist conditions can increase milling yield due to changes in endosperm content, shape of the grain and thickness of the bran coat (Simmons 1989). Protein quality can be reduced by heat stress during grain fill which can prolong gliadin synthesis and reduce glutenin synthesis, producing a higher gliadin:glutenin ratio in mature grain and consequently resulting in weaker dough properties (Blumenthal *et al.* 1993). Management of agronomic inputs may also have an effect on milling yield and dough quality. Nutrition management can increase gluten protein fractions with little effect on albumin and globulin proteins (Abrol *et al*. 1971; Ames *et al.* 2003; Saint Pierre *et al.* 2008; Tea *et al.* 2007). The impact of management is often overlooked due to it being included within environment, which can mask its effects. It can be argued that milling yield and protein quality of wheat are affected by cultivar, environment and management.

The aim of this chapter was to examine the effects of cultivar, environment and nutrition management on milling yield and protein quality of a range of wheat cultivars. Other chapters explore the influence of cultivar, environment and nutrition management on grain yield and quality (Chapter 3) and the stability of grain yield and grain quality in relation to site and season (Chapter 5).

4.3 Method and Materials (as per Chapter 3)

Experiments were conducted at Moora (30°59′S, 115°08′E) and Williams (33°01′S, 116°52′E) in the HRZ of WA in 2005, 2006 and 2007. Eight wheat cultivars (six bread wheat and two durum wheat) were tested at three levels of increasing nutrition, 'control', 'grower' and 'researcher' which were chosen to simulate low, medium and high fertilizer rates growers in the HRZ use (Hill *et al.* 2007). Basal fertilizer was superphosphate with added copper, zinc and molybdenum (P 9.0, S 10.1, Ca 19.0, Zn 0.30, Mo 0.06 w/w %). Nitrogen (Urea N 46 w/w %) was applied at three strategic times; immediately before sowing (IBS), four weeks after sowing (4WAS) (approximately Zadoks growth stage Z13-14) (Zadoks *et al.* 1974) and eight weeks after sowing (8WAS) (approximately Z30-31). Rate and timing were matched to achieve the minimum grain protein required for each commercial quality classification (Table 4.3). Potassium (K) (Muriate of Potash K 49.5% w/w %) was top dressed IBS at 100 kg/ha.

Experiments were a randomized block design with three replicates (the Williams experiment in 2006 had four replicates). A combined analysis of variance (ANOVA) was performed across the two sites and three seasons (6 environments). Least significant difference values were calculated at the 95% probability level. Further details on nutrition management, experimental design and data analysis are presented in Chapter 3. Details of the cultivars, environmental conditions and management regimes used in this study are contained in Tables 4.1, 4.2 and 4.3, respectively.

4.3.1 Flour Milling

Grain was cleaned prior to milling using a Carter-Day dockage tester to remove foreign material and small or broken seeds. Bread wheat cultivars were milled to flour using a Brabender Quadrumat Junior test mill (Brabender GmbH & Co, Duisburg, Germany) after tempering the grain to 13.5% moisture. Durum cultivars were milled to semolina using the Brabender Quadrumat Junior test mill after tempering the grain to 15.5% moisture.

4.3.2 Grain Protein Quantity

Grain protein percentage (grain% N x 5.7) at 11% moisture was determined by near infrared reflectance spectroscopy.

4.3.3 Mixograph Analysis

Physical dough properties were measured on two replicates of each treatment using a 10g Bohlin ReoMixer (Reologen i Lund AB, Sjöbo, Sweden), which conforms to the AACC Mixograph standard. A sample of 10g of the flour samples were evaluated on the ReoMixer using method AACC 54-40A (American Association of Cereal Chemists 2000). ReoMixer traces were analyzed using Remixer 32 Software (version 0.93-4, Reologen i Lund AB, Sjöbo, Sweden).

Water absorption was determined from measurement of initial buildup and peak height (measured in torque); high values indicate better water absorption. Dough strength was measured by the area below the mixograph curve (torque x minutes) after 10 minutes mixing and peak time (minutes); and dough stability was measured by breakdown (torque). Figure 4.1 illustrates the measurements taken for the mixograph.

Table 4.1. Cultivar, quality grade, year of registration, origin and pedigree of the cultivars used in experiments at Moora and Williams in 2005, 2006 and 2007.

	Cultivar	Quality Classification	Year of Registration	Origin	Pedigree
	Lang[e]	APH[a]	1999	LRC[1]	QT3765/Sunco
	Sunvale[e]	APH	1996	SU[2]	Cook*2/VPM1//3*Cook
Bread Wheat	Carnamah	AH[b]	1996	WADA[3]	Bolsena/1CH//77W:660
	GBA Sapphire[f]	AH	2003	GBA[4]	Janz/AUS24133//2*Janz
	Wyalkatchem	APW[c]	2001	WADA	Machete/84W129-504
	Stiletto	APW	1993	RAC[5]	Veranopolis/3*Spear/3/Dagger
Durum Wheat	Kalka	APDR[d]	2003	AGT[6]	Wollaroi*(Linghzi*Yallaroi#)*RH880009
	Wollaroi	APDR	1993	NSW DPI[7]	Guillemont Seln No.3/Kamilaroi Sib

[a]APH - Australian Prime Hard- used for the production of Chinese style yellow noodles and Japanese Ramen noodles and is often blended with lower protein wheat to produce flours suitable for a range of baked products, minimum grain protein content 13%, [b]AH - Australian Hard - Middle Eastern flat breads and Chinese steamed noodles, minimum grain protein content 11.5%, [c]APW - Australian Premium White - Asian Noodles, Middle Eastern and Indian style bread and Chinese steamed breads, minimum grain protein 10.5%, [d]APDR - Australian Premium Durum - wet and dry pasta products, minimum grain protein 13%, [e]Western Australia does not have an APH classification, these cultivars must be delivered to AH, [f]GBA Sapphire has an APH classification in Queensland and New South Wales. [1]LRC- Leslie Research Centre, Queensland; [2]SU- Sydney University; [3]DAFWA- Department of Agriculture and Food Western Australia; [4]GBA- Grain Biotech Australia; [5]RAC- Roseworthy Agricultural College, [6]AGT- Australian Grain Technologies, [7]NSW DPI – New South Wales Department of Primary Industries.

Table 4.2. Plot size, sowing date, rainfall, temperature and soil analysis for the experimental sites at Moora and Williams in 2005, 2006 and 2007

Location	Year	Environment Code	Plot Sizes		Sowing Date	Rainfall*		Temperature**		Soil Properties					
			Length	Width		GSR[a]	TR[b]	GSMIN[c]	GSMAX[d]	N[e]	P[f]	K[f]	S	OC[g]	pH
			m			mm		℃		mg/kg				%	$CaCl_2$
Moora	2005	M05	18	2.5	14 June 2005	465	501	7.1	19.8	23	13	26	3.3	0.81	5.2
	2006	M06	18	1.6	29 June 2006	178	407	8.1	21.6	33	30	31	4.6	1.06	6.7
	2007	M07	22	1.6	13 June 2007	246	406	8.8	20.2	33	38	40	35	1.78	5.4
Moora Long Term Average						367	460	8.1	19.9						
Williams	2005	W05	18	2.5	12 June 2005	416	510	6.6	17	49	55	72	11	3.08	5.3
	2006	W06	18	1.6	9 June 2006	201	342	6.1	18.8	33	33	79	10	3.46	5.0
	2007	W07	18	1.6	12 June 2007	361	463	5.5	18.1	20	69	114	7.7	4.01	5.0
Williams Long Term Average						432	540	6.8	17.2						

[a]Growing Season (May-October) Rainfall, [b]Total Yearly Rainfall, [c]Mean Growing Season Minimum Temperature, [d]Mean Growing Season Maximum Temperature, [e]Nitrate+Ammonium, [f]Meaured using the Colwell method (Colwell 1963), [g]Organic Carbon, *Rainfall records taken from the towns of Moora and Williams, **Temperature records taken from the towns of Badgingarra and Wandering

Table 4.3. Amount of basal fertiliser (kg/ha) and amount and timing of nitrogen (kg N/ha) per management regime at Moora and Williams in 2005, 2006 and 2007.

Basal Fertilizer	Control	Grower Average			Researcher		
Super Cu, Zn, Mo	100	150			200		
		Timing and Rate of N					
Protein Target (%)		*IBS* [a]	*4 WAS* [b]	*8 WAS* [c]	*IBS*	*4 WAS*	*8 WAS*
APH	0	25	25	25	50	50	75
AH	0	25	50		50	50	75
APW	0	25	50		50	50	50
APDR	0	25	25	25	50	50	75

[a]Immediately before Sowing, [b]4 Weeks After Sowing, [c]8 Weeks After Sowing

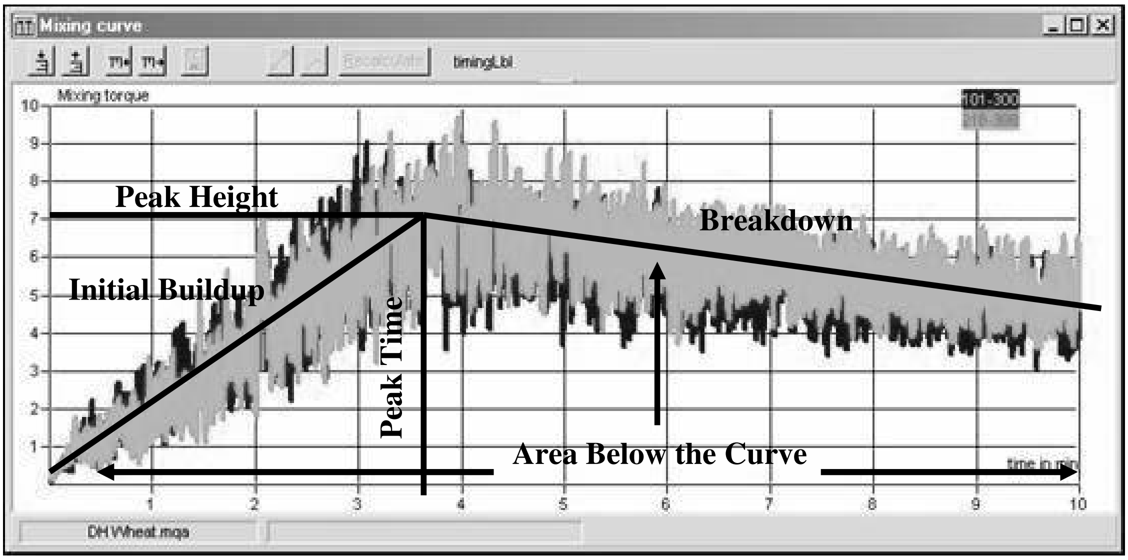

Figure 4.1. Measurements derived from the mixograph used to assess protein quality in this study.

4.4 Results

4.4.1 Climatic and Soil Conditions

The combination of sites and seasons differed widely in terms of amount and timing of rainfall and temperature (Table 4.2). Above average growing season rainfall (May-October) was recorded at both sites in 2005 but 2006 and 2007 had well below average growing season rainfall compared to the long term average. The soil at the Williams site had higher levels of nutrition compared to Moora (Table 4.2). Further details on soil and climatic conditions are presented in a previous chapter (Chapter 3).

4.4.2 Contribution to Variance

Main effects of cultivar and management were significant ($P<0.001$) for milling yield, grain protein quantity and quality. Environment (year, site and year.site) were not always significant and accounted for relatively smaller amounts of the variance with the exception of milling yield (Table 4.4). Cultivar was the dominant source of variation for dough strength (measured by mixograph peak time) and dough stability and was the second source of variation for milling yield, water absorption (mixograph peak height and initial buildup) and dough strength (area below the mixograph curve). The influence of cultivar on grain protein quantity was small (Table 4.4).

Management (i.e. level of nutrition) was the greatest source of variation for grain protein quantity, water absorption (mixograph peak height and initial buildup) and dough strength (area below the mixograph curve). Effects of nutrition on milling yield and dough stability (mixograph breakdown) were small. Given the highly variable nature of the WA climate, year was the principal source of variation for milling yield and the second source of variation for dough strength (mixograph peak time). Site was the second largest explanation of variation for grain protein quantity; effects on other variables were small. Environment (year.site) effects on milling yield, grain protein quantity and all quality parameters were small.

4.4.3 Cultivar

Effects of cultivar on milling yield, grain protein quantity and quality across years, sites and management practices are shown in Table 4.5. Among the bread wheat cultivars Stiletto had the highest milling yield while Carnamah was lowest. Lang and Sunvale had the highest levels of grain protein quantity, water absorption (mixograph peak height and initial buildup) and dough strength (area below the mixograph curve). Differences in peak time and breakdown were significant but small in importance, although Lang showed greater stability than Wyalkatchem (breakdown 1.3 versus 1.1). The results also indicate clear differences between cultivars based on commercial quality classifications. Cultivars Lang and Sunvale, classified as APH, exhibited superior grain protein quantity, water absorption and dough strength (area below the mixograph curve), compared to AH cultivars Carnamah and GBA Sapphire and APW cultivars Wyalkatchem and Stiletto. Differences between cultivars based on commercial quality classification for dough strength (peak time) and dough stability were small.

Wollaroi durum demonstrated superior semolina yield compared to Kalka and stronger gluten as indicated by peak height (water absorption) and area below the curve (dough strength). Wollaroi also displayed greater dough stability (breakdown).

4.4.4 Environment

The effects of environment (year, site and year.site) on milling yield, grain protein quantity and quality are shown in Table 4.6. Year and site both had highly significant effects on milling yield. However, the importance of the differences between seasons (6.56%) was greater than the differences between the two sites (1.81%) as indicated by examining the differences between sites within a season (0.99, 1.30 and 2.27% for 2005, 2006 and 2007 respectively). Similarly, year and site had highly significant effects on grain protein quantity, but the difference between years (1.4%) and sites (1.3%) was much smaller. Water absorption did not differ significantly between seasons, but showed a greater difference between sites. Dough strength and stability were significantly different between years but the effects of site were mixed.

Table 4.4. Significance (sig) and percentage of total variance for each source of variation (%) for milling yield, grain protein and grain protein quality of wheat grown at Moora and Williams in 2005, 2006 and 2007.

						Water Absorption				Dough Strength				Dough Stability	
		Milling Yield		Grain Protein		Peak Height		Initial Buildup		Area Below		Peak Time		Breakdown	
Source of variation	**d.f.**	**sig**	**%**	**sig**	**%**	**sig**	**%**	**sig**	**%**	**sig**	**%**	**sig**	**%**	**sig**	**%**
C	7	***	11	***	2	***	32	***	28	***	33	***	46	***	47
M	2	***	1	***	48	***	52	***	46	***	52	***	9	***	16
Y	2	***	74	***	11	NS	0	NS	0	***	1	***	26	***	19
S	1	***	11	***	26	***	5	*	4	***	3	NS	1	NS	0
E	2	***	1	***	0	***	2	***	6	***	2	***	3	***	5
C x M	14	***	0	***	8	***	1	***	3	***	1	***	1	***	1
C x Y	14	***	1	***	0	***	1	***	4	***	1	***	2	***	2
C x S	7	***	0	***	3	***	1	NS	1	**	0	***	2	***	3
C x E	14	***	0	***	0	***	0	**	1	**	0	***	1	***	1
M x Y	4	***	0	***	0	***	5	**	2	***	4	***	3	***	2
M x S	2	***	0	**	0	NS	0	NS	0	NS	0	NS	0	NS	0
M x E	4	NS	0	***	1	*	0	NS	1	***	1	*	1	NS	1
C x M x Y	28	***	0	***	0	**	0	*	1	**	0	***	1	***	1
C x M x S	14	NS	0	*	0	NS	0	NS	0	NS	0	***	1	***	1
C x M x E	28	***	0	*	0	*	0	*	1	NS	0	**	1	***	1
Y x S x R	13	NS	0	*	0	*	0	NS	1	**	0	NS	0	NS	0
Residual	299		0		0		0		1		0		0		0
Total	455														

*,**,*** Significant at P = 0.05, P = 0.01 and P = 0.001, respectively. NS= Not Significant.
C=Cultivar; M=Management; S=Site; Y=Year; E=Environment (Site.Year) R = Replicate

Table 4.5. Effects of cultivar on milling yield, grain protein, water absorption, dough strength and dough stability of wheat grown at Moora and Williams in 2005, 2006 and 2007.

				Water Absorption		Dough Strength		Dough Stability
	Cultivars	Milling Yield[A]	Grain Protein[A]	Peak Height[B]	Initial Buildup[B]	Area Below Curve[C]	Peak Time[D]	Breakdown[B]
Bread Wheat	Lang	67.1	11.7	5.7	3.5	34.7	3.6	1.3
	Sunvale	67.7	11.6	5.8	3.5	34.7	4.1	1.2
	Carnamah	65.7	11.0	5.5	3.3	32.8	3.8	1.2
	GBA Sapphire	67.2	11.1	5.4	3.3	32.5	3.8	1.2
	Wyalkatchem	67.7	10.8	5.2	3.0	30.7	4.1	1.1
	Stiletto	68.9	11.0	5.0	3.2	30.2	3.8	1.3
Durum Wheat	Kalka	62.5	12.1	3.8	2.3	21.1	6.1	0.4
	Wollaroi	64.6	12.0	4.4	2.5	25.7	4.6	0.7
	l.s.d*	0.3	0.1	0.1	0.2	0.8	0.2	0.1
	Grand Mean	66.4	11.4	5.1	3.1	30.3	4.2	1.1

*l.s.d P = 0.05, [A]=%, [B]=torque, [C]=torque x minutes, [D]=minutes

Table 4.6. Effects of year, site and environment (year.site) on milling yield, grain protein, water absorption, dough strength and dough stability of wheat grown at Moora (M) and Williams (W) in 2005, 2006, 2007 (Moora 2005 = M05).

			Water Absorption		Dough Strength		Dough Stability
Environment	**Milling Yield^A**	**Grain Protein^A**	**Peak Height^B**	**Initial Buildup^B**	**Area Below Curve^C**	**Peak Time^D**	**Breakdown^B**
2005	62.7	11.6	5.1	3.1	29.6	4.7	1.0
2006	69.2	12.0	5.1	3.0	30.6	3.9	1.2
2007	66.9	10.6	5.1	3.1	30.7	4.1	1.0
l.s.d	0.2	0.1	NS	NS	0.5	0.1	0.04
Moora	65.5	12.1	5.2	3.1	30.8	4.3	1.0
Williams	67.3	10.8	5.0	3.0	29.8	4.2	1.1
l.s.d*	0.1	0.1	0.1	0.1	0.4	NS	NS
M05	62.1	12.1	5.2	3.1	30.1	4.6	1.1
M06	68.6	13.3	5.3	3.2	31.9	4.2	1.1
M07	65.7	10.7	5.1	3.0	30.5	4.1	0.9
W05	63.1	11.1	5.0	3.0	29.2	4.7	0.9
W06	69.9	10.9	5.0	2.9	29.5	3.8	1.2
W07	68.0	10.6	5.1	3.1	31.0	4.2	1.0
l.s.d*	0.2	0.1	0.1	0.1	0.6	0.2	0.1

l.s.d* P = 0.05, ^{A}=%, ^{B}=torque, ^{C}=torque x minutes, ^{D}=minutes

4.4.5 Management

The effects of added nutrition on milling yield, grain protein quantity and quality are shown in Table 4.7. Increasing the level of nutrition had little effect on milling yield but did lead to an increase in grain protein quantity and the protein-related characteristics of water absorption and dough strength (area below the curve) and stability. There was a trend towards improving dough strength (peak time) and stability (breakdown) with improving nutrition.

Table 4.7. Effect of management on milling yield, grain protein, water absorption, dough strength and dough stability of wheat grown at Moora and Williams in 2005, 2006 and 2007.

			Water Absorption		Dough Strength		Dough Stabiltity
Management	Milling Yield[A]	Grain Protein[A]	Peak Height[B]	Initial Buildup[B]	Area Below Curve[C]	Peak Time[D]	Breakdown[B]
Control	66.6	10.0	4.6	2.7	26.7	4.5	0.9
Grower	66.1	11.4	5.1	3.1	30.3	4.1	1.1
Researcher	66.5	12.9	5.6	3.4	33.9	4.1	1.2
l.s.d*	0.2	0.1	0.1	0.1	0.5	0.1	0.04

l.s.d* P = 0.05, [A]=%, [B]=torque, [C]=torque x minutes, [D]=minutes

4.5 Discussion

This study has demonstrated the importance of partitioning the effects of 'management' from 'environment' and the relative importance of cultivar, environment and management effects in explaining variability in milling yield, grain protein quantity and quality in wheat. The results have shown that as the level of nutrition increased so did protein quantity, which led to a noted improvement in protein quality.

A review by Williams *et al.* (2008) into the effects of genotype, environment and interaction effects on wheat quality concluded that protein quality is influenced more by genetic factors than environmental factors. The results from this study agree, in part. However, many authors have grouped management variables within environment, thus confounding the effect of management with that of environment (year and site) (Anderson *et al.* 2005). It is important for future gains in grain quality that progress due to management factors is clearly delineated from gains due to other factors. This is especially relevant in the Western Australian environment where the soils are comparatively infertile and where management of soil fertility can be critical to grain quality.

This study has shown that when management is assessed independently of environment, in the HRZ of WA, it has a significant effect on protein quantity and quality (Table 4.4). As the level of nutrition increased so did grain protein quantity, water absorption, dough strength (area below the curve) and to a lesser extent dough stability (Table 4.7). Direct comparison with other studies on the effect of nutrition on protein quality is difficult, except where studies have examined the influence of N and S, alone or in combination. Tea *et al.* (2007) in France studied the influence of foliar N and S while Garrido-Lestache *et al.* (2003) in Spain examined the effects of N rate, timing, splitting and type. Both studies concluded that an increase in nutrition led to an increase in dough strength, a similar result to this study. Saint Pierre *et al.* (2008) in the USA studied the effects of increasing N and concluded that it led to an increase in dough stability as measured by the mixograph, again similar to this study. Souza *et al.* (2004) in moisture limited environments in the USA recorded an increase in water absorption between two rates of nitrogen but recorded no significant effect on grain protein quantity or mixograph stability.

The improvement in protein quality may be attributed to changes in the relative proportion of proteins in the grain. Wieser and Seilmeier (1998) in Germany demonstrated that increasing N strongly influenced gluten proteins and had almost no effect on albumins or globulins. Similarly, Abrol *et al.* (1971) in India concluded that by increasing nutrition protein quality increased; gliadin and glutenin proteins increased while the level of albumin and globulin fractions remained unchanged. The results from this study are similar to an observation by Saint Pierre *et al.* (2008) who reported that changes in protein composition were related to general increases in protein content.

Cultivar is often considered responsible for protein quality (Eagles *et al.* 2002; Panozzo *et al.* 1983). In this study cultivar was the predominant source of variation for dough strength (peak time). Dough strength is an expression of gluten content and depends on how much of the gliadin and glutenin proteins are present to form gluten: it is a measure of the extensibility and strength of the dough (Baker *et al.* 1971). Zhu and Khan (2001) from experiments carried out in the USA reported cultivar as having the greatest influence on mixograph mixing time.

Peak time for bread wheat in this study varied between 3.6-4.1 minutes (Table 4.5), compared with the 2.7-4.1 minutes for mixograph dough development time reported by Zhu and Khan (2001). Durum cultivars recorded peak time between 4.6-6.1 minutes (Table 4.5) which is significantly longer than the 2.2-3.3 minutes reported by Ames *et al.* (2003) from field experiments conducted in Canada to examine the effects of N fertilizer on protein quantity and gluten strength of durum wheat. As measured by mixograph peak time, bread wheat grown in the HRZ region of WA displayed dough strength comparable to the Hard Red Spring and Hard Red Winter market classes in the

USA. These market classes compete with quality classifications tested in this study. However, dough strength of durum was below that of Canadian cultivars. Comparisons of protein quality between the results of this study and similar Australian studies are difficult due to the mixograph being more commonly used in North America (Williams 2006).

Dough stability indicates the duration that optimal consistency of dough is maintained during mixing (Haraszi *et al.* 2008). Again, comparison between this study and other studies on the effect of nutrition on dough stability is difficult since management is often considered to be part of the environment term in the analysis. Nonetheless, Souza *et al.* (2004) researching the effects of genotype, environment and nitrogen management on the quality of spring wheat in the USA recorded no change in dough stability from nitrogen in either irrigated or moisture limited environments. Differences between this study and Souza *et al.* (2004) are perhaps attributable to the higher inherent soil fertility status of North American soils compared to WA soils.

Environment (year, site and year.site) had significant effects on milling yield, grain protein quantity and quality (Table 4.4). Year was the predominant source of variation for milling yield (Table 4.4). Milling yield is the percentage of extractable flour from grain and is an important technical and economic factor in the buying decisions of flour mills (Posner and Hibbs 1997). Simmons (1989) indicated that cool, moist conditions during grain fill can increase milling yield due to more favourable endosperm content, shape of the grain and thickness of the bran coat.

The highest milling yield (69.2%) was recorded in 2006 in these experiments. Climatic records for Moora and Williams (Table 4.2) indicate that maximum temperature and rainfall in the 2006 growing season was the highest during the study. Furthermore, the highest growing season rainfall and lowest growing season mean monthly maximum temperatures were recorded in 2005, when milling yields were lowest (62.7%). The apparent differences between these results and Simmons (1989) who indicated that cool, moist conditions during grain fill can increase milling yield, suggests that influences other than climatic factors may have affected milling yield in this study. Souza *et al.* (2004) found, similar to the results reported here, that environment was responsible for influencing milling yield with no impact from two different rates of nitrogen, similar to the results reported here.

Site had a major impact on the variance of grain protein quantity (Table 4.4), with the magnitude of differences between sites relatively large (Table 4.6). Nonetheless, the effects of site on grain protein quality were small (Table 4.4), with the magnitude of the differences between sites relatively small (Table 4.6). This trend suggests that wheat grown in Moora had higher grain protein quantity compared to Williams, but grain protein quality of wheat grown in Williams may be similar to that of wheat grown in Moora.

4.6 Conclusion

The results of this study indicate that bread wheat grown in the HRZ of WA can have comparable protein quality to that of wheats grown in other areas of the world. Protein quality of durum appears to be below that which has been previously reported and this can possibly be attributed to the poor adaptation of cultivars bred in New South Wales and South Australia when grown in WA. Durum production in WA is small and significant investment is required to develop cultivars better adapted to the WA environment if production is to increase.

Wheat growers in Australia are currently paid on grain protein quantity, which means growers in Moora could potentially be paid more for wheat than growers in Williams. However, protein quality results suggest differences between sites are small. Quick, accurate and reliable testing procedures at the time of delivery would allow growers and marketers to take advantage of differences in protein quality identified between sites in this study.

This study has also recorded an increase in protein quality as nutrition increased. The soils of WA are very old, highly weathered, have low levels of exchangeable nutrients and poor plant available water-holding capacity (Anderson *et al.* 2005). Moreover, low soil nutrition has been previously identified as one of the major factors limiting production in the HRZ of WA (Hill *et al.* 2007). The low nutrient status of WA soils may help to explain the differences in protein quantity and quality found in this study; it may also be limiting the protein quality of wheat grown in the HRZ.

The significant contribution of management highlights the importance of nutrition in plant breeding experiments (Chapter 3). On the light textured soils of WA, plant breeders and agronomists must consider the implications of nutrition management when interpreting experimental results and subsequent quality data. The nutritional management of breeding experiments must be based on a sound methodical approach, incorporating a combination of soil test results, grain yield potential and seasonal monitoring for the environment in question and not be simply based on levels that are either 'district practice' or 'non-limiting'.

4.7 Acknowledgements (as per Chapter 3)

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Chapter 5

Stability of grain yield and quality characteristics in wheat produced in the high rainfall zone of Western Australia.

This thesis chapter has been prepared as a manuscript to be submitted to Crop and Pasture Science

5. Chapter 5

5.1 Abstract.

The Western Australian (WA) wheat belt is situated in a highly variable Mediterranean-type climate which can result in large variations in grain production and quality characteristics from year to year. To determine if this variation can be reduced the dynamic and static stability of eight cultivars of wheat (*Triticum aestivum* and *T. turgidum var durum*) for grain yield, protein quantity and quality characteristics were examined from identical experiments grown across six environments (two sites x three years) in the High Rainfall Zone (HRZ) of south west WA. Data were subjected to analysis of variance, all cultivars were analysed for grain yield; bread and durum cultivars were analysed separately for grain protein quantity and quality characteristics. Regression analysis was used to examine stability of grain yield and quality characteristics between cultivars. The regression co-efficient (b) is a measure of stability of the cultivar to a range of environments. Cultivars which display b=1 for grain yield were considered to have dynamic stability, the ability to respond to changes in environment but in a predictable way. Cultivars which displayed b=0 for grain protein quantity and quality were considered to have static stability, i.e. consistent quality characteristics regardless of environmental variation.

Three bread wheat and one durum wheat cultivars were identified as displaying dynamic stability for grain yield. Static stability differences between bread wheat cultivars for protein quantity were not significant. Three cultivars displayed static stability for water absorption and one cultivar had static stability for dough strength. No significant static stability differences were observed between durum cultivars for protein quantity or quality.

The results from this study show it may be possible to breed better environmental stability for grain yield and protein quality. Furthermore, it was shown that some cultivars displayed static stability for water absorption and dough strength in the HRZ

environment that allows production of grain that demonstrates static stability for water absorption and dough strength. Improving dynamic stability for grain yield is important for growers thereby allowing them to take advantage of good seasons, and improving static stability for quality is important for end-users thereby reducing differences between years.

Keywords: grain yield, protein quality, wheat quality, stability

5.2 Introduction (as per literature review)

Stability of grain yield (Heinrich *et al.* 1983) and quality (Lemelin *et al.* 2005) has been defined as the ability of the cultivar to avoid large fluctuations over a range of environments and denotes consistency in rank relative to other cultivars in a given set of environments (Yue *et al.* 1997). Differential expression of traits across environments or genotype-environment interactions is the most common cause of instability in grain yield and quality (Romagosa and Fox 1993). Stable grain yield and quality characteristics across a wide range of environments are important for management, marketing and profit (Yan and Kang 2002) and guarantees constant procedures that minimise losses during processing (Grausgruber *et al.* 2000).

Becker and Léon (1988) have conducted an extensive review into stability analysis in plant breeding with particular attention to grain yield stability. They found that there is general agreement on the importance of yield stability but confusion over the definition of stability and on methods to measure and improve it. Since the review, researchers from North America and Europe have documented stability differences between bread wheat (Grausgruber *et al.* 2000; Peterson *et al.* 1992) and durum wheat (Rharrabti *et al.* 2003) for a range of physical and protein quality characteristics. Despite substantial international research showing stability differences between cultivars for grain yield and quality and the highlighted benefits of increasing the stability of grain yield and quality, research within Australia is limited.

There are two concepts of stability; static and dynamic. A cultivar that has static stability is defined as having unchanged performance regardless of any variation in environmental conditions (Becker and Léon 1988). Static stability is considered desirable for quality characteristics by the milling and baking industries (Grausgruber *et al.* 2000). However, quality characteristics in wheat usually respond to environmental conditions; therefore it may be unrealistic to expect the same level of performance across all environments (Grausgruber *et al.* 2000). Dynamic (Becker and Léon 1988) or agronomic (Becker 1981) stability means that the performance of a cultivar may change from environment to environment but in a predictable way. Dynamic stability would be considered desirable for grain yield; growers want cultivars which are able to maximise grain yield in environments favourable for achieving high as well as low yields of grain. Both concepts of stability are considered valuable but their application depends on the trait under investigation (Becker and Léon 1988). The current Australian commercial classification system for wheat has no requirements for cultivars to exhibit minimum stability requirements. Requiring cultivars to display the desired concept of stability for grain yield and quality characteristics prior to commercial release will benefit growers, marketers and processors by reducing yearly variation commonly observed in the variable Mediterranean-type climate of Western Australia.

Wheat in WA is currently grown mainly in the low to medium rainfall areas where annual rainfall varies between 300-450mm. Nonetheless, Poole *et al.* (2002) indicated that there is great potential for annual crop production in the High Rainfall Zone (HRZ) where annual rainfall varies between 450-800mm. In addition to the higher rainfall the HRZ has longer and cooler growing seasons and a longer period of frost risk compared to current wheat belt areas (Zhang *et al.* 2006). Research in the HRZ has focused heavily on increasing actual grain yield towards potential grain yield levels. Zhang *et al.* (2006) using the APSIM model concluded potential grain yield for wheat is between 5-8t/ha in the HRZ. However, a survey of commercially grown wheat crops in the HRZ has determined average grain yield is 2.7 t/ha (Hill and Wallwork 2002). Limitations such as water-logging, physical and chemical constraints to root growth, lack of adapted cultivars (Zhang *et al.* 2006) and the low nutrition status of soils (Hill *et al.* 2007) have been identified as limiting grain yield.

More recent research has focused on physical grain quality characteristics and protein quality characteristics. This research has shown that provided adequate nutrition is applied, minimum commercial grain protein levels can be achieved (Chapter 3). Protein quality characteristics such as dough strength for bread wheat cultivars were comparable to the Hard Red Spring and Hard Red Winter market classes in the USA. Dough strength of durum wheat was below that of Canadian cultivars (Chapter 4). However, research on grain yield and quality stability in the HRZ of the WA wheat belt has been limited. This chapter examines the stability of eight cultivars of wheat for grain yield, protein quantity and protein quality characteristics in relation to site and season in the HRZ of WA.

5.3 **Methods and Materials** (as per Chapter 3)

A series of identical experiments was conducted close to the towns of Moora (30°59′S, 115°08′E) and Williams (33°01′S, 116°52′E) in Western Australia in 2005, 2006 and 2007. Six bread wheat and two durum wheat cultivars were tested at three levels of nutrition management. These were described as 'control', 'grower' and 'researcher' and were chosen to simulate low, medium and high fertilizer rates used by growers in the HRZ (Hill *et al.* 2007). Basal fertilizer was Superphosphate, Copper, Zinc and Molybdenum (P 9.0, S 10.1, Ca 19.0, Cu 0.60, Zn 0.30, Mo 0.06 w/w %) which was drilled approximately 2cm below the seed at sowing. Nitrogen (Urea 46 N w/w %) was applied; immediately before sowing, four weeks after sowing (approximately Zadoks growth stage Z13-14) (Zadoks *et al.* 1974) and eight weeks after sowing (approximately Z30-31). Nitrogen rate and timing were matched to achieve the minimum grain protein required for each commercial quality classification. Potassium (Muriate of Potash 49.5% K w/w %) was top dressed immediately before sowing at 100 kg/ha.

Experiments were laid out as a randomized block designs with three replicates (the Williams experiment in 2006 had four replicates). Further details on experimental design are presented in Chapter 3. Details of the cultivars and management regimes used in this study are contained in Tables 5.1 and 5.2, respectively. Plot size, sowing date, rainfall, temperature and soil properties for the experimental sites at Moora and Williams in 2005, 2006 and 2007 are presented in Table 5.3.

5.3.1 Measurements

At maturity, all plots were mechanically harvested, grain yield recorded and a 2 kg sample retained for further analysis. Grain protein percentage (grain % N x 5.7) at 11% moisture was determined by near infrared reflectance spectroscopy. Before further analysis the remaining sample was cleaned using a Carter-Day dockage tester to remove foreign material and small or broken seeds. Physical dough properties were measured from a 10g sample of flour using a ReoMixer, which conforms to the AACC Mixograph standard, according to method AACC 54-40A (American Association of Cereal Chemists 2000).

Water absorption was determined from initial buildup and peak height (measured in torque); high values indicate better water absorption. Dough strength was measured by the area below the mixograph curve (torque x minutes) and peak time (minutes); and dough stability was measured by breakdown (torque). Further details on the measurements taken are presented in Chapters 3 and 4.

Table 5.1. Cultivar, quality classification, year of registration, origin and pedigree of the cultivars used in experiments at Moora and Williams in 2005, 2006 and 2007.

	Cultivar	Quality Classification	Year of Registration	Origin	Pedigree
Bread Wheat	Lang[e]	APH[a]	1999	LRC[1]	QT3765/Sunco
	Sunvale[e]	APH	1996	SU[2]	Cook*2/VPM1//3*Cook
	Carnamah	AH[b]	1996	WADA[3]	Bolsena/1CH//77W:660
	GBA Sapphire[f]	AH	2003	GBA[4]	Janz/AUS24133//2*Janz
	Wyalkatchem	APW[c]	2001	WADA	Machete/84W129-504
	Stiletto	APW	1993	RAC[5]	Veranopolis/3*Spear/3/Dagger
Durum Wheat	Kalka	APDR[d]	2003	AGT[6]	Wollaroi*(Linghzi*Yallaroi#)*RH880009
	Wollaroi	APDR	1993	NSW DPI[7]	Guillemont Seln No.3/Kamilaroi Sib

[a]APH - Australian Prime Hard- used for the production of Chinese style yellow noodles and Japanese Ramen noodles and is often blended with lower protein wheat to produce flours suitable for a range of baked products, minimum grain protein content 13%; [b]AH - Australian Hard - Middle Eastern flat breads and Chinese steamed noodles, minimum grain protein content 11.5%; [c]APW - Australian Premium White - Asian Noodles, Middle Eastern and Indian style bread and Chinese steamed breads, minimum grain protein 10.5%; [d]APDR - Australian Premium Durum - wet and dry pasta products, minimum grain protein 13%; [e]Western Australia does not have an APH classification, these cultivars must be delivered to AH; [f]GBA Sapphire has an APH classification in Queensland and New South Wales. [1]LRC- Leslie Research Centre, Queensland; [2]SU- Sydney University; [3]DAFWA- Department of Agriculture and Food Western Australia; [4]GBA- Grain Biotech Australia; [5]RAC- Roseworthy Agricultural College; [6]AGT- Australian Grain Technologies; [7]NSW DPI – New South Wales Department of Primary Industries.

Table 5.2. Amount of basal fertiliser (kg/ha) and amount and timing of nitrogen (kg N/ha) per nutrition regime at Moora and Williams in 2005, 2006 and 2007

Basal Fertilizer	Control	Grower Average			Researcher		
Super Cu, Zn, Mo	100	150			200		
		Timing and Rate of N					
Quality Classification		*IBS* [a]	*4 WAS* [b]	*8 WAS* [c]	*IBS*	*4 WAS*	*8 WAS*
APH	0	25	25	25	50	50	75
AH	0	25	50		50	50	75
APW	0	25	50		50	50	50
APDR	0	25	25	25	50	50	75

[a]Immediately before Sowing, [b]4 Weeks After Sowing, [c]8 Weeks After Sowing

Table 5.3. Plot size, sowing date, rainfall, temperature and soil analysis for the experimental sites at Moora and Williams in 2005, 2006 and 2007

Location	Year	Environment Code	Plot Sizes		Sowing Date	Rainfall*		Temperature**		Soil Properties					
			Length	Width		GSR[a]	TR[b]	GSMIN[c]	GSMAX[d]	N[e]	P[f]	K[f]	S	OC[g]	pH
			m			mm		℃			mg/kg			%	$CaCl_2$
Moora	2005	M05	18	2.5	14 June 2005	465	501	7.1	19.8	23	13	26	3	0.81	5.2
	2006	M06	18	1.6	29 June 2006	178	407	8.1	21.6	33	30	31	5	1.06	6.7
	2007	M07	22	1.6	13 June 2007	246	406	8.8	20.2	33	38	40	35	1.78	5.4
Moora Long Term Average						367	460	8.1	19.9						
Williams	2005	W05	18	2.5	12 June 2005	416	510	6.6	17	49	55	72	11	3.08	5.3
	2006	W06	18	1.6	9 June 2006	201	342	6.1	18.8	33	33	79	10	3.46	5.0
	2007	W07	18	1.6	12 June 2007	361	463	5.5	18.1	20	69	114	8	4.01	5.0
Williams Long Term Average						432	540	6.8	17.2						

[a]Growing Season (May-October) Rainfall, [b]Total Yearly Rainfall, [c]Mean Growing Season Minimum Temperature, [d]Mean Growing Season Maximum Temperature, [e]Nitrate+Ammonium, [f]Measured using the Colwell method (Colwell 1963), [g]Organic Carbon, *Rainfall records taken from the towns of Moora and Williams, **Temperature records taken from the towns of Badgingarra and Wandering

5.3.2 Statistical Analyses

Previous chapters in this series used a combined analysis of variance to examine the contribution to variance of cultivar, environment and nutrition management on grain yield and quality. The results were analysed using a combined analysis of variance (ANOVA) on data derived from six environments (two sites and three seasons). The effect of nutrition management was grouped within the environment term. Least significant difference values were calculated at the 95% probability level. The statistical significance of stability of cultivars in relation to nutrition management could not be examined in this chapter because of limited degrees of freedom.

Regression analysis was used to determine the stability of grain yield and grain quality characteristics. For each cultivar, a linear regression for each individual characteristic (for example grain yield) on the average characteristic of all cultivars for each environment was computed. A combined regression analysis was computed on all cultivars for grain yield. Bread and durum wheats were analysed separately for grain protein quantity and quality characteristics due to different grain protein characteristics of each species. The average characteristic of all cultivars at each environment is referred to as the 'environmental mean'.

When the individual cultivar characteristic is plotted against the average of all cultivars, the regression co-efficient (*b*) is a measure of phenotypic stability or responsiveness of the cultivar to a range of environments. Those cultivars with b=1 for grain yield, were considered to have dynamic stability (Eberhart and Russell 1966). Values of b significantly >1 describe cultivars which have increasing responsiveness to environmental change (below average stability). Cultivars with b values significantly <1 have greater resistance to environmental change (above average stability) (Findlay and Wilkinson 1963). For grain protein quantity and quality, those cultivars with b=0 were considered to have static stability (Findlay and Wilkinson 1963). Those cultivars with b < or >0 were interpreted as described for b=1. The b-values were tested for significant differences from *b*=1, *b*=0 using *t*-tests. All analyses were conducted using the GENSTAT (version 9) (VSN International, Herts, UK) statistical software package.

5.4 Results

5.4.1 Climate and Soil Conditions

Environments in this study were contrasting. Average to above average growing season rainfall was recorded at both sites in 2005, but well below average in 2006 and 2007. The dry start to the growing season at the Moora site in 2006 was responsible for delaying sowing well beyond the sowing dates in other environments. Soil tests revealed that the Williams site had higher nutrition than the Moora site (Table 5.3). Further details on climate and soil conditions are presented in Chapter 3.

5.4.2 Analysis of Variance and Regression Analysis

Combined analysis of variance revealed statistically significant differences between *b* values for grain yield ($P<0.05$) and between peak height ($P<0.01$) and area below the curve ($P<0.05$) for bread wheat cultivars (Table 5.4). The *b* values for grain yield ranged from 0.81 (Wollaroi) to 1.17 (GBA Sapphire). The b values for bread wheat cultivars Carnamah and GBA Sapphire were significantly greater than *b*= 1; bread wheat cultivars Lang, Sunvale and Stiletto and durum cultivar Kalka were not significantly different from *b*=1, and all thereby displayed dynamic stability. The b value for grain yield of Wyalkatchem was significantly less than b= 1, indicating no dynamic stability.

Lang, Sunvale and GBA Sapphire were not significantly different from *b*=0 for water absorption (peak height) and GBA Sapphire for dough strength (area below the curve) thereby displaying static stability. Differences between bread wheat cultivars for grain protein quantity, initial buildup, peak time and breakdown were not significant. Differences between durum wheat cultivars for grain protein quantity and quality regression parameters were not significant.

5.4.3 Grain Yield

Grain yields of all cultivars across environments are shown in Table 5.5. Mean grain yield across both sites was 2.36 t/ha; mean grain yield at Williams was approximately 1 t/ha higher than at Moora. Williams 2007 (3.85 t/ha) was the highest yielding environment while Moora 2005 (1.39 t/ha) was the lowest. Wyalkatchem (2.69 t/ha) and Carnamah (2.64 t/ha) had the highest mean yield. Wyalkatchem (2.23 t/ha) and Stiletto (3.17 t/ha) recorded the highest mean grain yield in Moora and Williams, respectively. Durum cultivars consistently recorded grain yields below those of bread wheat cultivars.

The responsiveness of cultivars for grain yield fell into four distinct categories (Figure 5.1). Lang and Sunvale showed general adaptability to all environments with *b* values close to 1 and mean grain yield close to the mean for all cultivars. GBA Sapphire, Carnamah and Stiletto had mean grain yield above the mean for all cultivars and responsiveness above 1, indicating their increasing responsiveness to environmental change. Wyalkatchem had mean grain yield above the mean for all cultivars and responsiveness below 1, indicating greater resistance to environmental change. Durum wheats Kalka and Wollaroi recorded mean grain yield below the mean for all cultivars and responsiveness below 1 (Figure 5.1).

The plot of linear regressions between four cultivars which displayed *b* values significantly > or <1 for grain yield is shown in Figure 5.2. In environments where yields were less than 2.5 t/ha, Wyalkatchem usually outperformed all cultivars to record the highest grain yield. However, in environments that were more conducive to high yields the relative grain yield of Wyalkatchem was reduced. Carnamah and GBA Sapphire both had grain yield higher than Wyalkatchem in high grain yield environments. The grain yield of Wollaroi in both low and high grain yield environments was well below the grain yield of bread wheat cultivars.

Table 5.4. Responsiveness (*b* values) of the cultivars for grain yield, protein quantity and protein quality characteristics of wheat grown at Moora and Williams in 2005, 2006 and 2007.

				Water Absorption		Dough Strength		Dough Stability
	Cultivar	Grain Yield[a]	Grain Protein[b]	Peak Height[b]	Initial Buildup[b]	Area below curve[b]	Peak Time[b]	Breakdown[b]
	Lang	1.03	1.03	0.60	0.74	0.82^^	0.91	0.88
	Sunvale	0.99	1.18	0.54	1.49	0.75^	1.35	0.66
Bread	Carnamah	1.13*	0.98	1.38^^	0.90	1.22^^^	0.63	1.33
Wheat	GBA Sapphire	1.17*	0.99	-0.21	0.90	0.01	0.78	0.70
	Wyalkatchem	0.86*	0.79	2.2^^^	1.14	1.8^^^	1.45	1.26
	Stiletto	1.05	1.01	1.48^^	0.84	1.38^^^	0.85	1.14
	Standard Error'			0.49		0.28		0.36
Durum	Kalka	0.91	1.18	0.62	0.74	0.74	1.72	0.14
Wheat	Wollaroi	0.81*	0.99	2.23	1.26	1.00	-0.27	0.12
	Standard Error'	0.06						
Significance of difference		 >	NS NS	>> NS	NS NS	>> NS	NS NS	NS NS

* ^ >,** ^^ >>,*** ^^^ >>> Significant at P = 0.05, P = 0.01, P=0.001, respectively. *Signficantly different from *b* =1, ^Significantly different from *b* =0, [a]Grain yield was tested for difference to *b* =1, [b]Grain quality characteristics were tested for differences to *b* =0, 'Standard Error has only been included for significant differences.

Table 5.5. Grain yield (t/ha) of eight cultivars of wheat grown at Moora and Williams in 2005, 2006 and 2007.

	Moora				Williams				Mean across
Cultivar	2005	2006	2007	Mean	2005	2006	2007	Mean	site.year
Lang	1.28	2.09	1.72	1.70	3.29	1.81	3.71	2.94	2.32
Sunvale	1.06	2.09	1.70	1.61	2.77	1.85	3.69	2.77	2.19
Carnamah	1.58	2.37	2.41	2.12	3.44	1.73	4.33	3.16	2.64
GBA Sapphire	1.45	2.15	1.85	1.82	3.34	1.84	4.23	3.14	2.48
Wyalkatchem	1.84	2.60	2.25	2.23	3.26	2.20	3.97	3.14	2.69
Stiletto	1.78	2.39	2.14	2.10	3.30	1.93	4.27	3.17	2.63
Kalka	1.02	1.79	1.60	1.47	2.44	1.39	3.35	2.39	1.93
Wollaroi	1.09	1.91	1.66	1.55	2.41	1.56	3.23	2.40	1.97
Mean	1.39	2.17	1.92	1.83	3.03	1.79	3.85	2.89	2.36
LSD (P=0.05)	0.08	0.28	0.09		0.28	0.19	0.35		

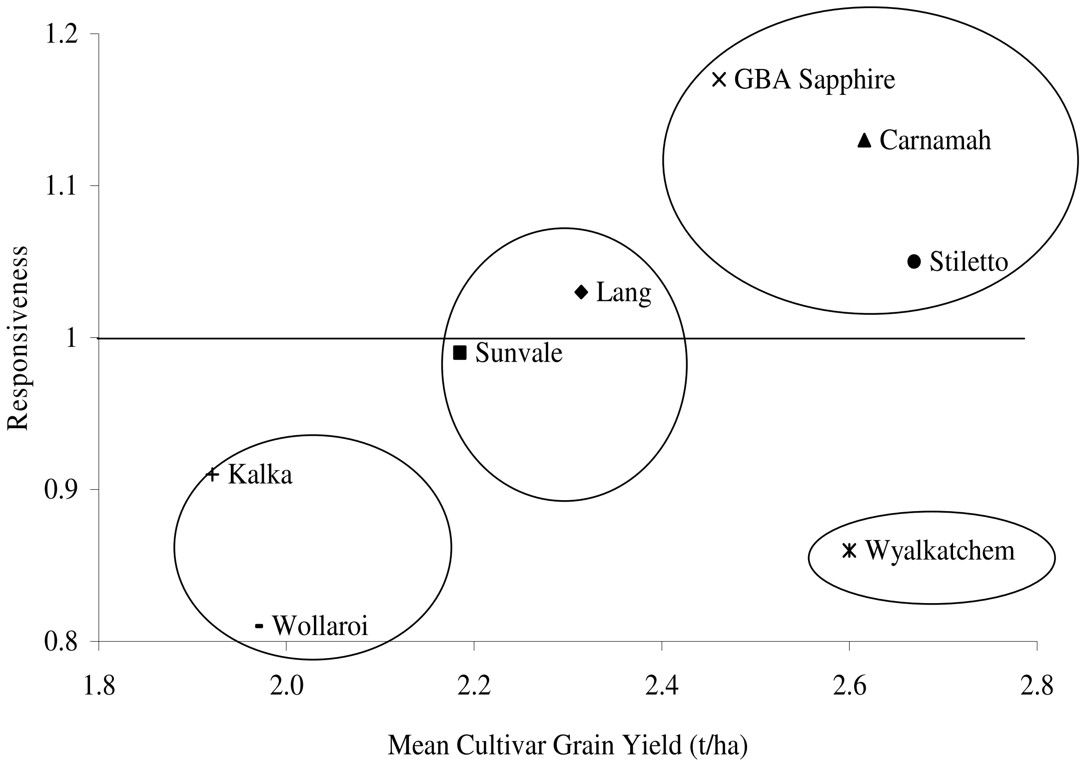


Figure 5.1. Plot of responsiveness for mean grain yield across environments for eight cultivars of wheat grown at Moora and Williams in 2005, 2006 and 2007.

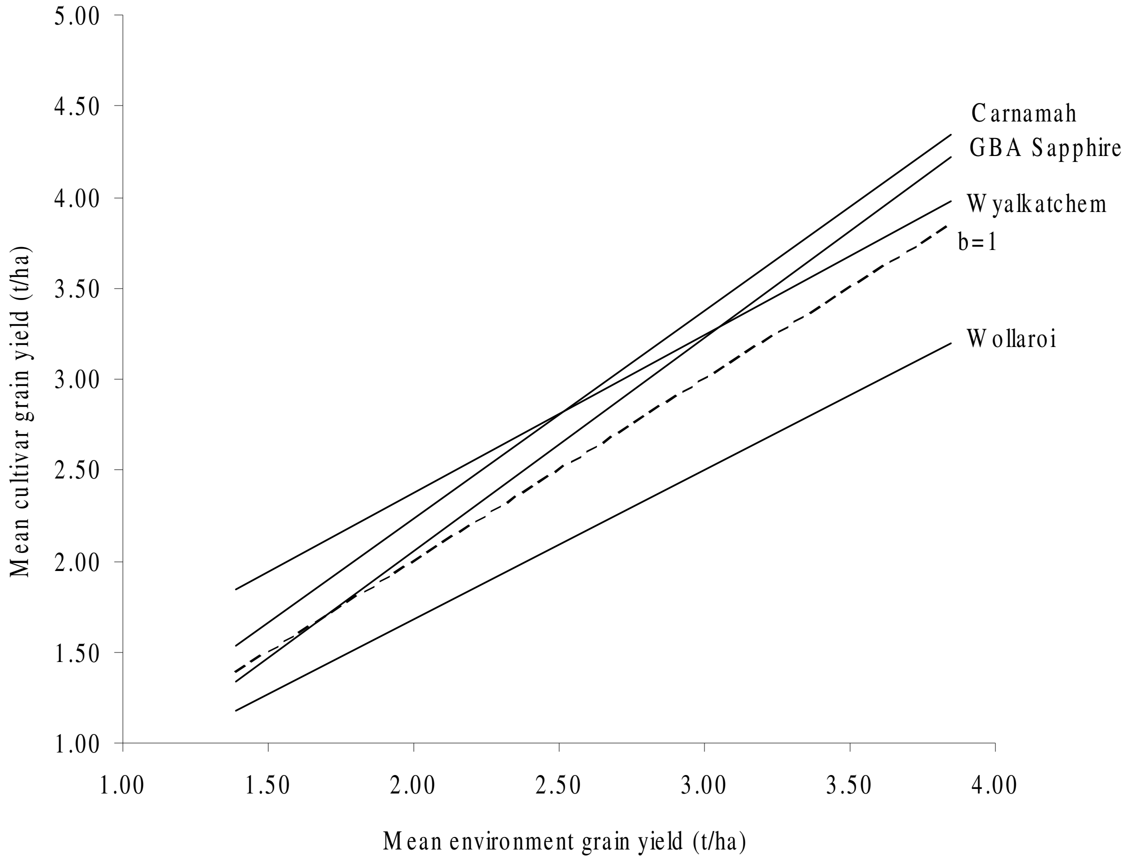


Figure 5.2. Plot of linear regressions between individual grain yield of four wheat cultivars and mean environment grain yield calculated from six environments.

5.4.4 Protein Quality

For bread wheat cultivars higher mean peak height and area below the mixograph curve was found in the grain harvested from Moora compared to Williams (Table 5.6). Overall mean peak height and area below the curve for both sites was 5.44 and 32.16, respectively. Values for mean peak height and mean area below the curve for Moora and Williams distinctly show the three quality classifications tested. Lang and Sunvale which are both Australian Prime Hard (APH) cultivars had greater peak height and area below the curve compared to Australian Hard (AH) and Australia Premium White (APW) cultivars. The highest peak height (5.69) and area below the curve (34.69) were recorded at Moora in 2006.

The responsiveness of bread wheat cultivars for peak height and area below the curve fell into four distinctive categories, which again grouped cultivars according to commercial classification. Bread wheat cultivars displayed similar responsiveness for both peak height and area below the curve (Figure 5.3 and 5.4). Wyalkatchem and Stiletto (APW) had peak height and area below the curve below the mean for all cultivars and *b* values significantly greater than 0, indicating their increasing responsiveness to environmental change. Carnamah and GBA Sapphire (AH) both had peak height and area below the curve close to the mean for all cultivars; Carnamah had *b* values significantly >0 compared to GBA Sapphire which had *b*=0. Lang and Sunvale (APH) had above mean peak height and area below the curve compared to the mean for all cultivars; for both cultivars, peak height had *b*=0, and for area below the curve *b* significantly >0.

The plot of linear regressions between bread wheat cultivars for peak height and area below the curve is shown in Figure 5.4. Lang and Sunvale (APH) consistently recorded peak height and area below the curve above the mean for all cultivars in environments that were both low and high for peak height and area below the curve. Carnamah, Wyalkatchem and Stiletto all recorded an increase in peak height and area below the curve as the environment improved. GBA Sapphire displayed static stability, recording similar peak height and area below the curve regardless of environment.

5.5 Discussion

Growers in WA face large variations in grain yield, while marketers and processors contend with large variations in grain quality, due to the variable nature of the Mediterranean-type climate in the Western Australian wheat belt. Possible effects of climate change, i.e. lower seasonal rainfall and increased temperatures in south west Western Australia (Foster 2007), could contribute to even greater variability in grain yield and quality than currently experienced. In addition, a keynote address by Edwards (1997) to the International Wheat Quality Conference highlighted areas of change in the market requirements of wheat. One of these changes was that stability of quality will assume increased importance in international markets; that is the product must meet quality specifications consistently. It is thus foreseeable that improvements in the stability of grain yield and grain quality will be required by growers, marketers and processors to address future variability and market requirements.

5.5.1 Dynamic Stability of Grain Yield

Consistently high grain yield was not found in this study for combination of sites and seasons. Mean grain yield varied between 1.39 t/ha at Moora in 2005 to 3.85 t/ha at Williams in 2007 (Table 5.5). Potential grain yield estimated by the method of French and Schultz (1984) (assuming an average water loss of 110 mm and a water use efficiency of 20 kg/ha.mm of growing season rainfall and the long term GSR for the two sites described in Table 5.3) is 5.1 t/ha for Moora and 6.4 t/ha for Williams. Actual grain yield in commercial wheat crops in the HRZ of WA is around 2.7 t/ha (Hill and Wallwork 2002). Mean grain yield in this study was 2.36 t/ha (Table 5.4) which is well below potential levels based on long term growing season rainfall, but is around 75% of the potential yield calculated for each site.season combination and in line with commercial yields. Higher grain yields at Williams were probably related to a combination of better inherent soil chemical fertility, cooler growing season maximum temperatures and generally higher rainfall compared to Moora (Table 5.3). Further discussion on the impact of environment on grain yield can be found in Chapter 3.

Table 5.6. Mixograph peak height and area below the mixograph curve for six bread wheat cultivars grown at Moora and Williams in 2005, 2006 and 2007

		Moora								Williams								Mean across site.year	
		2005		2006		2007		Mean		2005		2006		2007		Mean			
Cultivars	Commercial Classification	PH[1]	ABC[2]	PH	ABC	PH	ABC	PH	ABC	PH	ABC	PH	ABC	PH	ABC	PH	ABC	PH	ABC
Lang	APH	5.53	32.71	6.01	37.08	5.54	33.86	5.69	34.55	5.84	35.11	5.71	34.81	5.74	34.78	5.76	34.90	5.73	34.73
Sunvale	APH	6.09	35.31	5.96	36.46	5.80	34.24	5.95	35.34	5.85	33.70	5.71	34.27	5.69	34.57	5.75	34.18	5.85	34.76
Carnamah	AH	5.66	33.65	5.77	35.46	5.48	32.58	5.64	33.90	5.19	30.89	5.45	32.70	5.37	31.85	5.34	31.81	5.49	32.86
GBA Sapphire	AH	5.42	32.58	5.28	32.28	5.34	32.58	5.35	32.48	5.40	32.06	5.43	32.70	5.31	32.65	5.38	32.47	5.36	32.48
Wyalkatchem	APW	5.20	29.95	5.66	34.05	5.28	31.31	5.38	31.77	4.66	27.46	5.15	30.74	5.01	30.65	4.94	29.62	5.16	30.69
Stiletto	APW	4.92	28.98	5.46	32.79	4.90	29.94	5.09	30.57	4.82	27.97	5.07	30.34	5.06	30.89	4.98	29.73	5.04	30.15
Mean		5.47	32.20	5.69	34.69	5.39	32.42	5.52	33.10	5.29	31.20	5.42	32.59	5.36	32.57	5.36	32.12	5.44	32.61
LSD (P=0.05)		0.30	1.79	0.35	2.31	0.29	1.98			0.38	2.27	0.28	1.75	0.31	1.72				

[1]PH=Mixograph Peak Height (measured in torque), [2]ABC=Area below the mixograph curve (torque x minutes)

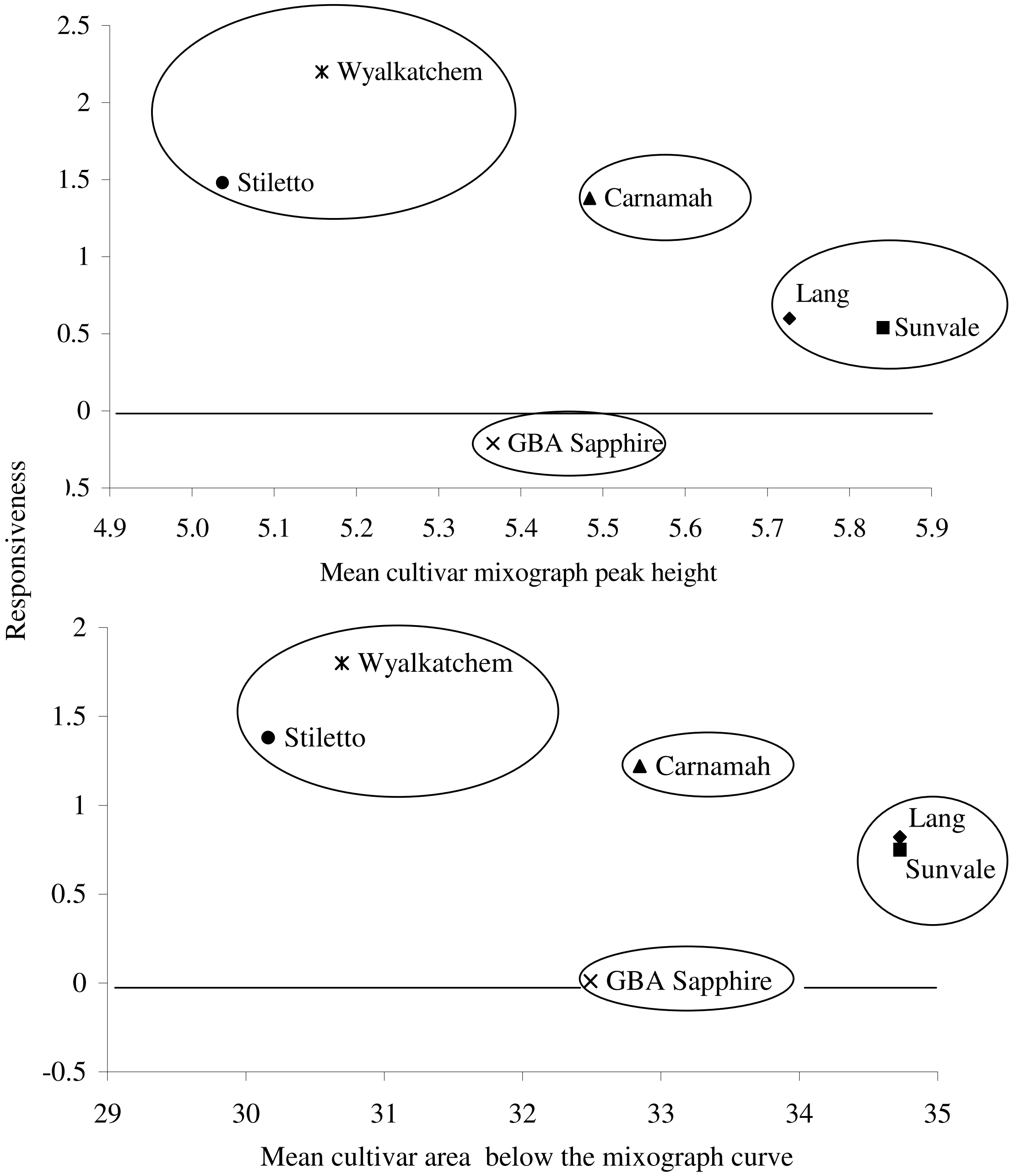
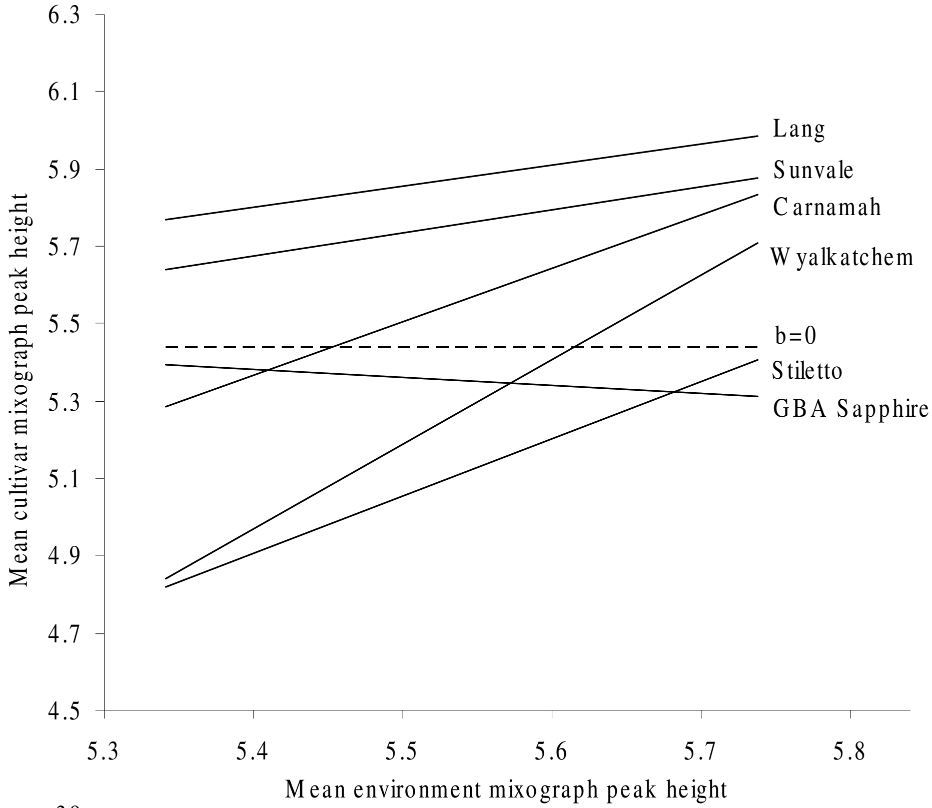


Figure 5.3. Plot of responsiveness for mixograph peak height and area below the mixograph curve to environments for bread wheat cultivars grown at Moora and Williams in 2005, 2006 and 2007.



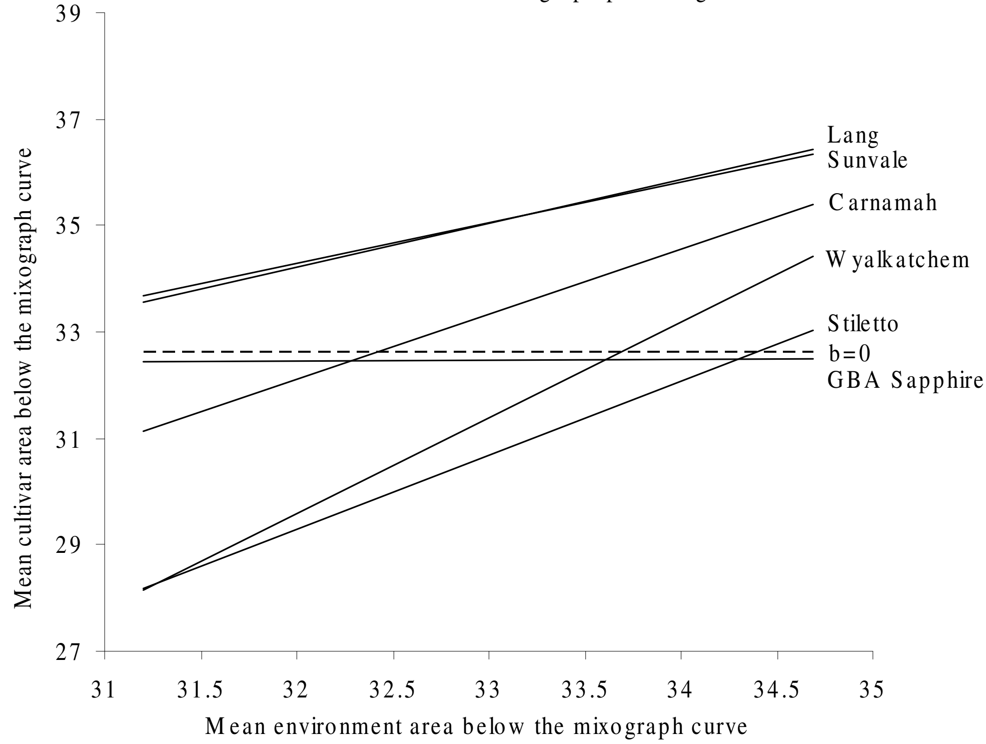


Figure 5.4. Plot of linear regressions between bread wheat cultivars and environmental mean for mixograph peak height and area below the mixograph curve.

Significant grain yield differences were recorded between bread wheat cultivars and durum cultivars. These differences are an indication of the lack of specific adaptation of the durum cultivars to the WA environment. The two highest average yielding cultivars Wyalkatchem (2.69 t/ha) and Carnamah (2.64 t/ha) have been bred for the WA environment. Conversely, the difference between bread wheat and durum wheat indicates that there is considerable potential for breeding durum cultivars with adaptation to the WA environment and more specifically the HRZ.

Wheat cultivars Lang, Sunvale, Stiletto and Kalka all had *b*-values not significantly different from *b*=1; varieties Carnamah and GBA Sapphire had *b* values >1. These cultivars display dynamic stability, the ability to respond to the environment but in a predictable way, which growers consider desirable for grain yield. Furthermore, these cultivars may act as potential check cultivars or parents of future cultivars which can be used to improve dynamic grain yield stability in an increasingly variable environment due to the forecasted effects of climate change. Grain yield stability differences between cultivars recorded in this study are similar to those of Peterson *et al.* (1992) in bread wheats and Tesemma *et al.* (1998) in durum wheat.

5.5.2 Static Stability of Grain Protein Quantity and Quality in Bread Wheat Cultivars

Greater consistency was found for peak height and area below the curve for each of the site x season combinations tested. The range between environments for peak height (range 5.29-5.96, mean 5.44, Table 5.5) and area below the curve (range 31.20-34.69, mean 32.61) was narrow, with the exception of one environment. At Moora 2006 peak height (5.69) and area below the curve (34.69) were above other environments. This environment also produced grain with protein quantity well above other environments (13.3%, data presented in Chapter 3) and may be the reason why Moora 2006 had peak height and area below the curve greater than in other environments.

Consistency for peak height and area below the curve was found between the three different commercial classifications of bread wheat tested. Australian Prime Hard cultivars Lang and Sunvale, bred and selected for conditions in eastern Australia, tended to have higher peak height and area below the curve compared to AH cultivars Carnamah and GBA Sapphire and APW cultivars Wyalkatchem and Stiletto bred and selected under conditions more typical of the Western Australian environment. These results indicate that cultivars with desirable water absorption and dough strength are likely to be stable across variable environments and will express their traits in the HRZ environment of Western Australia if grown under good conditions of fertility and management (Chapter 4).

Values of b among bread wheat cultivars for peak height ranged from -0.21 (GBA Sapphire) to 2.2 (Wyalkatchem), while b values for area below the curve ranged from 0.01 (GBA Sapphire) to 1.38 (Stiletto). Carnamah, Wyalkatchem and Stiletto had b values significantly >0 for peak height. All bread wheat cultivars except GBA Sapphire had b values significantly >0 for area below the curve. Lang, Sunvale and GBA Sapphire for peak height and GBA Sapphire for area below the curve displayed static stability which is considered to be a desirable quality characteristic (Grausgruber *et al.* 2000). While significant stability differences were recorded between bread wheat cultivars for water absorption and dough strength, direct comparisons with other studies is difficult due to the select nature of the mixograph characteristics tested.

The responsiveness of GBA Sapphire for both peak height and area below the curve contrasts with the comments of Grausgruber *et al.* (2000); they observed that quality characteristics in wheat usually react to environmental conditions and therefore it is unrealistic to expect the same level of performance across all environments. GBA Sapphire had static stability (b=0) for both peak height and area below the curve suggesting a cultivar can maintain its quality from environment to environment. Moreover, it indicates the potential of GBA Sapphire to be used as a check cultivar against which future cultivars can be assessed for stability of water absorption and dough strength. The results of GBA Sapphire indicate the HRZ of WA is an environment where stable water absorption and dough strength can be produced.

Values of *b* amongst bread wheat cultivars for grain protein quantity, water absorption (measured by mixograph initial buildup), dough strength (measured by peak time) and dough stability (measured by mixograph breakdown), showed large variation but did not differ significantly. These results contrast with the results of Grausgruber *et al.* (2000) who reported differences in the stability of wheat cultivars for protein content from a set of experiments using eight cultivars across 15 environments (site.year) in north-east Austria. Lukow and McVetty (1991) used eight cultivars across 6 (site.year) environments in Canada and reported significant differences in *b* values for mixograph development time. Peterson *et al.* (1992) recorded differences in *b* values for mixograph peak time and mixograph mixing tolerance from 18 cultivars across 14 environments (site.year) in the USA. The results of this study may differ with those reported above due to the number of cultivars tested, the differing genetic base of Australian cultivars and the environments in which they were tested.

5.5.3 Static Stability of Grain Protein Quantity and Quality in Durum Wheat Cultivars

Large variations between *b* values amongst durum cultivars Kalka and Wollaroi were recorded for grain protein quantity and all protein quality characteristics, but the differences were not statistically significant (Table 5.4). In contrast to the results of this study significant stability differences between durum cultivars for grain protein quantity were reported previously by Rharrabti *et al.* (2003). Differences between durum cultivars for protein quality stability have been reported previously (Letta *et al.* 2008; Rharrabti *et al.* 2003), nevertheless, the quality characteristics examined were wet gluten and SDS volume and not mixograph characteristics as investigated in this study. No studies to examine the stability of mixograph characteristics for durum wheats have been published.

The reason for the lack of significant differences between cultivars in this study is perhaps due to the limited number of cultivars tested. Letta *et al.* (2008) used nine and Rharrabti *et al.* (2003) ten cultivars in their studies on stability of durum quality. Nonetheless, based on the large variations observed and the recorded significant differences between bread wheat cultivars for protein quality there is potential for stability differences to exist between durum cultivars grown in the HRZ of WA. For durum production to increase in WA, stability of quality will be particularly important if the forecast of increased variability in rainfall and temperature affects south west WA (Foster 2007).

5.6 Conclusion

This study has reported significant dynamic and static stability differences in wheat for grain yield and some important quality attributes of wheat. The dynamic stability of cultivars Lang, Sunvale, Stiletto and Kalka for grain yield and the static stability of GBA Sapphire for water absorption and dough strength indicates that the HRZ of WA is an environment that can produce stable grain yield and protein quality. These differences can be used to identify check cultivars to be used in testing programmes and for environments where similarity of performance for quality characteristics can be of advantage.

The importance of dynamic stability for grain yield and static stability for grain quality may increase if forecasted lower seasonal rainfall and increased temperatures in south west WA contribute to even greater variability than currently experienced and as end-users increase the requirements for consistent quality. The current Australian classification system has no requirements for cultivars to achieve minimum dynamic or static stability requirements. However, the results of this study suggest that it may be possible to identify check cultivars which display the desired concept of stability and can subsequently be used to define minimum stability standards which future cultivars must achieve before being released. The National Variety Testing (NVT) programme in Australia which examines the performance of wheat cultivars across many environments may provide a significant resource to determine the most appropriate check cultivar.

5.7 Acknowledgments (as per Chapter 3)

Special thanks must be given to all the staff of Kalyx Agriculture for assistance throughout the project. We wish to thank Mr. Geoff Higham, Mr. David Brown and Mr. Don McKinley for supplying land used for the experiments. The assistance of Department of Agriculture and Food, Western Australia in particular Mr. Troy Adriansz and Dr. Ben Biddulph for technical advice and Mr. Andrew Van Burgel for assistance in data analysis is greatly appreciated. Special mention to Dr. Joe Panozzo and Miss Cassandra Black for conducting the mixograph analysis. This research was funded by Kalyx Agriculture, Department of Agriculture and Food, Western Australia, Curtin University of Technology and Mr. Darren Hughes.

Chapter 6

General Discussion

6. General Discussion

6.1 Introduction

Cultivar by environment interactions in wheat is complex; significant resources have been invested to understand the effects. Nonetheless, cultivar by environment studies tend to neglect the impact of management which is often included as part of the environment term (Anderson *et al.* 2005) and may be overlooked when assessing variability of grain yield and quality. This study has found that nutrition as one part of management can significantly increase the grain yield and quality of wheat grown in the High Rainfall Zone (HRZ) of Western Australia. Researchers need to understand the compounding effects of management on cultivar by environment interactions and not simply ignore its effects. At the practical level it is more important for farmers to manage variables such as time of sowing, nutrition, rotations, weed and disease control as appropriate to their location rather than to expend much effort on their choice of cultivar as the means of addressing environmental variability. However, this study has identified differences in the stability of cultivars for grain yield and quality characteristics that may be useful for selection at the farm scale.

Given the known effects of management on grain yield and quality of wheat, should future cultivar by environment studies be expanded to include management as a main effect? Should environment represent the effects of climate and soil type with all other effects to be included in management? Perhaps Figure 6.1 better illustrates all factors which affect the grain yield and quality of wheat compared to Figure 2.1 in Chapter 2, which illustrates traditional thinking on factors which affect yield and quality.

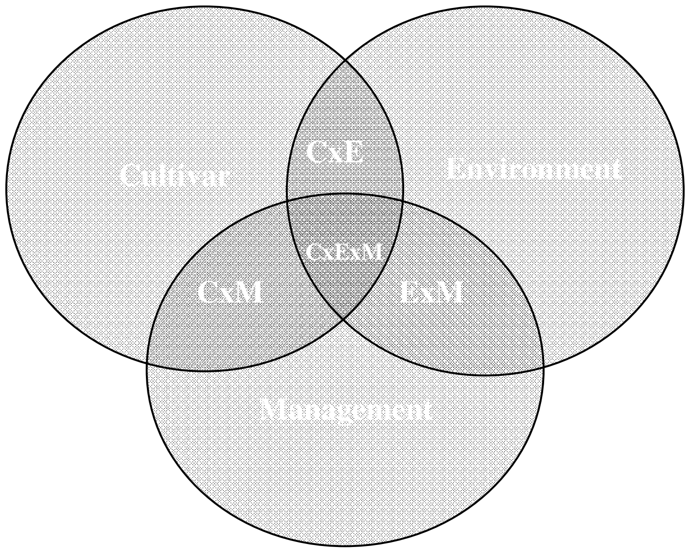


Figure 6.1. Cultivar, environment, management and interactions on grain quality in wheat.

The results of this study do not discount the importance of cultivar or environment. Breeding cultivars for increasing grain yield and improved grain quality and agronomic characteristics is important. Similarly, identifying and overcoming/minimising local constraints to production is also important. This chapter, under the headings cultivar, environment and management, expands the context of some of the issues raised in the discussion section of Chapters 3, 4 and 5 and raises further points of discussion.

6.2 Cultivar

Cultivar had a small but significant effect on grain yield and quality characteristics (Chapter 3 and 4). It was responsible for 2% of the variation for grain yield and grain protein and up to 6% for 1000 seed weight (Chapter 3). Cultivar was, however, the predominant source of variation for dough strength (mixograph peak time 46%) and dough stability (mixograph breakdown, 47%; Chapter 4). These results indicate that the influence of cultivar may be more through contributions to grain quality than through contributions to grain yield in the WA environment.

Chapters 3 and 5 detail the need to develop cultivars which are better adapted for yield and quality to the longer and cooler growing conditions of the HRZ; for this to happen there must be commercial incentives. The HRZ of WA consists of 4.8 million ha of which 3.7 million ha is available for agriculture (Hill and Wallwork 2002); of this approximately 864,000 ha is sown to annual grain crops (Zhang *et al.* 2006). Moreover, potential grain yield for wheat in Kojonup is 5.7 t/ha (Zhang *et al.* 2006) which is considerably higher than the 2.7 t/ha found in a recent survey of commercial crops (Hill *et al.* 2007). Considerable potential for increased production and the possibility of greater returns based on end point royalties may provide the commercial incentives needed to develop cultivars better adapted to environmental conditions in the HRZ.

This research has also identified significant stability differences between cultivars for grain yield, water absorption and dough strength (Chapter 5). The Australian wheat industry is moving towards a deregulated market, meaning many marketing organisations now have the opportunity to export bulk cargos of wheat to international customers. Therefore, stability differences identified between cultivars may offer potential commercial benefits. Prior to commercial release cultivars are commonly submitted to the National Variety Testing (NVT) program, which examines the grain yield and quality of cultivars in many different environments throughout Australia. The NVT assesses protein quantity but does not currently conduct widespread protein quality assessments. Grain marketing organisations could potentially take publically available

NVT data and subject it to stability analysis, thereby identifying cultivars which display stable grain protein. Thus cultivars that are found to have consistent grain protein and the locations in which they are produced could be identified allowing marketing organisations to offer customers greater consistency of raw material.

The results of this study recorded no significant stability differences between cultivars for grain protein quantity (Chapter 5). However, the results of Grausgruber *et al.* (2000) demonstrated stability differences between cultivars for grain protein quantity. Inclusion of a wider range of genotypes in breeding experiments compared to those examined in this experiment, may lead to grain protein quantity stability differences being identified between cultivars when grown in the variable WA environment.

It is possible that due to market requirements (Edwards 1997) and the impact of climate change (Foster 2007) the importance of grain yield and quality stability in wheat will increase. Developing minimum stability standards and incorporating them into the commercial classification system, which currently has no minimum stability standards, may help to reduce some of the large variations in yield and quality often experienced in the variable Mediterranean-type climate of WA. Perhaps check cultivars can be used to define these minimum standards.

Check cultivars display known grain yield and quality characteristics and are routinely used throughout breeding and cultivar evaluation programmes to assess the performance of developing germplasm. The use of check cultivars for stability evaluation is not new. Busch *et al.* (1969) indicated that knowledge of response and relative stability of check cultivars can assist the breeder in selections for stable cultivars. However, using check cultivars to define minimum stability standards is new. Check cultivars must therefore display i) the desired concept of stability and ii) inherent high/low properties depending on the characteristic under investigation.

In this study GBA Sapphire displayed static stability for both water absorption (peak height) and dough strength (area below the mixograph curve), which is considered desirable by the milling and baking industry (Grausgruber *et al.* 2000). Cultivars Lang, Sunvale, Stiletto and Kalka displayed dynamic stability for grain yield which is considered desirable by growers (Chapter 5). The desired concept of stability depends upon the characteristics under investigation, however, is only part of what a check cultivar must display.

Check cultivars must also display inherent high/low properties for the characteristic under investigation. For example, Figure 6.2i displays dynamic stability of three cultivars ‘a’, ‘b’ and ‘c’. Cultivar ‘b’ is likely to record mean grain yield in any environment. Cultivar ‘c’ is likely to record below mean yield in any given environment. Cultivar ‘a’ is likely to record above mean grain yield in any environment. Therefore, cultivar ‘a’ could be considered a check cultivar for stable grain yield; it displays the qualities needed, dynamic stability and inherently high grain yield. Figure 6.2ii displays static stability of cultivars ‘a’, ‘b’ and ‘c’. Again it depends on the characteristics under investigation but cultivar ‘a’ could be considered desirable for water absorption and dough strength having both static stability and inherent high characteristics. Cultivar ‘c’ could be considered desirable for screenings; static stability and inherently low properties. Based on the results of this study (Chapter 5) Stiletto is a possible check cultivar for grain yield stability, dynamic stability and above mean grain yield. For water absorption and possibly dough strength Sunvale may act as a possible check cultivar for static stability and above mean water absorption and dough strength.

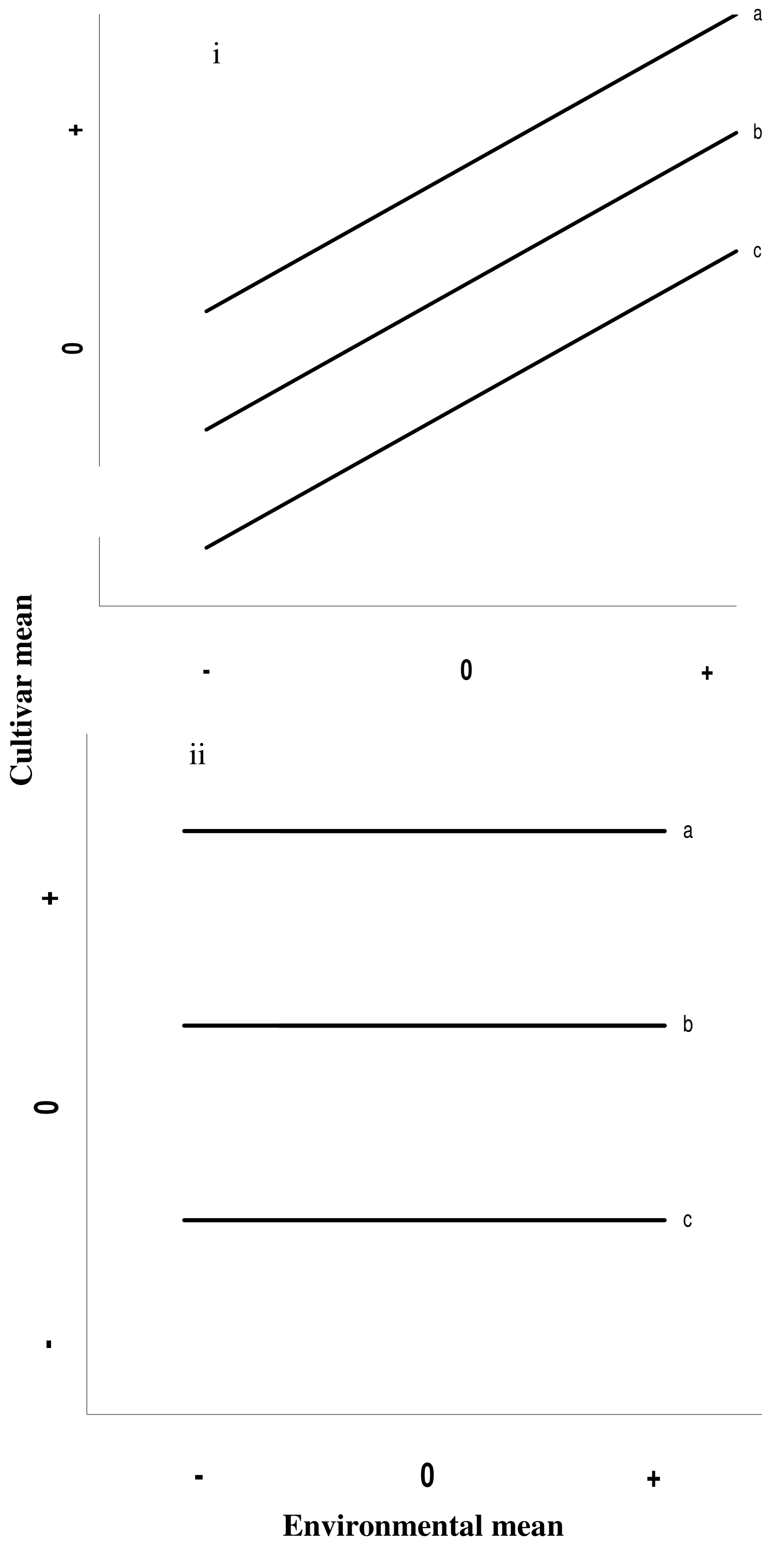


Figure 6.2. Plot of linear regression between dynamic (i) and static (ii) concepts of stability for cultivars a, b and c.

6.3 Environment

Environment is a term used widely throughout scientific agricultural literature but its definition is sometimes not clear. Basford and Cooper (1998) defined environment as a set of biophysical factors (eg. water and temperature) that influence the growth and development of the cultivars and thereby influence the expression of the trait(s). Traditional cultivar by environment studies often describe environment as a combination of climate, soil and management. This study has defined environment as year, site and combinations of years x sites. This implies that environment is a combination of climate (largely rainfall and temperature), crop history and soil type. However, the inclusion of soil type can also complicate the definition since deficiencies in soil properties can often be overcome through management. For example, liming to correct soil pH can be used to improve soil characteristics and crop performance. Crop history can also obscure the definition of environment because growers have management control over which crops are grown. Therefore, an accurate definition of environment may always be complicated by management factors. Perhaps a more appropriate definition for environment should include only those factors which influence growth and development of the plant, but are beyond reasonable control of the grower.

The results of this study have indicated that environment accounted for almost 90% of the variation for grain yield, milling yield and selected grain quality characteristics (Chapters 3 and 4). Within environment, site was consistently responsible for greater than 50% of the variation for grain yield and quality characteristics. To increase grain yield and quality, researchers and growers need to identify local constraints to production and techniques to overcome and minimise these constraints. Furthermore, growers must use a number of management techniques to lessen the impact of environment on yield and quality. For example techniques such as reduced tillage sowing systems, summer weed control and stubble retention will allow growers to establish crops on minimal stored soil moisture. Furthermore, raised bed systems will minimise water-logging on susceptible soils and the timing of nitrogen application in relation to environmental status and crop demand will be increasingly important. Perhaps more importantly a grower must maintain flexibility within the farm system to reduce the negative impact of environment in below average seasons and to maximise the positive effects of environment in above average seasons.

The significant environmental differences identified in Chapters 3 and 4 also identify potential commercial opportunities for both grain marketers and growers. The crop grown at Moora had significantly higher grain protein quantity, water absorption and dough strength than the same cultivars grown at Williams. Although significant the magnitude of the differences between sites for protein quality were relatively small compared to differences between sites for protein quantity. Growers are commonly paid on protein quantity; therefore growers in Moora are likely to be paid higher prices than growers in Williams. Grain marketers filling orders for specific quality requirements could possibly source some higher protein wheat in Moora at a higher price but source the remainder from Williams to provide a sample that still meets the milling/baking requirements of the customers. As indicated in Chapter 4, quick, accurate and reliable testing procedures at the time of delivery are needed to allow growers and marketers to take advantage of differences in protein quality identified between sites.

Despite aiming to choose sites with similar soil nutrition, soil test results show Williams had higher N, P, K, S and organic carbon compared to Moora (soil test results are in Chapter 3). The results of this study (Chapters 3 and 4) have demonstrated that site was responsible for 50-76% of the variation for grain yield, 1000 seed weight, screenings, test weight and Hagberg falling number. Higher grain yield, 1000 seed weight, test weight and lower screenings and Hagberg falling number was recorded at Williams. Low soil nutrition has previously been identified as limiting production in the HRZ of WA (Hill *et al.* 2007), therefore the discrepancy in soil nutrition between Williams and Moora may help to explain some of the overwhelming impact of site recorded in this study. Choosing sites with more even soil nutrition may have reduced the impact of site on the results of this study.

6.4 Management

This study has defined management as practices, techniques or options reasonably available to growers to influence the growth and development of the crop and the expression of quality traits(s). Management, which in this study was increasing levels of nutrition, was the predominant source of variation and resulted in significant increases in grain protein quantity, water absorption and dough strength. There was a trend towards increased dough stability with increasing levels of nutrition (Chapter 4). Detailed discussion on the response of protein quality to added nutrition is given in Chapter 4; nonetheless, the low nutrient status of WA soils appears to be restricting protein quality.

To further explore the impact of increasing nutrition on quality, regression analysis as outlined by Findlay and Wilkinson (1963), was used to examine the stability of cultivars for grain yield, grain protein quantity and quality. Due to limitations within the experimental design differences were not tested for statistical significance. The results represent trends in the data and discussion has focused on possible reasons and potential implications of the identified trends.

All cultivars recorded an increase in grain yield and grain protein as nutrition increased; however, the level of response was governed by cultivar (Table 6.1). The responsiveness of cultivars to increasing nutrition for grain yield and grain protein quantity is presented in Figures 6.3 and 6.4, respectively. Carnamah/Stiletto (2.28 t/ha) recorded the highest and Wollaroi (1.65 t/ha) the lowest grain yield at the control level of nutrition. As nutrition increased to ‘grower’ and ‘researcher’ levels, the order of cultivars from highest to lowest began to change. At the ‘researcher’ level of nutrition Wyalkatchem (3.04 t/ha) had the highest and Kalka (2.08 t/ha) the lowest grain yield. Similar changes in the order of cultivars for increasing nutrition were also evident for grain protein quantity. At the ‘control’ level of nutrition Wollaroi (10.5 %) had the highest and Carnamah/Stiletto (9.5%) the lowest grain protein quantity. At the ‘researcher’ level the durum cultivar Kalka (13.9%) recorded the highest level of grain protein quantity and the APW cultivar Wyalkatchem (11.9%) the lowest. Lang and Sunvale (APH cultivars) displayed similar responsiveness to nutrition for both grain yield and protein.

Table 6.1. Cultivar by Management interactions for Grain Yield, Grain Protein, Water Absorption and Dough Strength for wheat grown at Moora and Williams in 2005, 2006 and 2007.

					Water Absorption	Dough Strength
	Cultivar	**Management Regieme**	**Grain Yield^{A}**	**Grain Protein^{B}**	**Peak Height^{C}**	**Area Below Curve^{D}**
Bread Wheat	**Lang**	**Control**	1.90	10.3	5.1	30.6
		Grower	2.50	11.6	5.8	35.2
		Reseacher	2.55	13.3	6.3	38.4
	Sunvale	**Control**	1.85	10.2	5.2	30.2
		Grower	2.25	11.6	5.8	34.4
		Reseacher	2.46	13.2	6.5	39.6
	Carnamah	**Control**	2.28	9.5	4.9	28.6
		Grower	2.81	10.7	5.4	32.5
		Reseacher	2.76	12.7	6.1	37.5
	GBA Sapphire	**Control**	2.08	9.8	4.8	28.4
		Grower	2.48	11.1	5.3	32.1
		Reseacher	2.82	12.4	6.0	37.0
	Stiletto	**Control**	2.28	9.5	4.4	25.6
		Grower	2.66	11.0	5.0	30.2
		Reseacher	2.86	12.6	5.7	34.7
	Wyalkatchem	**Control**	2.21	9.7	4.7	27.1
		Grower	2.76	10.8	5.1	30.5
		Reseacher	3.04	11.9	5.6	34.6
Durum Wheat	**Kalka**	**Control**	1.69	10.2	3.5	19.4
		Grower	2.00	12.1	3.8	21.2
		Reseacher	2.08	13.9	4.1	22.7
	Wollaroi	**Control**	1.65	10.5	3.9	23.4
		Grower	2.07	12.1	4.6	26.7
		Reseacher	2.18	13.5	4.7	27.1
	l.s.d*		0.5	0.2	0.2	1.3

*l.s.d P = 0.05, ^{A}=t/ha, ^{B}=%, ^{C}=torque, ^{D}=torque x minutes

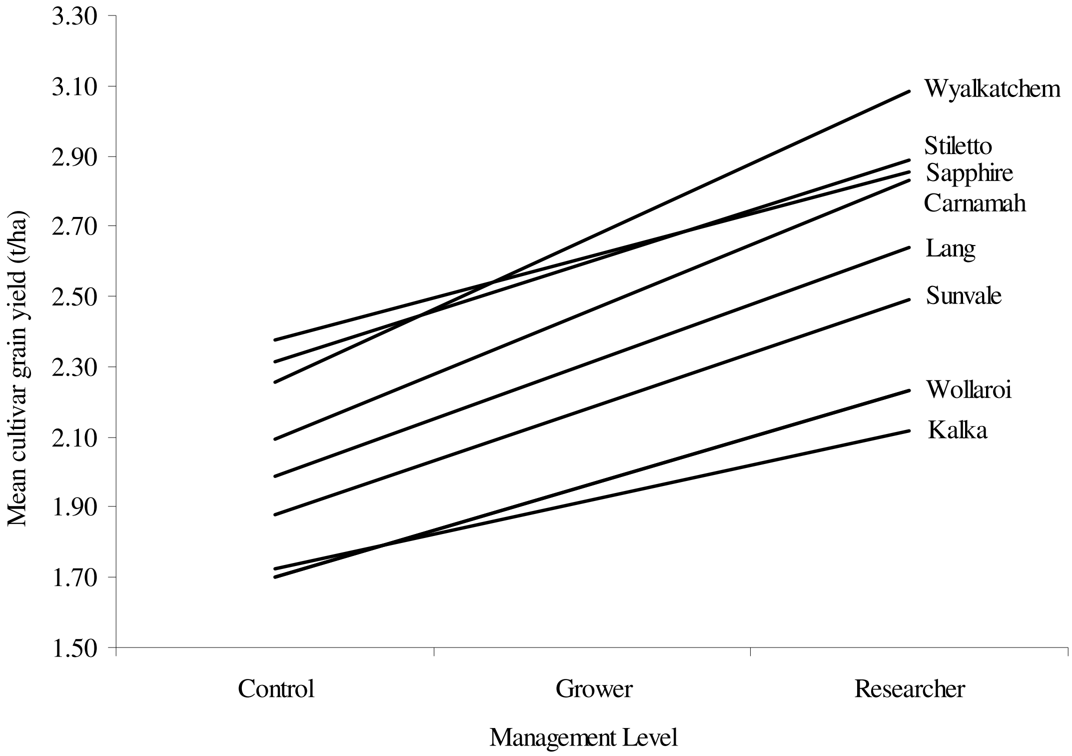


Figure 6.3. Plot of linear regressions between individual wheat cultivars for grain yield and mean nutrition regime grain yield.

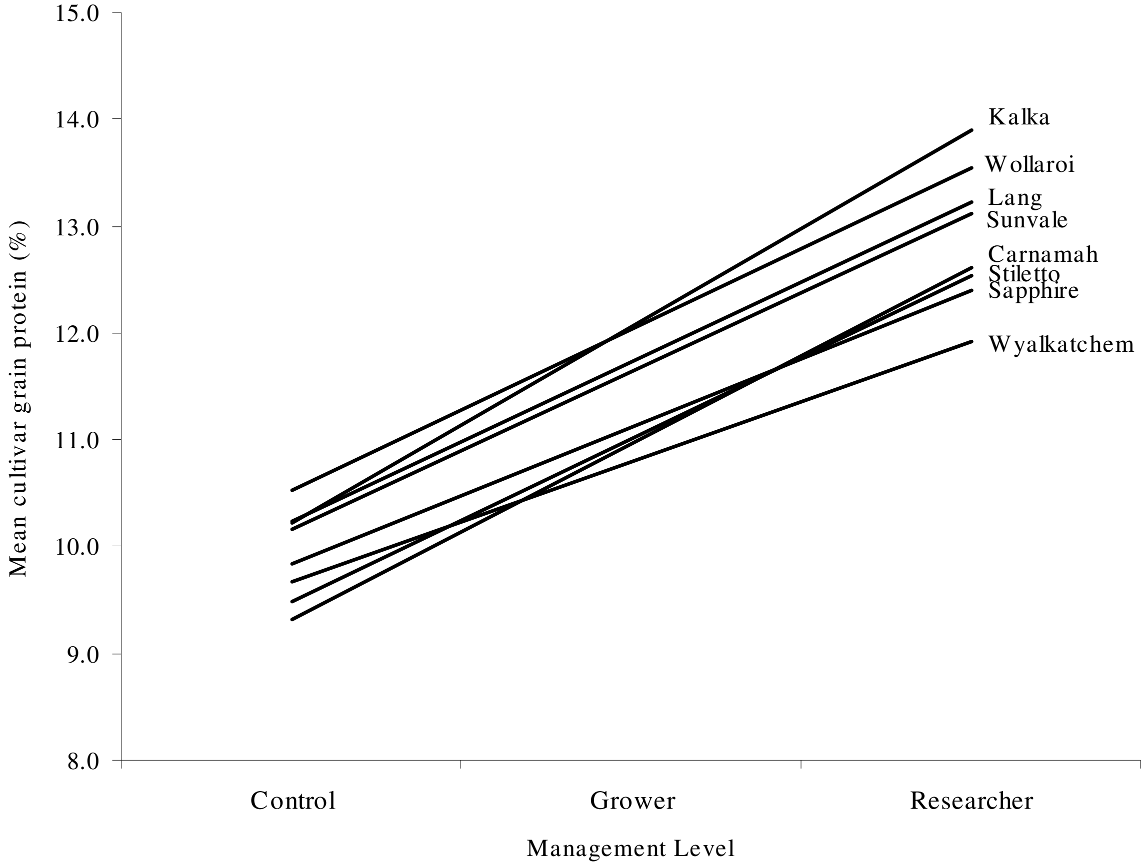


Figure 6.4. Plot of linear regressions between individual wheat cultivars for grain protein and mean nutrition regime grain protein.

Water absorption (peak height) and dough strength (area below the curve) increased as the level of nutrition increased (Table 6.1). Stiletto (APW cultivar) recorded the lowest peak height (4.4) and area below the curve (25.6) at the 'control' level of nutrition. Sunvale (APH cultivar) recorded the highest peak height and area below the curve at the researcher level of 'nutrition'. Lang and Sunvale (APH cultivars) consistently recorded greater peak height and area below the curve over all nutrition regimes compared to other cultivars. Unlike grain yield and protein quantity, protein quality tended to respond to increasing nutrition in a similar way.

Only minor changes in the order of cultivars for water absorption and dough strength were recorded as nutrition increased from 'control' to 'research'. Responsiveness of cultivars to increasing nutrition for peak height (i) and area below the curve (ii) are presented in Figure 6.5. (The responsiveness of durum cultivars has also been illustrated in Figure 6.5, however, due to the different protein quality properties of bread and durum wheats direct comparisons should not be made.) Stiletto had slightly higher peak height and area below the curve compared to Wyalkatchem at the 'researcher' level than at the 'control' level. Sunvale also had greater area below the curve compared to Lang at the 'researcher' level than at the 'control' level.

Observed changes in the responsiveness of cultivars to increasing levels of nutrition may relate to the different abilities of cultivars to take up and utilise nutrients, otherwise termed efficiency. Cultivars can differ in their utilisation of nutrients due to differences in morphology and physiology of the root system (Rengel 1999). Osborne and Rengel (2002) and Damon and Rengel (2007) examined the efficiency of wheat to utilise phosphorus and potassium, respectively, in a series of glasshouse and field experiments, using largely Western Australian developed cultivars in the WA environment. Osborne and Rengel (2002) demonstrated that there was large variation between cultivars in growth and P efficiency. Cultivars were considered P efficient if they recorded high shoot dry weight, high relative shoot growth at deficient compared with sufficient P supply and high P utilisation efficiency (shoot P uptake = shoot P content- seed P content).

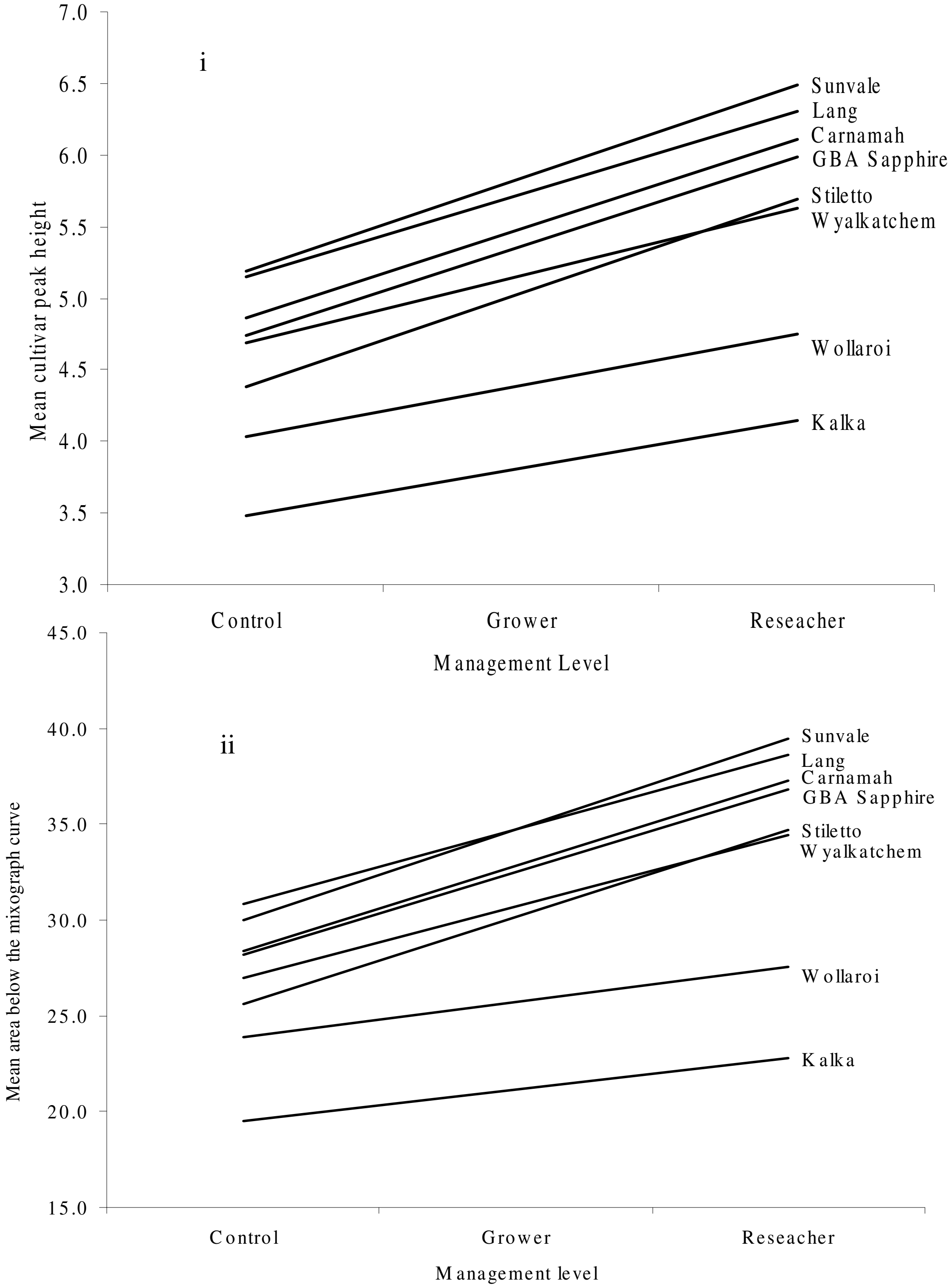


Figure 6.5. Plot of linear regressions between individual cultivars for (i) water absorption (peak height) and (ii) dough strength (area below the mixograph curve) and mean nutrition water absorption (peak height) and dough strength (area below the curve).

Unfortunately this study did not rank cultivars for P efficiency for grain yield. Damon and Rengel (2007) reported significantly different responses between cultivars in low soil K environments for grain yield and were able to identify K-efficient and K-inefficient cultivars. K-efficient cultivars had the ability to maintain a high harvest index in K deficient environments while K-inefficient cultivars had reduced harvest index in K deficient environments. Damon and Rengel (2007) and this study have used three cultivars in common Stiletto, Wyalkatchem and Carnamah; Stiletto was more efficient in utilising K, followed by Wyalkatchem then Carnamah.

Differences in the efficiency of cultivars to utilise nitrogen have also been observed. Anderson and Hoyle (1999) under WA conditions concluded that cultivars could be either yield efficient (high yield increase per unit of applied nitrogen) or protein efficient (high grain protein increase per unit of applied nitrogen); no cultivars were both yield and protein efficient. Liao *et al.* (2004) also under WA conditions demonstrated differences between wheat cultivars for N uptake efficiency. Cultivars which had vigorous early shoot and root growth appeared to have greater propensity to capture N in sandy soils. These reported efficiency differences between cultivars for nitrogen, phosphorus and potassium, three essential nutrients for plant growth, may explain the stability differences recorded here.

This study demonstrated a significant increase in grain yield and quality to increasing levels of nutrition management and has documented positive effects of other management factors on grain quality. This suggests that there are potential commercial benefits for breeding companies to release cultivars with ‘management packages’; recommendations on such things as time of sowing, seeding rate, nutrition and disease control. Management packages would need to be developed for targeted environments and not developed as general recommendations across broad environments. Breeding companies invest significant resources to commercialize a cultivar and often have only limited time to recoup this investment. Significant portions of this investment are often recouped through end point royalties. Providing management guidelines to growers may help them to maximize grain yield and ensure consistent quality is achieved which in turn may extend the commercial 'life' of cultivars and the return on investment.

Chapter 7

Conclusions and Future Research

7. Conclusions and Future Research

7.1 Hypothesis

In relation to the hypothesis developed at the end of Chapter 2;

> *That management per se has a significant impact on grain quality of wheat grown in the south west of Western Australia.*

It has long been accepted that cultivar and environment have an effect on grain quality in wheat and the results of this study have confirmed their effect. However, when management, in this case nutrition, is included as a main variable and not hidden within environment it can have a greater effect than either cultivar or environment on characteristics such as grain protein quantity, the single biggest indicator of wheat quality and on other quality factors such as water absorption and dough strength. This study has primarily assessed nutrition because it is one of the biggest limiting factors to grain production in the HRZ, however, there are many more management factors which still need to be researched. Under WA conditions successful management is essential for profitability and research into both breeding and agronomy must acknowledge the contribution of management to grain quality and not ignore its effects. Based on the results of this study this hypothesis is accepted.

7.2 Aims

As against the aims described in Chapter 2;

1. *To examine physical grain and protein quality characteristics of selected wheat cultivars grown in the HRZ of WA.*

Physical and protein quality characteristics of selected cultivars grown in the HRZ of WA were examined and it was determined that with appropriate nutrition management minimum commercial grain protein requirements can be achieved. This study has also demonstrated that bread wheat grown in the HRZ of WA can display dough strength comparable to the Hard Red Spring and Hard Red Winter grades in the USA. These grades compete directly with the Australian grades tested in this study.

2. *To examine increasing levels of nutrition and their impact on physical and dough characteristics of wheat grown in the HRZ of WA.*

Increasing levels of nutrition led to a significant increase in grain protein quantity, dough strength, water absorption, Hagberg falling number and screenings. It also led to a significant reduction in 1000 seed weight and test weight. There was a trend to improved dough stability as nutrition increased. It was suggested that because of the low nutritional status of the soils used in the experiments, increasing levels of nutrition possibly led to a change in the gliadin:glutenin ratio in the grain which subsequently resulted in the improvements in dough quality characteristics.

3. *To determine the relative impact of cultivar, environment and management on physical and dough quality traits of wheat.*

Cultivar was the predominant source of variation for dough strength measured by peak time (46%) and dough stability (47%). Environment (year, site and year.site) was the predominant source of variation for grain yield (89%), 1000 seed weight (86%), screenings (90%), test weight 87%), Hagberg falling number (90%) and milling yield (86%). Management was the predominant source of variation for grain protein quantity (48%), water absorption measured by mixograph peak height (52%) and mixograph initial buildup (46%) and dough strength measured by area below the mixograph curve (52%).

4. *To determine if cultivars vary in stability for grain yield and grain quality characteristics when grown in the HRZ of WA.*

Wheat cultivars grown in the HRZ of WA do vary in both dynamic and static stability. Four cultivars (three bread and one durum) displayed dynamic stability for grain yield. Three bread wheat cultivars displayed static stability for water absorption and one bread wheat cultivar static stability for dough strength. Dynamic and static stability differences recorded between cultivars for grain yield, protein quantity and quality characteristics in some sites and seasons indicates that it may be possible to breed better environmental stability for these traits.

7.3 Future Research

i. **Analysis of large datasets incorporating a substantial number of cultivars, environments and management options/techniques to determine the relative contribution to variance**. Large datasets have been developed throughout Australia, to encompass wide genetic diversity, many environments and numerous management options/techniques for grain yield and quality. A combined analysis would be complicated due to a large number of potentially unbalanced experimental designs, however, statistical procedures exist which would allow this to happen. By identifying the largest contributors to variance it may help with the allocation of research investment.

ii. **Breeding locally adapted cultivars for the HRZ.** The HRZ has higher rainfall, longer and cooler growing seasons and higher potential grain yield than traditional low-medium rainfall areas of the wheat belt. Wheat breeding in WA has traditionally focussed on adapting cultivars for low-medium rainfall areas because the HRZ was typically dominated by livestock enterprises. More adapted genetics, such as increased water and nutrient use efficiency or better water logging tolerance, need to be developed to take advantage of the longer and cooler growing conditions in the HRZ thereby maximising potential grain yields.

   Wheat breeding organisations such as AGT, Intergrain, and particularly HRZ Wheats Pty Ltd all have a growing interest in the high rainfall area because of the potential for increased cropping and high yields from the zone; particularly HRZ Wheats who target this zone exclusively, and regard WA as potentially their largest market, but also the most challenging environment.

iii. **Identifying and overcoming local/on-farm constraints to production in the HRZ.** Results of this study have shown site to be the predominant source of variation for grain yield. This perhaps indicates that grain yield is largely limited by local or on-farm constraints. Identifying local constraints; such as low soil nutrition which was identified in this study or subsoil constraints such as compaction, acidity or salinity and eliminating or minimising these constraints will perhaps have the biggest effect on increasing grain yield in the HRZ

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9. Appendices

2005 Moora Experimental Details

Experimental Design		Rotation
Study Design:	Randomised Block Design	2002 *Trifolum Subterraneum L.*
Replications:	3	2003 *Trifolum Subterraneum L.*
Plot Width (m):	2.5 m	2004 *Trifolum Subterraneum L.*
Plot Length (m):	20 m	

Sowing Details

Sowing Date:	14/06/2005
Seeder Type:	Knifepoint
Number of Rows:	10
Row Width: (mm)	220
Seed Bed:	Poor - weed clodding
Stubble Cover (%):	0
Soil Moisture:	Good
Sowing Depth (cm):	2

Crop Protection

Date	Product	Rate
14/06/2005	Paraquat 135 g a.i/L + Diquat 115 g a.i/L	4 L/ha
	Chlorpyrifos 500 g a.i/L	1 L/ha
	Trifluralin 400 g a.i/L	1.5 L/ha
	Alcohol Alkoxylate 1000 g a.i/L	0.1 % v/v
22/07/2005	Clopyralid 300 g a.i/L	120 g/ha
	Metsulfuron 600 g a.i/L	3 g/ha

Nitrogen Application Details

	IBS	4 WAS	8 WAS
Application Date:	14/06/2005	22/07/2005	24/08/2005
Method:	Topdressed	Topdressed	Topdressed
Zaddocks	0	Z14	Z31

Soil Characteristics

	0-10 cm	10-20 cm	20-30 cm
Texture	sandy loam	loam	loam
Colour	Brown	Brown	Brown/Orange
Nitrate Nitrogen	22 mg/kg	6 mg/kg	4 mg/kg
Ammonium Nitrogen	1 mg/kg	3 mg/kg	1 mg/kg
Phosphorous Colwell	13 mg/kg	16 mg/kg	18 mg/kg
Potassium Colwell	26 mg/kg	16 mg/kg	15 mg/kg
Sulphur	3.3 mg/kg	3 mg/kg	4.1 mg/kg
Organic Carbon	0.81 %	0.45 %	0.12 %
Reactive Iron	400 mg/kg	745 mg/kg	965 mg/kg
Conductivity	0.056 dS/m	0.023 dS/m	0.025 dS/m
pH Level ($CaCl_2$)	5.2 pH	4.7 pH	4.5 pH
pH Level (H_2O)	5.9 pH	5.3 pH	4.9 pH

← N

Replicate 3	Replicate 2	Replicate 1
buffer	*buffer*	*buffer*
Lang Control	Sapphire Control	Lang Researcher
Lang Grower	Kalka Control	Wyalkatchem Grower
Lang Researcher	Kalka Grower	Lang Control
Kalka Grower	Wollaroi Grower	Sunvale Grower
Wyalkatchem Researcher	Sapphire Grower	Carnamah Grower
Kalka Control	Lang Grower	Wollaroi Grower
Carnamah Grower	Wollaroi Researcher	Wyalkatchem Control
Wyalkatchem Control	Stiletto Researcher	Stiletto Control
Sunvale Researcher	Sunvale Control	Lang Grower
Carnamah Control	Lang Control	Stiletto Grower
Sapphire Grower	Sunvale Grower	Sunvale Researcher
Wyalkatchem Grower	Sunvale Researcher	Kalka Researcher
Sapphire Researcher	Wyalkatchem Grower	Kalka Grower
Wollaroi Researcher	Wollaroi Control	Sapphire Grower
Kalka Researcher	Carnamah Control	Wyalkatchem Researcher
Stiletto Control	Stiletto Grower	Carnamah Control
Wollaroi Grower	Wyalkatchem Researcher	Wollaroi Researcher
Carnamah Researcher	Lang Researcher	Sunvale Control
Stiletto Researcher	Sapphire Researcher	Wollaroi Control
Wollaroi Control	Carnamah Grower	Sapphire Researcher
Sunvale Grower	Carnamah Researcher	Sapphire Control
Sapphire Control	Stiletto Control	Carnamah Researcher
Stiletto Grower	Kalka Researcher	Stiletto Researcher
Sunvale Control	Wyalkatchem Control	Kalka Control
buffer	*buffer*	*buffer*

fence

Figure 8.1: Plot layout for the 2005 Moora experiment

2006 Moora Experimental Details

Experimental Design

Study Design: Randomised Block Design
Replications: 3
Plot Width (m): 1.76
Plot Length (m): 20

Rotation

2005 *Lupinus angustifolius L.*

Sowing Details

Sowing Date: 29/06/2006
Seeder Type: Morris Gumbo
Number of Rows: 8
Row Width: (mm) 220
Seed Bed: friable
Stubble Cover (%): 15
Soil Moisture: excellent
Sowing Rate (kg/ha): 2-3

Crop Protection

Date	Product	Rate
28/06/2006	Glyphosate 540 g a.i/L	2 L/ha
	Trifluralin 400 g a.i/L	1.6 L/ha
	Chlorpyrifos 500 g a.i/L	1 L/ha
29/08/2006	MCPA Amine 625 g a.i/L	1.4 L/ha

Nitrogen Application Details

	IBS	4 WAS	8 WAS
Application Date:	29/06/2006	27/07/2006	23/08/2006
Application Method:	Topdressed	Topdressed	Topdressed
Crop Stage:	Z00	Z13	Z31

Soil Characteristics

	0 - 10 cm	10-20 cm	20-30 cm
Texture	Sandy Laom	Sandy Loam	Sandy Loam
Colour	Brown	Brown	Brown/Orange
Nitrate Nitrogen	31 mg/kg	11 mg/kg	4 mg/kg
Ammonium Nitrogen	2 mg/kg	1 mg/kg	1 mg/kg
Phosphorous Colwell	30 mg/kg	23 mg/kg	17 mg/kg
Potassium Colwell	31 mg/kg	29 mg/kg	19 mg/kg
Sulphur	4.6 mg/kg	4.5 mg/kg	4.6 mg/kg
Organic Carbon	1.06 %	0.76 %	0.38 %
Reactive Iron	418 mg/kg	869 mg/kg	1656 mg/kg
Conductivity	0.091 dS/m	0.031 dS/m	0.023 dS/m
pH Level ($CaCl_2$)	6.7 pH	4.5 pH	4.8 pH
pH Level (H_2O)	7.2 pH	5.3 pH	5.4 pH
Exchangeable Ca	4.16 meq/100g	1.19 meq/100g	0.53 meq/100g
Exchangeable Mg	0.35 meq/100g	0.09 meq/100g	0.05 meq/100g
Exchangeable Na	0.06 meq/100g	0.05 meq/100g	0.04 meq/100g
Exchangeable K	0.07 meq/100g	0.06 meq/100g	0.04 meq/100g
Exchangeable Al	0.00 meq/100g	0.04 meq/100g	0.05 meq/100g

N →

Replicate 3	Replicate 2	Replicate 1
buffer	*buffer*	*buffer*
Carnamah Grower	Kalka Control	Lang Control
Kalka Grower	Wyalkatchem Grower	Lang Grower
Sunvale Grower	Lang Grower	Lang Researcher
Kalka Control	Wollaroi Grower	Sunvale Control
Sunvale Researcher	Carnamah Grower	Sunvale Grower
Lang Grower	Wyalkatchem Researcher	Sunvale Researcher
Sapphire Researcher	Wollaroi Researcher	Carnamah Control
Wollaroi Researcher	Sapphire Control	Carnamah Grower
Sunvale Control	Wyalkatchem Control	Carnamah Researcher
Sapphire Control	Wollaroi Control	Sapphire Control
Wyalkatchem Grower	Stiletto Grower	Sapphire Grower
Wollaroi Grower	Sunvale Researcher	Sapphire Researcher
Wyalkatchem Control	Kalka Researcher	Wyalkatchem Control
Lang Researcher	Sapphire Researcher	Wyalkatchem Grower
Wollaroi Control	Sapphire Grower	Wyalkatchem Researcher
Sapphire Grower	Sunvale Control	Stiletto Control
Carnamah Control	Kalka Grower	Stiletto Grower
Kalka Researcher	Carnamah Control	Stiletto Researcher
Stiletto Researcher	Lang Researcher	Kalka Control
Stiletto Grower	Stiletto Researcher	Kalka Grower
Lang Control	Stiletto Control	Kalka Researcher
Stiletto Control	Carnamah Researcher	Wollaroi Control
Carnamah Researcher	Lang Control	Wollaroi Grower
Wyalkatchem Researcher	Sunvale Grower	Wollaroi Researcher
buffer	*buffer*	*buffer*

fence & road

Figure 8.2: Plot layout for the 2006 Moora experiment

2007 Moora Experimental Details

Experimental Design

Study Design:	Randomised Block Design
Replications:	3
Plot Width (m):	24
Plot Length (m):	1.76

Rotation

2004 *Triticum aestivum*
2005 *Hordeum vulgare*
2006 *Lupinus angustifolius L.*

Sowing Details

Sowing Date:	13/06/2007
Seeder Type:	Knifepoint + Presswheels
Number of Rows:	8
Row Width: (mm)	220
Seed Bed:	friable
Stubble Cover (%):	20
Soil Moisture:	adequate
Sowing Depth (cm):	2.5

Crop Protection

Date	Product	Rate
24/01/2007	Glyphosate 540 g a.i/L	900 mL/ha
	Trisulfuron 750 g a.i/kg	35 g/ha
5/06/2007	Paraquat 135 g a.i/L +	2 L/ha
	Diquat 115 g a.i/L	
	Pendimethalin 330 g a.i/L	2.2 L/ha
	Chlorpyrifos 500 g a.i/L	1 L/ha
13/06/2007	Paraquat 135 g a.i/L +	2 L/ha
	Diquat 115 g a.i/L	
	Trifluralin 400 g a.i/L	1.6 L/ha
	Chlorpyrifos 500 g a.i/L	1 L/ha
19/07/2007	Bromoxynil 250 g a.i/L +	750 ml/ha
	Diflufenican 25 g a.i/L	
	Clopyralid 300 g a.i/L	300 ml/ha
	Metsulfuron 600 g a.i/kg	3 g/ha
	Alcohol Alkoxylate 1000 g a.i/L	0.1 % v/v

Nitrogen Application Details

	IBS	4 WAS	8 WAS
Application Date:	13/06/2007	25/07/2007	22/08/2007
Placement:	topdressed	Topdressed	Topdressed
Wheat stage:	Z00	Z14/23	Z31

Soil Characteristics

Sample Depth	0 - 10 cm
Texture	loam
Colour	Brown
Nitrate Nitrogen	27 mg/kg
Ammonium Nitrogen	6 mg/kg
Phosphorous Colwell	38 mg/kg
Potassium Colwell	40 mg/kg
Sulphur	35.2 mg/kg
Organic Carbon	1.78 %
Reactive Iron	0.101 mg/kg
Conductivity	909 dS/m
pH Level ($CaCl_2$)	5.4 pH
pH Level (H_2O)	6.2 pH

← N

Replicate 3	Replicate 2	Replicate 1
buffer	*buffer*	*buffer*
Wyalkatchem Researcher	Stiletto Researcher	Lang Control
Carnamah Grower	Sapphire Grower	Lang Grower
Kalka Grower	Kalka Control	Lang Researcher
Lang Control	Wyalkatchem Researcher	Sunvale Control
Sunvale Researcher	Carnamah Researcher	Sunvale Grower
Wyalkatchem Grower	Sunvale Control	Sunvale Researcher
Stiletto Control	Wyalkatchem Grower	Carnamah Control
Carnamah Researcher	Lang Grower	Carnamah Grower
Wollaroi Control	Wyalkatchem Control	Carnamah Researcher
Sapphire Control	Sapphire Researcher	Sapphire Control
Wyalkatchem Control	Wollaroi Grower	Sapphire Grower
Wollaroi Researcher	Carnamah Control	Sapphire Researcher
Lang Researcher	Carnamah Grower	Wyalkatchem Control
Stiletto Researcher	Sapphire Control	Wyalkatchem Grower
Kalka Control	Sunvale Grower	Wyalkatchem Researcher
Wollaroi Grower	Kalka Researcher	Stiletto Control
Stiletto Grower	Lang Control	Stiletto Grower
Carnamah Control	Lang Researcher	Stiletto Researcher
Sunvale Grower	Wollaroi Control	Kalka Control
Sapphire Grower	Sunvale Researcher	Kalka Grower
Kalka Researcher	Wollaroi Researcher	Kalka Researcher
Sapphire Researcher	Kalka Grower	Wollaroi Control
Sunvale Control	Stiletto Grower	Wollaroi Grower
Lang Grower	Stiletto Control	Wollaroi Researcher
buffer	*buffer*	*buffer*

fence

Figure 8.3: Plot layout for the 2007 Moora Experiment.

2005 Williams Experimental Details

Experimental Design

Study Design:	Randomised Block Design
Replications:	3
Plot Width (m):	2.5
Plot Length (m):	20

Rotation

2004 *Lupinus angustifolius L.*

Sowing Details

Sowing Date:	28/06/2005
Seeder Type:	knifepoint
Number of Rows:	10
Row Width: (mm)	220
Seed Bed:	Friable
Stubble Cover (%):	15
Soil Moisture:	Good
Sowing Depth (cm):	3

Crop Protection

Date	Product	Rate
28/06/2005	Trifluralin 400 g a.i/L Chlorpyrifos 500 g a.i/L Paraquat 135 g a.i/L + Diquat 115 g a.i/L	1.6 L/ha 1 L/ha 2 L/ha
17/08/2005	Trisulfuron 750 g a.i/kg Esterfied oil 704 g a.i/L	15 g/ha 1 % v/v
16/10/2005	Trisulfuron 750 g a.i/kg Propiconazole 250 g a.i/L Alcohol Alkoxylate 1000 g a.i/L	15 g/ha 250 mL/ha 0.1 % v/v

Nitrogen Application Details

	IBS	4 WAS	8 WAS
Application Date:	28/06/2005	22/07/2005	17/08/2005
Method:	Topdressed	Topdressed	Topdressed
Zaddocks	Z00	Z14	Z15/24

Soil Characteristics

Sample Depth	0-10 cm	10-20 cm	20-30 cm
Texture	loam	loamy clay	loam
Gravel	10-15 %	45-50 %	45-50 %
Colour	Dark Brown	Brown	Brown
Nitrate Nitrogen	41 mg/kg	10 mg/kg	9 mg/kg
Ammonium Nitrogen	8 mg/kg	4 mg/kg	4 mg/kg
Phosphorous Colwell	55 mg/kg	9 mg/kg	9 mg/kg
Potassium Colwell	72 mg/kg	41 mg/kg	34 mg/kg
Sulphur	11.2 mg/kg	7.1 mg/kg	6.9 mg/kg
Organic Carbon	3.08 %	0.85 %	0.62 %
Reactive Iron	422 mg/kg	735 mg/kg	387 mg/kg
Conductivity	0.102 dS/m	0.039 dS/m	0.034 dS/m
pH Level ($CaCl_2$)	5.3 pH	5.2 pH	5.2 pH
pH Level (H_2O)	5.8 pH	6 pH	5.9 pH

← N

Replicate 3	Replicate 2	Replicate 1
buffer	*buffer*	*buffer*
Sapphire Control	Lang Control	Kalka Grower
Wollaroi Control	Sapphire Researcher	Carnamah Grower
Lang Grower	Stiletto Crontrol	Carnamah Control
Sunvale Researcher	Kalka Control	Wyalkatchem Control
Wollaroi Control	Wyalkatchem Control	Kalka Control
Wyalkatchem Researcher	Stiletto Grower	Stiletto Crontrol
Carnamah Researcher	Wollaroi Researcher	Sunvale Grower
Wyalkatchem Control	Wollaroi Control	Sunvale Control
Sunvale Control	Wyalkatchem Researcher	Wollaroi Control
Sapphire Researcher	Sapphire Grower	Wollaroi Researcher
Stiletto Crontrol	Wyalkatchem Grower	Kalka Researcher
Carnamah Grower	Lang Grower	Wollaroi Control
Lang Researcher	Carnamah Grower	Sapphire Control
Wollaroi Researcher	Wollaroi Control	Sunvale Researcher
Carnamah Control	Sunvale Control	Sapphire Grower
Lang Control	Carnamah Researcher	Lang Researcher
Kalka Grower	Sunvale Grower	Carnamah Researcher
Kalka Researcher	Sunvale Researcher	Lang Grower
Stiletto Grower	Carnamah Control	Stiletto Grower
Sapphire Grower	Kalka Grower	Lang Control
Kalka Control	Kalka Researcher	Wyalkatchem Researcher
Wyalkatchem Grower	Lang Researcher	Wyalkatchem Grower
Stiletto Researcher	Sapphire Control	Stiletto Researcher
Sunvale Grower	Stiletto Researcher	Sapphire Researcher
buffer	*buffer*	*buffer*

Track

Figure 8.4: Plot layout of the 2005 Williams experiment

2006 Williams Experimental Details

Experimental Design

Study Design: Randomised Block Design
Replications: 4
Plot Width (m): 1.76
Plot Length (m): 20

Rotation

2005 *Lupinus angustifolius L.*

Sowing Details

Sowing Date: 9/06/2006
Seeder Type: Morris Gumbo
Number of Rows: 8
Row Width: (mm) 220
Seed Bed: Friable
Stubble Cover (%): 15
Soil Moisture: dry
Sowing Depth (cm): 2

Crop Protection

Date	Product	Rate
8/06/2006	Paraquat 135 g a.i/L +	2 L/ha
	Diquat 115 g a.i/L	
	Chlorpyrifos 500 g a.i/L	1 L/ha
	Trifluralin 400 g a.i/L	1.6 L/ha
25/07/2006	Bromoxynil 250 g a.i/L +	500 mL/ha
	Diflufenican 25 g a.i/L	
	Clopyralid 300 g a.i/L	200 mL/ha
	Metsulfuron 600 g a.i/kg	4 g/ha
	Alcohol Alkoxylate 1000 g a.i/L	0.1 % v/v
4/10/2006	Trisulfuron 750 g a.i/L	15 g/ha
	Petroleum Oil 838 g a.i/L	1 % v/v

Nitrogen Application Details

	IBS	4 WAS	8 WAS
Application Date:	9/06/2006	11/07/2006	22/08/2006
Application Method:	Topdressed	Topdressed	Topdressed
Crop Stage:	Z00	Z13	Z16-Z30

Soil Characteristics

Depth	0 - 10 cm	10-20 cm	20-30 cm
Texture	Clay	Clay	Clay
Gravel			5
Colour	Grey	Brown/Grey	Brown/Grey
Nitrate Nitrogen	31 mg/kg	7 mg/kg	6 mg/kg
Ammonium Nitrogen	2 mg/kg	1 mg/kg	1 mg/kg
Phosphorous Colwell	33 mg/kg	7 mg/kg	7 mg/kg
Potassium Colwell	79 mg/kg	49 mg/kg	63 mg/kg
Sulphur	10.4 mg/kg	9.1 mg/kg	8.3 mg/kg
Organic Carbon	3.46 %	1.43 %	1.01 %
Reactive Iron	816 mg/kg	882 mg/kg	806 mg/kg
Conductivity	0.065 dS/m	0.03 dS/m	0.037 dS/m
pH Level ($CaCl_2$)	5 pH	5.1 pH	5.4 pH
pH Level (H_2O)	5.8 pH	6.1 pH	6.4 pH

The plot layout for Williams 2006 (Figure 8.5) has been spread over two pages. Combined the experiment looked liked this.

Replicate 3	Replicate 4
Replicate 1	Replicate 2

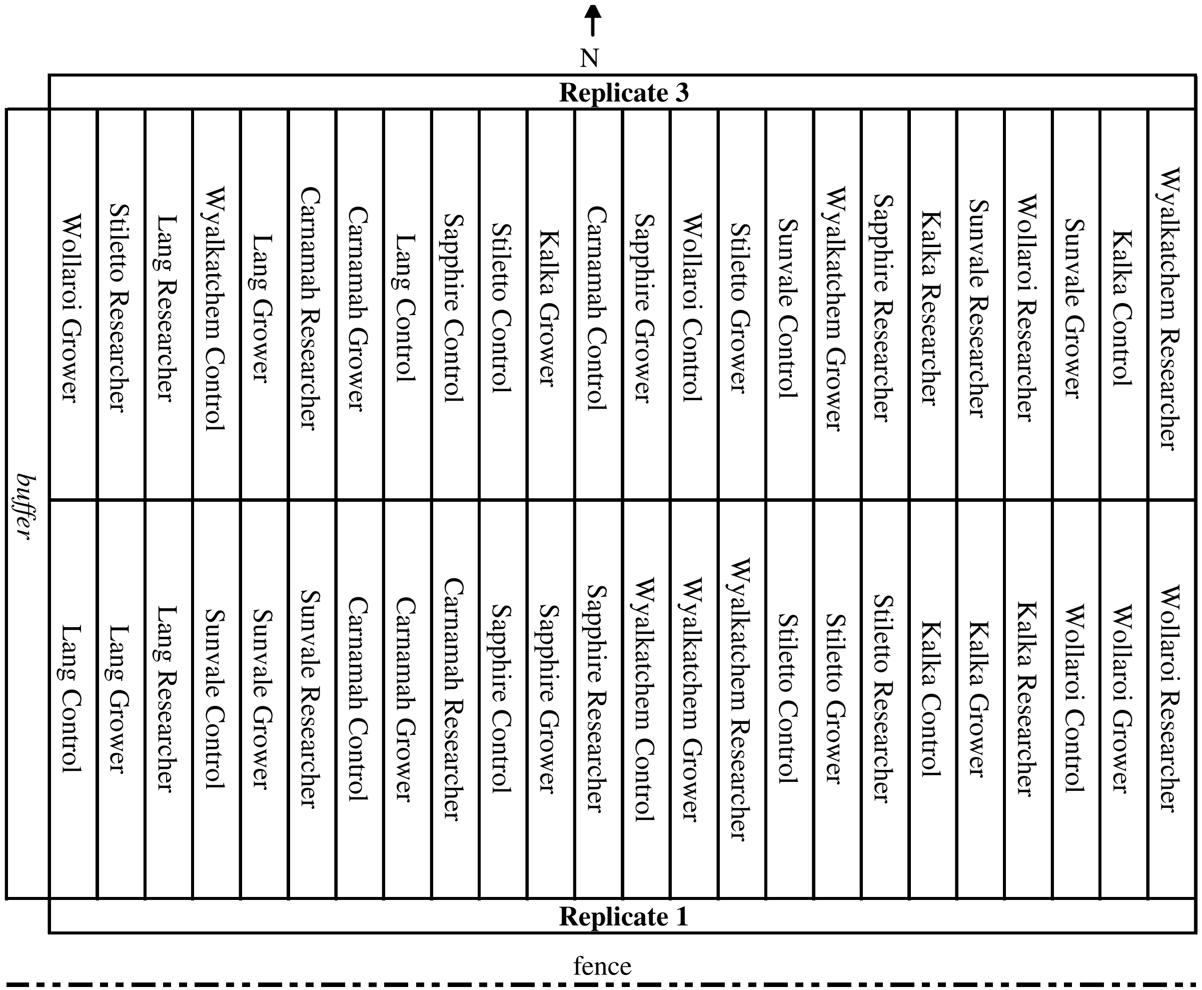

Figure 8.5a: Plot layout for replicates 1 and 3, Williams 2006.

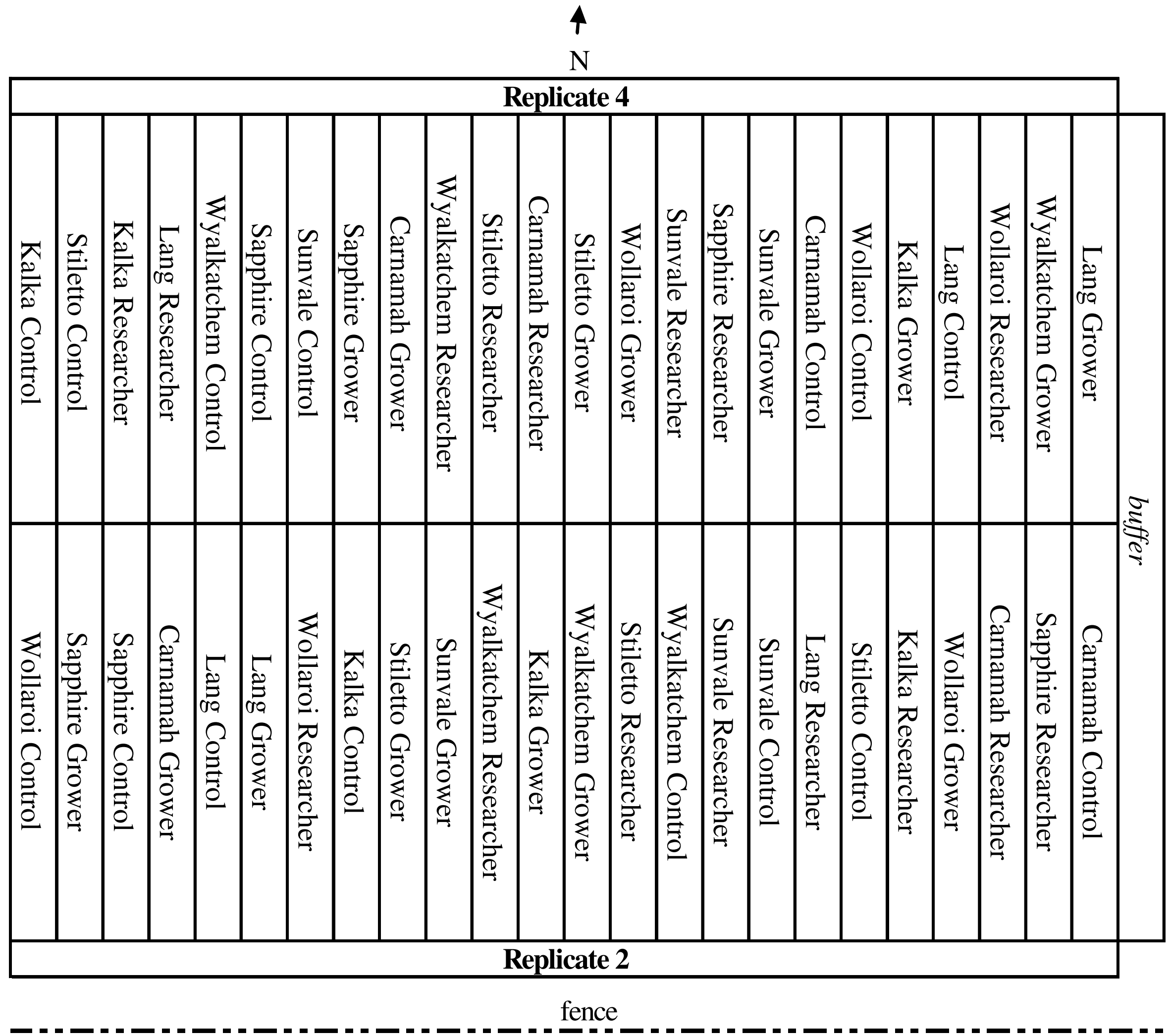

Figure 8.5b: Plot Layout for replicates 2 and 4, Williams 2006.

2007 Williams Experimental Details

Experimental Design

Study Design:	Randomised Block Design
Replications:	3
Plot Width (m):	20
Plot Length (m):	1.76

Rotation

2004 *Trifolium subterraneum L.*
2005 *Triticum aestivum*
2006 *Lupinus angustifolius L.*

Sowing Details

Sowing Date:	12/06/2007
Seeder Type:	Knifepoint + Presswheels
Number of Rows:	8
Row Width: (mm)	220
Seed Bed:	Friable
Stubble Cover (%):	0
Soil Moisture:	damp
Sowing Depth (cm):	3

Crop Protection

Date	Product	Rate
12/06/2007	Glyphosate 540 g a.i/L	2 L/ha
	Trifluralin 400 g a.i/L	1.6 L/ha
	Chlorpyrifos 500 g a.i/L	1 L/ha
25/07/2007	Tralkoxydim 400 g a.i/kg	380 g/ha
	Petroleum Oil 432 g a.i/L	0.75 % v/v
15/07/2007	MCPA LVE 600 g a.i/L	600 ml/ha

Nitrogen Application Details

	IBS	4 WAS	8 WAS
Application Date:	12/06/2007	16/07/2007	6/08/2007
Application Method:	Topdressed	Topdressed	Topdressed
Crop Stage:	Z00	Z13	Z31

Soil Characteristics

	0 - 10 cm
Texture	Sandy Loam
Gravel	25-30
Colour	Brown/Grey
Nitrate Nitrogen	16 mg/kg
Ammonium Nitrogen	4 mg/kg
Phosphorous Colwell	69 mg/kg
Potassium Colwell	114 mg/kg
Sulphur	7.7 mg/kg
Organic Carbon	4.01 %
Reactive Iron	653 mg/kg
Conductivity	0.061 dS/m
pH Level ($CaCl_2$)	5 pH
pH Level (H_2O)	5.5 pH

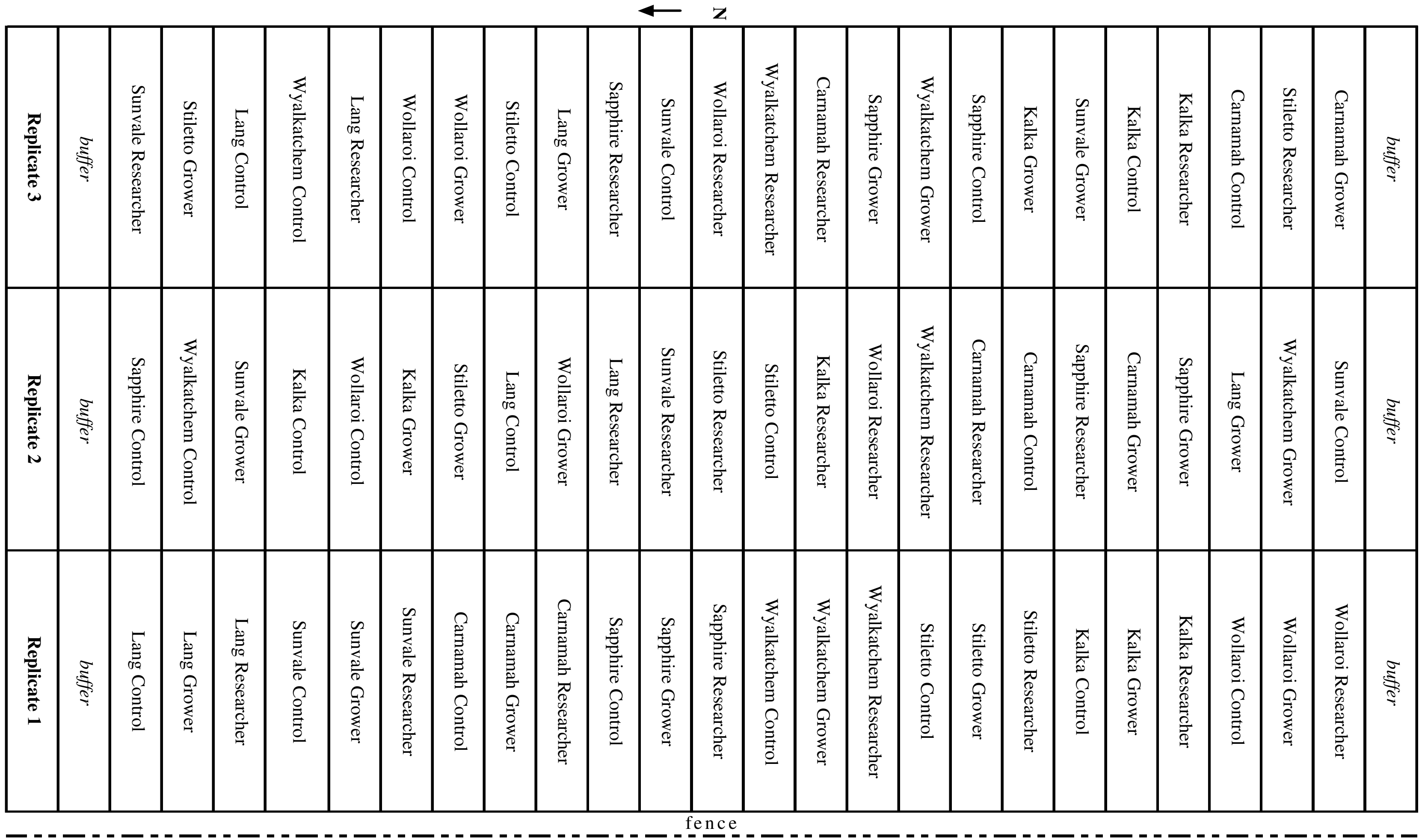

Figure 8.6: Plot layout for Williams 2007.