Faculty of Science and Engineering
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Adaptations for Growing Wheat in a Drying Climate

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This thesis is presented for the Degree of
Doctor of Philosophy
of
Curtin University

July 2011

This thesis is dedicated to the people who pioneered farming in the marginal parts of southwest Australia, people like my grandfather.

Norman Lorenzo Percival Sprigg (Percy)
(13.09.1913 - 26.12.2009)

…and of course my best friend and wife to be, Sally.

Declaration

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

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

Signature: …….

Date: ……...

Abstract

Declining rainfall in the winter months in southwest Australia could have large impacts on wheat production in the area, particularly in those parts where production is historically limited by water supply.

It is expected that the climate in southwest Australia will become drier, particularly in the winter months. These months have historically received the most rainfall in southwest Australia and make an important contribution to the in-season water supply to spring wheat (*Triticum aestivum*). Published simulation studies of wheat yield in the medium rainfall (325 to 450 mm annual rainfall) parts of the southwest Australian wheatbelt suggested that reductions in winter rainfall after 1975 have not reduced grain yields because soil water supply during these months often exceeds crop demand. However, the effect of recent changes in rainfall distribution on wheat production in more water-limited production areas (≤ 325 mm annual rainfall) is not known. This study aims to investigate the effects of changes in rainfall distribution on wheat yield in marginal parts of the southwest Australian wheatbelt.

Two field experiments were conducted at Merredin Research Station, Western Australia (31.50°S, 118.22°E, mean annual rainfall 313 mm) in 2008 and 2009. Water supply to 'Rainfall Distribution' treatments were partly controlled with the use of rainout shelters and irrigation. The experiments investigated the effects and interactions of rainfall distribution, row spacing (23 cm and 60 cm), genotype and timing of nitrogen on growth, water use and grain yield of spring wheat. Results from the experiments showed that wheat yields in out of season dominant rainfall varied according to water storage at sowing. Widening row spacing reduced biomass and slowed water use but did not increase grain yield due to increase evaporation in season and residual water left in the soil after maturity. Data from the 2009 experiment was used to calibrate the Agricultural Production Systems Simulator (APSIM) crop model, which in turn was used to investigate the effects of recent and projected climate change on wheat yield in marginal wheat growing areas of southwest Australia. Row spacing, nitrogen rates and timing, and phenology treatments were included in the simulations to test for interactions with changes in climate. The simulation was run for eight locations that span the fringe of the southwest Australian wheatbelt and compared the 35 years preceding 1975 with the 35 years following 1975.

In northern parts there were large reductions in June and July rainfall after 1975 and the slight increase in out of season rainfall didn't result in sufficient water storage before seeding to compensate for it. In central parts, the decrease in growing season rainfall after 1975 was almost equivalent to the increase in out of season rainfall but grain yield declined. In eastern

parts there was little change to growing season rainfall and grain yield benefitted by having additional stored soil water at seeding from increased out of season rainfall. In southern parts there was little change in rainfall pre and post 1975 and subsequently little change in grain yield. Two climate change scenarios from the online climate change scenario generator OzClim were applied to historical climatic data to create two plausible future climates (‘optimistic’ and ‘pessimistic’) for the year 2030. Both future climates resulted in reduced grain yields for each location when compared to the 1975 to 2009 time period.

The worrying thing for producers was that none of the strategies tested aided wheat yield in the predicted changing climate. It was hypothesised that widening row spacing would slow biomass accumulation and water use by the crop, which would result in more post-anthesis water use and grain yield when the crop was growing largely from stored soil water at seeding. The results showed that widening row spacing did indeed slow water use and provide more water post-anthesis, but wheat yields were consistently lower due to lack of head density, increased evaporation from the soil surface and the inability of the crop to use all the available water before maturity.

Findings in this thesis suggest that there is scope to breed wheat genotypes that are better suited to wide rows, and would allow growers to exploit the practical advantages of wide rows while minimizing the disadvantages. Field experiments suggested that early vigour and tillering (and head density) were important to grain yield in wide rows and it is suggested that a genotype suited to wide rows would include early vigour to reduce evaporation and increase competition with weeds, heavy tillering so that grain yield isn’t limited by sink-size and a vigorous root system with a good lateral spread to access all available soil water.

In addition to highlighting the sensitivity of wheat production to changes in climate in marginal southwest Australia, and identifying the potential for row spacing and genetic interactions to be exploited, this study has identified gaps in knowledge that will benefit wheat producers if filled. Firstly there are some key unknown factors about the effects of climate change on Australian wheat production such as the effect of the interaction between elevated atmospheric CO_2, increased temperatures and water deficit on wheat growth and yield. Also, the likely effect of climate change on the frequency, timing and severity of frosts is unknown. Both of these are fundamental to the successful development of strategies to adapt to climate change, and maintain grain production in a region that is very important to the prosperity of Australia’s rural industries.

Acknowledgements

The harder I tried to complete this thesis under my own steam, the more I was found wanting. So firstly I would like to thank God for being my foundation in all things and making the completion of this doctorate possible.

Thank you to all Australian grain growers and the GRDC for financial support through a Grains Research Scholarship. Thank you also to the GRDC for the important role you play in helping our grain growers be some of the best and most efficient in the world.

I owe a great deal of gratitude to my three supervisors; Professor Bob Belford, Dr. Steve Milroy and Adjunct Professor David Bowran - the three wise men. Thank you for your expert opinions and guidance throughout the duration of my PhD studies. I hope one day I am able to contribute as much to agriculture as you have.

I also need to thank the many people at the Department of Agriculture and Food, Western Australia's Merredin Research Station for their generous support in conducting the field experiments. Dr. Bob French for this expertise and for the use of his equipment, Laurie Maiolo for many days help and attention to detail, Glen Reithmuller for his technical expertise, and Alan and Matt Harrod and Elmer for the many days they spent working on the experiments, including keeping an eye on the sky, and opening and closing rainout shelters. The experiments would not have been possible without the help of all of you.

To Dr. Doug Abrecht from the Centre for Cropping Systems, Northam, thank you for your unwavering enthusiasm and for going out of your way to help a young researcher. Thanks also for your passion for the industry, long may it continue.

Mario D'Antuono, thank you for your expert assistance in data analysis and for always making time for me, even when you were very busy.

Thanks to Muresk staff and students who helped in the field or in the labs at one stage or another; Ian 'Rossi Boot' Ross, Dr. James 'Crayfish' Fisher, Dr. Pippa (I wouldn't dare call her anything else) Michael, Dr. Roger 'BFC' Mandel, Georgia 'Cousin Georgia' Trainor and Amanda 'Hugginkiss' Finaughty.

To all the kind staff at Muresk Campus; you have all helped me out at one stage or another, not because you had to, but because you could. You have been my extended family for a third of my life, so thanks also for the good times. Long may Muresk continue to be an integral part of agriculture in this state and country.

I would like to make a special mention to two people who encouraged me to continue studying. Mr. Gary Lane while I was a year 11 and 12 student at Cunderdin Agricultural

College and Dr. Lionel Martin while I was an undergraduate at Muresk. I probably wouldn't be where I am today if not for the belief you showed in a simple farm kid from Mukinbudin.

Thank you to my family for allowing me the opportunity to undertake this doctorate and for your support throughout.

My final thank you goes to my fiancée Sally, who has sacrificed and endured a lot so that I could pursue my dreams. Thank you for your support and thank you for helping me to become a better person.

Lastly, to all those who share a passion for agriculture. Let's work together to ensure a sustainable future for farming and the country towns that rely on it.

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Chapter one

Introduction

“Whether you think that you can, or that you can't, you are usually right.”

- Henry Ford

1. Introduction

1.1 The Australian and Western Australian wheat industry

Wheat (*Triticum aestivum*) is the major crop produced in Australia with approximately 11-13 Mha planted annually and between 10 and 25 Mt of grain produced, most of which is exported (ABARE 2010). Depending on total production, Australia exports 7-17 Mt of grain worth between $3-5 billion to the national economy (ABARE 2009). Western Australia is typically the state producing the highest proportion of wheat, producing about 40 percent of the national crop (ABARE 2010).

Wheat yields in Australia are typically between one and two tonnes per hectare (1.6 t/ha average between 2000 and 2009) (FAO 2011); low relative to other major wheat producing areas like North America (2.7 t/ha), South America (2.3 t/ha), Europe (3.5 t/ha) and China (4.2 t/ha) (FAO 2011).

Wheat production in Australia is conducted primarily on a dryland, broadacre basis and yield is therefore sensitive to variation in rainfall. Australia is subject to extreme rainfall conditions, such as drought, and annual production figures vary more than for any of the major wheat producing nations (ABARE 2009). Western Australia has been regarded as the safest production state in Australia with 24 percent coefficient of variation (average total production 7.5 Mt) in the period 1995-96 to 2008-09 versus 37 percent for New South Wales (5.7 Mt), 30 percent for South Australia (2.9 Mt), 36 percent for Victoria (2.1 Mt) and 40 percent for Queensland (1.2 Mt) (ABARE 2009).

Rainfall is regarded as the most important limiting factor to wheat production in Australia (Nix 1975), which is reflected in the variation in production figures. A change in climate, and in particular rainfall, has the potential to impact greatly on the industry.

1.2 Effect of climate change

A risk assessment of climate change impacts on Australia's wheat industry by Howden & Jones (2004) claimed that without adaptation the combined effects of possible increases in atmospheric carbon dioxide concentrations, associated temperature increases and rainfall changes pose a large risk to the industry. They concluded that by the year 2070 the scope for potential declines in wheat production is large (about 50 percent of total wheat production or $2 billion p.a. to the national economy) while the scope for increases in crop production is limited (to about 10 percent or $0.4 billion). While parts of the Australian wheat growing region are expected to benefit from the change in climate (such as north-eastern Australia), the southwest Australian wheatbelt has a high likelihood of significant yield reductions unless

either the effects of climate change are mitigated, or adaptation to the likely impacts of climate change occurs.

Already, most of the southwest Australian wheatbelt has seen a reduction in rainfall (IOCI 2002; Ludwig, Milroy, and Asseng 2009), although thus far it is thought not to have affected wheat grain yields in medium rainfall areas (325 mm to 450 mm) because most of the change has been in June and July when crop and evaporative demand are low and rainfall is relatively high (Ludwig, Milroy, and Asseng 2009). If climate projections are correct, however, we may see substantial grain yield declines if adaptations aren't made to the system (Farre, Foster, and Charles 2007).

In the east and northeastern parts of the southwest Australian wheatbelt, change in rainfall has been different to areas further south and west. Decline in growing season (i.e. winter) rainfall has not been as severe and there has been a trend towards increased out of season rainfall (i.e. summer) rainfall (see section 2.4.1). If this climate trend continues, then wheat crops in these regions will be more reliant on out of season rainfall for production. Other marginal parts of the southwest wheatbelt (≤ 325 mm annual rainfall) have seen declines in growing season rainfall, without increases in out of season rainfall, which may result in producers extending fallow periods so as to store soil water before seeding. Using extended fallow periods to store soil water reduces the crops' reliance on growing season rainfall and lowers production risk (Oliver, Robertson, and Weeks 2010). Adaptations to the production systems are required to increase wheat yields under this scenario (wheat crops growing more from stored soil water at seeding) and this may require adaptation in both crop management and wheat genetics.

1.3 Adaptation through wheat management

Management for a drying climate should be tailored around maximizing water use efficiency; that is maximizing the amount of grain produced per millimetre of rainfall. It is likely that, under the climate change scenarios discussed in this thesis, wheat production will become more reliant on stored soil water; either from increased out of season rainfall and reduced in season rainfall, or from extended fallow periods aimed at reducing production risk. A problem associated with production systems based on stored soil moisture is that the crop may grow a lot of biomass early in the season and use the majority of the soil moisture before anthesis, leaving little moisture for the filling of grain after anthesis. This can have negative effects on grain yield and individual grain weight (van Herwaarden et al. 1998). Not only can this affect yields, it can also reduce grain marketability due to small grains (Sharma and Anderson 2004).

Widening row spacing has been used in sorghum to slow the use of stored soil water by the crop and increase grain yields in regions where post anthesis drought is common (McLean et

al. 2003; Routley et al. 2003). Blackwell, Pottier, and Bowden (2006) found a similar effect in wheat in a season with stored soil moisture at sowing and in-season drought, on a shallow soil with high fertility. However, the majority of research into crop row spacing in wheat, conducted mostly with growing season dominant rainfall, suggests that there is a yield decline as row spacing is increased (Amjad and Anderson 2006; Doyle 1980). Studies investigating water use pre- and post-anthesis in varying row spacings indicate that soil moisture can be conserved until after anthesis in wider crop row spacings (Eberbach and Pala 2005; Tompkins, Fowler, and Wright 1991; Winter and Welch 1987).

Widening row spacing slows water use through reduced biomass resulting in less water demand by the crop (Tompkins, Fowler, and Wright 1991). The same effect is achieved through altering the level of nitrogen available to the plant in early growth (Norton and Wachsmann 2006). However, in southwest Australia, Ward et al. (2007) found fertiliser application increased the proportion of transpiration by the crop (T) compared to soil evaporation (E), while total ET remained the same. While, Van Herwaarden et al. (1998), in eastern Australia, showed that high levels of nitrogen and the associated increased biomass and crop water use can be detrimental to grain yield under terminal drought conditions.

Therefore, widening row spacing and altering nitrogen rates and timing may be management strategies wheat producers can employ to slow water use and reduce the risk of terminal drought when the crop is grown largely from stored soil water.

1.4 Adaptation though wheat genetics

Much has been written on breeding wheat for tolerance to abiotic stresses (in particular drought), yet due to the complicated nature of drought tolerance there appears to be little progress in tolerance to drought even when physiological pre-breeding approaches are taken (Chaves et al. 2002) . In Australia, where water deficit stress is the biggest hindrance to crop production, the majority of varieties released to commercial cultivation still come from empirical breeding methods and not as a result of physiologically focused pre-breeding (Araus et al. 2002; Richards 1996).

Reynolds, Majeeb-Kazi & Sawkins (2005) identified four groups of traits that might be beneficial for drought tolerance. These groups are thought to be genetically independent of each other, making pyramiding of traits possible. The four groups identified were:

I. *Pre-anthesis growth*

   Long coleoptile and large seed to aid with crop establishment in marginal soil moisture conditions; early vigour, and stem carbohydrate reserves accumulated before anthesis to aid with grain fill after anthesis.

II. *Water extraction*

Good deep root systems with good access to water. This is difficult to measure from the surface but is linked to high relative leaf water content and lower canopy temperature. Soil water can be measured in different layers to give an indication of where roots are extracting from, but that demonstrating significant differences in water content due to root extraction is very difficult in clayey soils with high total water content.

III. *Water use efficiency*

Efficient conversion of soil water into grain through awn photosynthesis, high harvest index and low ^{13}C discrimination (linked with transpiration efficiency).

IV. *Photoprotection*

Morphological leaf traits such as cuticle wax, pubescence, leaf posture/rolling, and small erect leaves resulting in decreased radiation load on the surface of the leaf.

While this thesis does not explicitly test these traits, it does consider their worth in light of a changing climate and how they might interact with management strategies for a changing climate. This thesis particularly considers genetic interaction with row spacing as it is lacking in the literature. Amjad and Anderson (2006) found that the longer-seasoned cultivar Camm tended to yield comparatively better than shorter-seasoned cultivars in wider rows, partly due to increased biomass. While there have been many experiments in southwest Australia on genetic interactions with other management factors such as time of sowing (Sharma et al. 2008), nitrogen application (Anderson and Hoyle 1999) and plant density (Anderson et al. 2004) there have been few (Amjad and Anderson 2006) on the interaction with row spacing in the region and indeed other wheat growing parts of the world (Lafond 1994). This may be partly due to the practical difficulties, such as the extra time and mechanical work, involved in conducting row spacing field experiments.

1.5 Thesis objectives

The aim of this thesis is to investigate genotype by environment by management (G*E*M) interactions that contribute to grain yield in wheat produced in marginal parts of southwest Australia.

Specific objectives include:

a) Investigate the effects of a shift in rainfall distribution to a more out of season dominant pattern on wheat water use and yield in low rainfall (< 325 mm) southwest Australia (E)

b) Compare the performance of a range of genotypes under contrasting rainfall distributions (G*E)

c) Determine the effect of crop management (row spacing and nitrogen) on wheat water-use and yield (M)

d) Investigate the interactions of wheat genotype, crop management (nitrogen rate and crop row spacing) and environment (shift in rainfall distribution) on wheat water-use and yield (G*E*M)

e) Extrapolate field results through crop modelling to investigate the effects of row spacing on wheat yield reliability and responsiveness under climate change scenarios to extrapolate (E*M).

Chapter two

Literature review

"No student knows his subject: the most he knows is where and how to find out the things he does not know"

- Woodrow T. Wilson

2. Literature Review

2.1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) (2007) predicts an increase in global temperature of 0.2^{o}C for each of the next two decades as a result of increasing levels of global atmospheric carbon dioxide and other greenhouse gases. Global atmospheric CO_2 has risen from 280ppm in the pre-industrial period to 379ppm in 2005 and IPCC scenarios suggest that levels will continue to rise over the next century. This is expected to have flow on effects on climatic factors such as changes in wind patterns, precipitation, temperature and the frequency of extreme weather events. All of these things (including the rise in CO_2 itself) have the potential to impact on agriculture on a global scale. Crop growing regions in the mid to high latitudes are predicted to benefit from an increase in local mean temperature of 1 to 3°C while other regions, such as Australia and lower latitudes, are predicted to see a reduction in crop productivity as a result of climate change. Globally, the IPCC predicts with 'medium confidence' that the potential for food production will increase with increases in local average temperature over a range of 1 to 3°C, but above this, production is projected to decrease.

The global community relies on plants for all its food either directly or indirectly. Fewer than 100 plant species in total are used for food (Burger 1981) of which 50 are actively cultivated, while 17 provide 90 percent of human food supply (Harlan 1976). Of most importance are eight cereal grains that provide 56 percent of global food energy and 50 percent of the protein consumed on earth (Stoskopf 1985). Of these, wheat, rice and maize account for 85 percent of world production of cereals (Koohafkan and Stewart 2008) and the majority of the world's population live on wheat and rice (Stoskopf 1985). The Food and Agriculture Organisation (FAO) of the United Nations (2006) predict that the total usage of cereals will be 339 kg/person.year by 2050, up from 309 kg/person.year in 1999/2001. With an expected increase in population in the period from 2000 to 2050 the FAO forecasts that cereal production will need to increase from 1.9 billion tonnes in 2001 to 3 billion tonnes by 2050. With large increases in food demand expected and the threat of climate change, food production and security are likely to be increasingly important world issues in the coming decades.

Wheat is Australia's largest crop with 10-25 million tonnes grown annually from 11-13 million hectares with production worth between 3 and 5 billion dollars to the national economy (ABARE 2010). In Australia, the positive effects on crop production from greater atmospheric CO_2, particularly in C_3 grass crops like wheat (Long et al. 2004), are expected to be outweighed by the negative impacts of a reduction in precipitation in many of the grain growing regions, and the predicted increase in average temperature (Howden and Jones 2004;

Watterson et al. 2007). In already marginal wheat growing regions of Australia (≤ 325 mm annual rainfall), climate change poses a very real threat to the economic sustainability of wheat production and therefore farming in the area. The aim of this literature review is to define the current limitations to wheat production in Mediterranean-type environments in Australia and to discuss the management and genetic approaches available to meet the challenge of producing wheat under the shadow of climate change. Discussion will focus particularly on marginal parts (≤ 325mm annual rainfall) of the wheat growing region of southwest Australia. As a part of this I have analysed rainfall patterns over the past 70 years for eight locations in marginal parts of the southwest Australian wheatbelt (section 2.4.1).

2.2 Water use efficiency and radiation use efficiency

There are two major drivers of grain production in crops. One relates grain yield to water use (Passioura 1977) and the other to intercepted radiation by the crop (Monteith 1977). In Australia, grain production is most commonly related to water use as water is frequently the most limiting factor to production (Nix 1975). Therefore radiation use efficiency will be covered briefly first and water use efficiency will be covered in greater detail second with the remaining content of this literature review discussed in relation to water use efficiency.

2.2.1 Radiation use efficiency

Monteith (1977) found that the interception of solar radiation by a number of crops in Britain was a good indicator of biomass production. The identity provided below relates radiation interception to biomass production and grain yield;

$$GY = RI \times RUE \times HI$$

Where RI is radiation interception by the crop, RUE is radiation use efficiency and HI is harvest index. RI is a function of the leaf area index of the crop (LAI) and the canopy extinction coefficient (k), which is a measure of canopy architecture that determines how much radiation is intercepted for a given LAI.

RUE is the amount of dry matter accumulated per unit of radiation intercepted by the crop. It correlates positively with leaf nitrogen content (Sinclair and Horie 1989) and is adversely affected by extreme temperature and water deficit (Sinclair and Muchow 1999), which is why in low rainfall wheat growing regions of southwest Australia, where water deficit is common, crop production is more commonly related to the most limiting resource – water.

2.2.2 Water use efficiency

Passioura (1977) described grain yield (GY) as a function of the water used by the crop (WU), the efficiency with which that water is converted into biomass (transpiration efficiency

or TE), and the proportion of the biomass that is used in grain production (harvest index or HI);

$$GY = WU \times TE \times HI$$

French and Schultz (1984) suggested that potential water use efficiency was 20 kg/ha of grain per millimetre of water used by wheat crops in southern Australia. Twenty-two years later Sadras and Angus (2006) benchmarked WUE for a number of locations around the world including south-eastern Australia, North American Great Plains, China Loess Plateau and the Mediterranean Basin and found potential WUE had increased to more like 22 kg/ha.mm but grain yields often fell significantly below that mark. The increase in WUE over the time period was attributed to improved genotypes through greater harvest index and possibly increased atmospheric CO_2 concentration. Water-use-efficiency can also be negatively affected on soils with low plant available water capacity (Oliver et al. 2009) and rainfall distribution which does not match the pattern of production (Sadras and Rodriguez 2007). When water use efficiencies are substantially lower than potential WUE it is likely that stresses other than water, such as weeds, disease, poor nutrition and/or inhospitable soils are affecting yield more than water stress (Passioura 2004). In a study of 334 wheat fields from across Australia, Hochman, Holzworth, and Hunt (2009) calculated WUE to be 15.2 kg/ha per mm of water use (evapotranspiration or ET) in the crop and found that ET accounted for 69 percent of observed yield variation. Using the crop model APSIM to improve plant density, time of sowing and nitrogen application the authors simulated WUE to be 21.4 kg/ha.mm (similar to the potential suggested by Sadras and Angus, 2007).

Water use

Available soil water is reliant on rainfall in most wheat growing areas of Australia. Rainfall cannot be controlled, but the efficiency of storage of this rainfall in soil, and the subsequent availability of water to the crop, can be influenced by management. Water availability at sowing can be partly controlled by summer weed control, fallowing and reduced evaporation (through ground cover) (Passioura 1977).

Evaporation (E) is also a factor after the crop is sown, as soil water lost to evaporation from the soil surface is not available for transpiration (T) by the crop. Most of the water leaving the soil early in the crop life cycle is through E, particularly when the soil surface is wet and the leaf area index (the unit area of leaf per unit area of soil surface) is below 1 (Ritchie 1983). In Mediterranean-type environments E often accounts for 40% of the total water use (Siddique et al. 1990). Reducing E early in the crop's lifecycle can be achieved by increasing ground cover, that is, by developing a fuller crop canopy faster so that radiation is intercepted by the crop rather than driving evaporation from the soil surface (Passioura 2004). This can be

achieved through genetic means by increased early vigour (Richards and Lukacs 2002), and through management by increasing plant density (Puckridge and Donald 1967), and canopy leaf area by nitrogen fertilisation (Norton and Wachsmann 2006). Stubble retention (> 2t/ha) can also slow water evaporation from the soil surface (Bond and Willis 1970). Figure 2.1 shows the effect canopy size can have on evaporative loss from the soil surface.

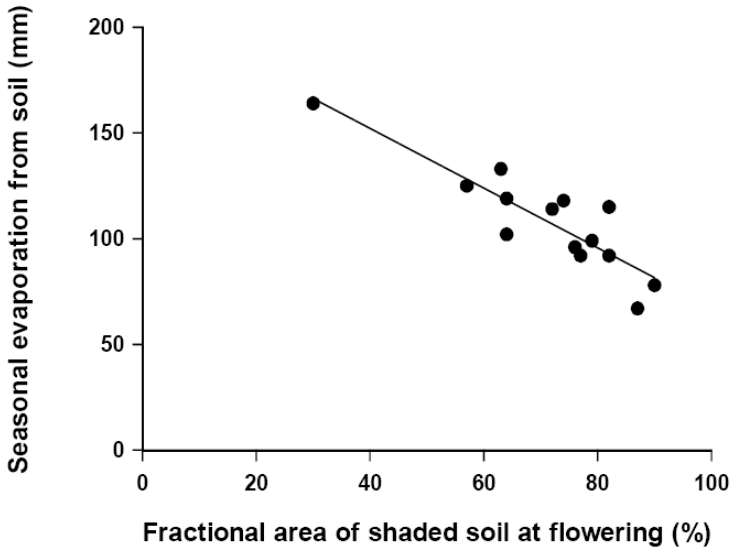


Figure 2.1: Evaporative loss of water from soil under wheat canopies of different size varied by nitrogen fertiliser (Passioura 2004).

While water use by the crop is important throughout its lifecycle, soil water is most directly converted into grain when it is used after anthesis, when the grain is being filled. Kirkegaard et al. (2007) found late water use can be converted into grain at up to 60 kg/ha.mm, while the potential conversion rate for the whole season is thought to be 20 kg/ha.mm (French and Schultz 1984).

Transpiration efficiency

Reduced evaporation means more water is available for use by the crop as transpiration. How much dry matter is produced per unit of water transpired by the crop is referred to as transpiration efficiency (TE). TE is negatively related to the evaporative demand of the environment, as the rate of water loss from leaves is proportional to the vapour pressure deficit – the difference between the vapour pressure in the saturated leaf cavities and the less than saturated atmosphere (Tanner and Sinclair 1983). Therefore, accumulating biomass during the cooler months when evaporative demand is lower (through timely sowing and early vigour) is a means of increasing seasonal TE (Fischer and Wood 1979). Transpiration is closely tied to photosynthesis and biomass production so manipulating the efficiency with which transpired water is converted into biomass for a given evaporative demand is difficult (Passioura 1977). There is some genetic variation that can be exploited, however, to select

varieties that transpire more efficiently for each unit of biomass produced. Farquhar and Richards (1984) found that wheat genotypes that discriminated less against ^{13}C isotope tended to fix more carbon per unit of water transpired, i.e. they had increased transpiration efficiency This is discussed further in section 2.5.3.

Harvest index

Harvest index is strongly influenced by the proportion of water the crop uses after anthesis (Passioura 1977). Due to the inherent variability and low predictability of total and seasonal rainfall in southern Australia (Stephens and Lyons 1998a), it is difficult to know what quantity of water should be used before anthesis. Producers can therefore only manage and chose cultivars for the average.

Achieving a correct flowering time is important in ensuring the correct partitioning of water-use pre and post anthesis. This is especially important in determinant crops such as wheat (Richards 1991). If the crop flowers before the optimal time then harvest index may be high but yield may suffer as the biomass required to produce a large number of seeds is not available (Kerr, Siddique, and Delane 1992). Passioura (2002) developed a schematic graph of grain yield of wheat, biomass at harvest, and harvest index in relation to the proportion of available water supply used before flowering (Figure 2.2). In much of southern Australia it is also important that flowering doesn't occur too early as it increases the chance of reduced yields from frost damage (Loss 1989). This limits the extent to which flowering can be brought forward.

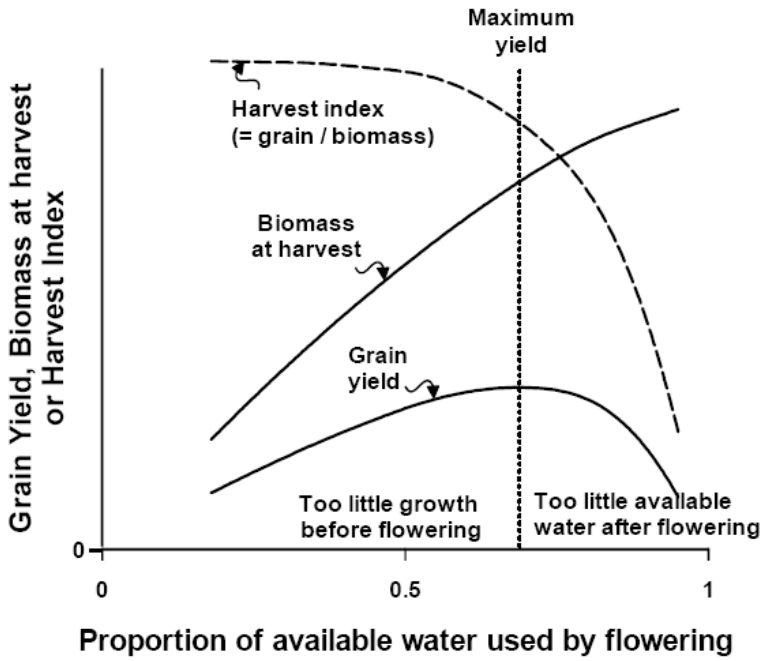


Figure 2.2: Schematic graph of grain yield of wheat, biomass at harvest, and harvest index in relation to proportion of the available water supply used by flowering. The scale of the y-axis is arbitrary (Passioura 2002).

The proportion of water-use before and after anthesis can also be altered through management factors such as nitrogen application (van Herwaarden et al. 1998), plant density (Fawcett 1964) and crop row spacing (Tompkins, Fowler, and Wright 1991). All these things will be covered in greater detail in other parts of this review.

2.3 Environmental, management and genetic factors driving grain yield in the southwest Australian wheatbelt

Wheat grain yields in southwest Australia have increased from an average of about 1t/ha in the 1980's to about 2t/ha in the late 1990s (Figure 2.3). While it has been suggested that some of this yield increase has been due to increasing atmospheric CO_2 levels (Howden, Gifford, and Meinke 2010), it has also been attributed to improved crop management techniques and genetics (Anderson 2010). Compared to other major wheat growing regions in the world such as Europe (3.5t/ha), North America (2.7t/ha), South America (2.3t/ha) and China (4.2t/ha), Australia (1.6t/ha) had the lowest average wheat yield from 2000 to 2009 (FAO 2011). Discussed in this section are the environmental parameters (E) that effect crop yield in southwest Australia, and the management strategies (M) and improvements to wheat genetics (G) that have allowed producers to commercially grow wheat in these regions.

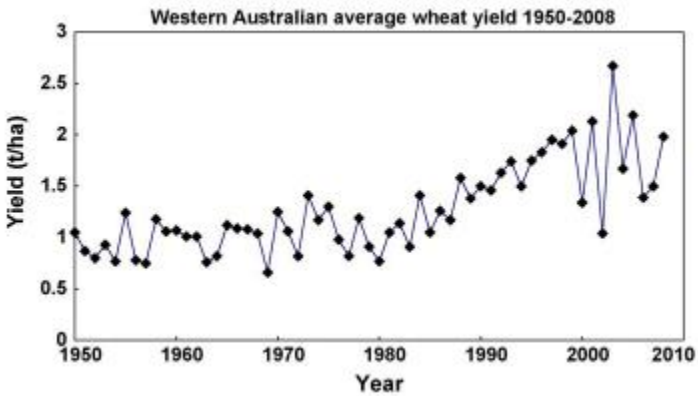


Figure 2.3: Average yield of wheat in southwest Australia 1950-2007 (Anderson 2010).

2.3.1 Environment

The southwest Australian wheatbelt has a Mediterranean-type climate characterized by long, hot, dry summers and short, mild, wet winters. Field studies investigating the importance of G, E, and M on wheat yield in southwest Australia suggest that E has the largest impact by far, accounting for about 80 percent of the variation in wheat yield from season to season (Anderson 2010). Major environmental factors that affect wheat yields include rainfall, temperature and solar radiation.

Rainfall

Water is the most important factor in wheat production in Australia (Nix 1975). All of the wheat produced in southwest Australia is rain fed. Average rainfall in the cropping region of southwest Australia ranges from < 300 mm to > 600 mm annually with ~80 percent falling in the growing season of May to October. Winter rainfall has been generally reliable and usually exceeded crop demand due to mild temperatures, low evaporations rates and slow crop growth rates (Loss and Siddique 1994). Stephens and Lyon (1998a) regressed Australian shire wheat yields against monthly rainfall between the years 1976-87 and found that wheat yields showed positive correlations with rainfall for most months, while the correlations decreased in strength as the analysis moved to higher rainfall zones. For all agrometeorological zones, wheat yield was most strongly correlated with May rainfall. May rainfall allows early sowing and crop growth during the cooler months when evaporative demand is low (refer to section 2.2.2) and lowers the risk of terminal drought (Kerr, Siddique, and Delane 1992).

Due to the strong correlation between growing season rainfall and wheat yield in Mediterranean-type climates, French and Schultz (1984) developed an empirical estimate for water use efficiency or WUE (i.e. the amount of biomass or grain produced per unit of water used) and suggested the potential for wheat is about 55 kg/ha of biomass per mm of water used and 20 kg/ha of grain per mm of water used. They also found that time of sowing and soil water content at sowing had a substantial influence on yield. Sites with lower growing season rainfall tended to achieve higher WUE. While transpiration efficiency was the same, less water was lost to evaporation when rainfall from sowing to maturity was reduced (about 60 mm evaporation when rainfall to maturity was less than 150 mm, compared to about 110 mm when growing season rainfall was greater than 150 mm).

Temperature

Wheat leaves perform at maximum photosynthesis with day temperatures of about 18°C (Bird, Cornelius, and Keys 1977). In the wheatbelt of southwest Australia, temperatures can constrain wheat growth by being both too high and too low at different times of the year (Loss and Siddique 1994). Winter growing months are cooler than the optimum for wheat with mean minimum temperatures ranging between 4 and 7°C, maximums between 14 and 18°C and mean temperatures in the range of 10 to 14°C. Coolest temperatures occur in the southern and eastern parts of the southwest Australian wheatbelt where mean temperatures are 10 to 12°C in the winter months (Foster 2000).

Growth rates are restricted by low temperatures in midwinter but are generally not low enough to cause long-term freezing damage (Loss and Siddique 1994). Frost damage to stem and ears during early spring are more common and crops may sustain permanent damage that can result in reduced yields (Loss 1989). The risk of frost damage in the period between ear

emergence and the weeks following anthesis causes wheat producers in southwest Australia to manage time of sowing with crop phenology so that the crops are not susceptible to large-scale frost damage, whilst avoiding the high temperatures and drought stress of late spring and summer (Kerr, Siddique, and Delane 1992).

In many of Australia's grain growing regions, flowering and grain filling typically occur when ambient temperatures are rising and soil moisture is diminishing. High temperatures can affect grain filling with the duration, final individual grain weight and grain yield all affected (Wardlaw et al. 1989; Wardlaw and Wrigley 1994). However, water deficit is thought to have a greater impact than temperature on grain size and weight in Australia (Panozzo and Eagles 1999). An increase in temperature without a change in precipitation, windspeed and humidity exacerbates the effect of water deficit stress during grain filling due to increased crop evapotranspiration. Asseng et al. (2011) suggested that average growing season temperature variations of ± 2°C can cause variations in grain yield of up to 50 percent. Increased temperatures at grain filling also alter grain quality by increasing A-type granules in endosperm starch (Panozzo and Eagles 1998), and increasing grain protein while altering the make-up of protein (Panozzo and Eagles 2000). These grain quality parameters are particularly affected by accumulated degrees over 30°C in the first 14 days after anthesis (Panozzo and Eagles 2000; Panozzo and Eagles 1998).

Broadly speaking, phasic development in spring wheat is driven by temperature and photoperiod (Angus et al. 1981). Therefore, an increase in temperature will accelerate development in wheat cultivars. However, even with the inbred nature of modern wheat varieties, there are large genetic differences in temperature and photoperiod sensitivity (Slafer and Rawson 1994) which will allow cultivars with more suitable phenology to be bred in the event of rising temperatures. A third mechanism affecting the rate of development of wheat (especially in winter wheats) is vernalisation, which causes the shoot apex to remain vegetative until a cold requirement (temperatures between 1 and 10°C) is met (Setter 2000).

Solar radiation

The interception of solar radiation, or more particularly the photosynthetically active wavelengths of solar radiation, drives the growth of crops when water or nutrients, e.g. N, are not limiting (Monteith 1977). Solar radiation also affects crop growth through its influence on temperature and evaporation regimes. Mean midday radiation in most Mediterranean-type climates (such as southwest Australia) is typically 6-10 MJ m^{-2} day^{-1} in winter and is unlikely to limit crop growth to any great extent due to coinciding low temperatures and crop leaf areas (Loss and Siddique 1994). Solar radiation levels increase to 25-30 MJ m^{-2} day^{-1} in summer (Loss and Siddique 1994).

2.3.2 Management

The management factors discussed below have been developed to fit the environment outlined above. As rainfall is the generally the most limited resource to wheat production in southwest Australia, the management factors discussed below are those deemed as being most important to crop water supply and demand.

Time of sowing

From the very early days of wheat production in Australia it was identified that managing the development of crops to avoid the harsh Australian summer period was an important part of wheat production (Synnott 1938). In southwest Australia the distribution of rainfall and temperature means that late finishing crops are subjected to hot, dry conditions that can be detrimental to yield (Loss and Siddique 1994). Kerr, Siddique and Delane (1992) found early sowing to be important to grain yield in the low rainfall, north eastern part of the southwest Australian wheatbelt. Delayed sowing resulted in reduced dry matter and subsequently fewer grains per m^2, which generally was not compensated for by increased kernel weight. This finding was confirmed by Sharma et al. (2008) in 27 cultivar x time of sowing experiments conducted over three seasons in southwest Australia. Sharma and his co-workers found sowing time to account for 10 percent of the variability in yield, with a general trend of higher yields in earlier sown crops, especially when crop phenology was matched to meet an optimal flowering time; this finding was consistent with earlier work by Anderson, Heinrich, and Abbotts (1996) in southwest Australia.

Farmers are not always able to sow when they would like to as they are restricted by opening rains and soil moisture, the time involved with the operation and perhaps the need to wait for a weed germination (Kirkegaard and Hunt 2010). However, farmers have been able to improve timeliness with the advent on no-till (one pass), larger seeding implements and wider row spacings (more hectares seeded per hour), and dry sowing (sown before opening rains).

Plant density

The influence of plant spacing and population on wheat growth and yield are best described through the effect they have on resource use of the crop; radiation, soil water and mineral nutrients.

Wheat crops sown at higher density are generally able to capture more sunlight as a canopy through increased leaf area for a given area of soil (leaf area index or LAI); this results in more photosynthesis in the crop, especially early in the growing season, and increased dry matter (Satorre 1999). Much of the radiation arriving at the crop canopy early in the crops lifecycle isn't used by the crop due to low LAI. Increasing plant density can result in the capture of more radiation early in the growing season (Puckridge and Donald 1967). The

relationship between radiation interception and plant population is linear in the early part of the season as individual plants have similar dry matter production rates (Satorre 1999). As the crop develops and competition for light takes place between crop plants, dry matter production is reduced on a per plant basis as plant density increases (Figure 2.4).

The beneficial effects (in terms of grain yield) of increasing plant density on radiation resource usage interact with water usage. Where soil water is not limited, grain yield would increase with increased plant density until a point where it would plateau (Darwinkel 1978). In water limited environments however, the relationship is more quadratic (Fawcett 1964).

In Australia care needs to be taken by the producer to limit soil water use before anthesis so as to leave some resource for grain filling (Passioura 1983). This is particularly the case in a Mediterranean-type climate such as in southwest Australia (Siddique et al. 1990). While increased plant density can reduce evaporation from the soil surface early in the season, making more water available for transpiration (Passioura 2004), the extra biomass produced as a result of increased radiation interception can result in increased water use before anthesis (Doyle and Fischer 1979). Fawcett (1964) discovered in field experiments near Narrabri in northern New South Wales that when the wheat crop was not subjected to water deficit around anthesis, plant density had little effect on yields. When there was water stress at anthesis, however, grain yield was markedly reduced by plant densities above the optimum.

Extensive field work by Anderson et al. (2004) in southwest Australia found that rainfall, sowing time, soil type and cultivar could all have impacts on optimum plant density. In growing seasons of < 205 mm (which are common in low rainfall parts of the wheatbelt) optimum plant density increased as growing conditions improved with pre-sowing rainfall, earlier sowing and increased growing season rainfall. Other analysis in southwest Australia suggests that the optimum plant density for wheat aimed at not under-utilising available resources is 40.6 + (34.6 × expected grain yield in t/ha) plants/m^2 (Shackley 2000). This translates to target populations of around 75 plants/m^2 for crops expected to yield around 1 t/ha; and 110 plants/m^2 for 2 tonne crops. Anderson et al. (2004) confirmed this positive relationship between optimal plant density and site yield, up to yields of about 3 t/ha. Other southwest Australian studies suggest that increasing plant density can have a limited impact on grain yield (Eastham and Gregory 2000).

Perhaps of more interest than plant density is head density (that is the number of heads per unit area of soil surface). Anderson (2004) found tiller numbers and head numbers increased as optimal plant density increased up to about 400/m^2 and 300/m^2 respectively before the response levelled out (Anderson 2004).

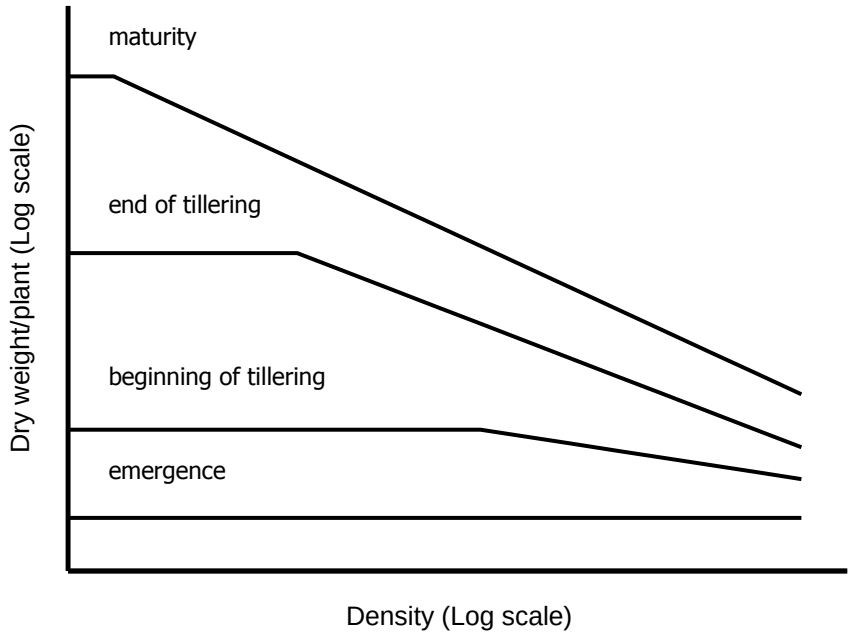


Figure 2.4: The linear relationship of log plant weight to log plant density for various crop stages plot as cited in Satorre (1999).

Crop row spacing

Wheat crops sown at narrower row spacings generally have increased LAI early in the season and are therefore able to intercept more solar radiation (Olsen and Weiner 2007; Wall and Kanemasu 1990a). With ample resources, wheat plants should be spaced equidistant from each other so as to reduce competition between neighbouring plants and to ensure maximum usage of radiation, soil water and mineral nutrient resources (Fawcett 1964). For practical reasons, wheat is typically grown in rows, so under favourable growing conditions narrow row spacings should result in increased LAI (at least early in the growing season), dry matter production and grain yields. There is much literature that indicates that in the field narrow row spacing increases dry matter production (Eberbach and Pala 2005; Johnson, Witters, and Ciha 1981; Karrou 1998; Tompkins, Fowler, and Wright 1991; Winter and Welch 1987).

Work by Eberbach and Pala (2005) in the Mediterranean climate of Syria found that total ET was the same when row spacing increased from 17 cm to 30 cm (373 mm total) but on the narrow spacing more of the water was used in transpiration (185mm T and 183mm E) compared to the wider (172mm T and 205 mm E). Tompkins, Fowler, and Wright (1991) and Johnson, Witters, and Ciha (1981) both found increased proportions of transpiration, as well as less total ET, in narrower rows compared to wide rows in the more temperate climate of North America with winter wheat. In southern Australia in a mediterranean-type climate, Kleemann and Gill (2010) observed small reductions in seasonal ET in 54 cm row spacing

compared to 36 cm spacings. In sparse canopies in southwest Australia Yunusa (1993) found no difference in evaporation between row spacings ranging from 9 cm to 36 cm.

Increasing row spacing without changing sowing rate results in increased competition within each row. Intra-row competition can result in reduced numbers of plants (Amjad and Anderson 2006) and tillering (Stapper and Fischer 1990a), which in turn can affect head number per unit area (Lafond 1994; Lafond and Derksen 1996; Tompkins et al. 1991) and grain yield (Photiades and Hadjichristodoulou 1984; Wall and Kanemasu 1990a). Producing and maintaining heads has been found to be important in water scarce environments (Blum and Pnuel 1990) and is an important driver of wheat yield in southwest Australia (Zhang et al. 2010).

Generally, wheat grain yields decline as crop row spacing increases (Karrou 1998; Amjad and Anderson 2006; Photiades and Hadjichristodoulou 1984; Tompkins, Fowler, and Wright 1991; Wall and Kanemasu 1990b; Winter and Welch 1987). A series of experiments testing the effect of row spacing on wheat yield was carried out across the wheatbelt of southwest Australia in the 1980's and 1990's, and suggested there was a eight percent decrease in grain yield for every 9 cm increase in row spacing from 9 cm to 54 cm (Shackley 2000). A number of row spacing experiments have been conducted on the Merredin Research Station (313 mm annual rainfall, 212 mm growing season rainfall). Yunusa et al.(1993) found no yield difference in row spacings ranging from 9 cm to 36 cm in a low yielding season in 1989. Reithmuller (pers comm.) has been running a long-term experiment on a red brown earth at Merredin to test the effects of row spacing and stubble treatment (retained or burnt) on grain yield. Figure 2.5 shows the comparative yield of 36cm row spacings versus 18cm row spacings in cereals. In this circumstance, a polynomial trend line suggests that when grain yield exceeds 1t/ha, crops grown on wider row spacings become relatively lower yielding than those on conventional (narrower) spacings, irrespective of the presence or absence of stubble.

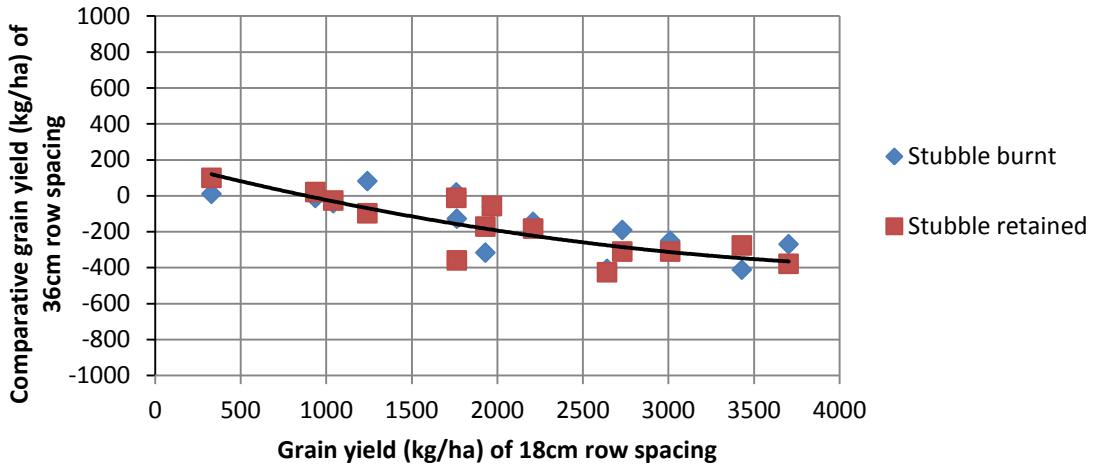


Figure 2.5: Comparative yield of cereals at 36 cm row spacing vs. 18 cm row spacing at Merredin from 1987 to 2007 under stubble burnt and stubble retained systems (Riethmuller, pers comm)

There is also evidence to suggest that in high yielding environments (such as under irrigation), widening row spacing does not decrease grain yield. In the North China Plain, irrigated winter wheat grown on 7.5 cm row spacings increased grain yield over 15, 22.5 and 30 cm row spacing in one of five seasons, while 15 cm row spacing increased grain yield over 22.5 and 30 cm row spacing also in one of five seasons (albeit a different season). Interestingly, the two seasons that saw a row spacing effect were the driest in the series of experiments and had the lowest yields (average 4.8 versus 6.7 t/ha in other three seasons) (Chen et al. 2010). In southern New South Wales, Australia, irrigated wheat grown on 17, 30 and 45 cm row spacings exhibited no significant difference in yield at 4.7 t/ha (Stapper and Fischer 1990b)

Interaction of Row Spacing and Seeding Rate

There is surprisingly little written on the interaction of row spacing and seeding rate. Published research comes predominately from North America. The lack of study in this field may in part be due to the lack of interaction found when extending row spacing was first trialled (with the advent of no-till systems) in the 1980s and 1990s (Johnson et al. 1988: Lafond 1994; Lafond and Derksen 1996).

In Canada, Lafond (1994), tested the interaction of three row spacings (10, 20 and 30 cm) and six seeding rates (ranging from 34 to 202 kg/ha) in durum wheat, spring wheat and barley in the northern Great Plains, under zero-tillage. In this situation there was a slight increase in grain yield as row spacing increased in durum wheat (5.8 percent average over four years) and barley (2.4 percent), but no difference was observed in spring wheat. Increasing row spacing decreased plant density and head density, but this was compensated by the number of grains per head. There was only a seeding rate by row spacing interaction in two of 12 cases,

causing the author to conclude that seeding rate need not be adjusted for changes in row spacing. In this situation head density was important to yield and increased seeding rate resulted in increased yield through increased head density. This was attributed to the low tillering capacity and short pre-anthesis period (< 60 days). Similar responses to row spacing have been demonstrated in other Canadian studies looking at similar treatments under conventional management (Lafond and Derksen 1996) and in winter wheat (Mcleod et al. 1996). In other work done in Montana by Chen et al. (2008), grain yield declined when row spacing was increased from 15 to 30 cm and the yield differential was the same at four different seeding rates (108 to 430 seeds/m^2). The narrow row spacing treatment accumulated biomass faster and had about 40 more heads/m^2, which resulted in about 400 kg/ha extra yield. In high yielding (average 5t/ha) winter wheat in north-eastern and mid-Atlantic USA, there was also a decrease in head density when row spacing was increased from 10 cm to 20 cm, which resulted in a reduction in yield, while varying seeding rate from 288 to 567 seeds/m^2 had little effect on the results (Johnson et al. 1998). Tompkins et al. (1991) found a row spacing (9 and 35 cm) by seeding rate (36 and 140 kg/ha) interaction for grain yield, that suggested yield was greater in the 9-140 treatment than the other three. In the same study, widening row spacing decreased grain yield, again due to a reduction in head density.

Australian studies on the topic are limited. Doyle (1980) varied row spacing (18 to 36 cm) and seeding rate (22 to 44 kg/ha) in northern New South Wales, and found widening row spacing reduced grain yield in three of five seasons but there was no interaction with seeding rate. In climates similar to southwest Australia (Mediterranean type), Karou (1998) found no interaction between row spacing (12 and 24 cm) and seeding rate (200 to 400 grains/m2) in durum wheat in semi-arid Moroco and Photiades and Hadjichristodoulou (1984) found no interaction (row spacings 16 to 32 cm / seeding rate 100 and 150 kg/ha) in barley in Cyprus. Industry literature from southwest Australia shows that both decreasing seeding rate (from 60 to 30 kg/ah) and increasing row spacing (from 30 to 60 cm) could improve grain yield, on a shallow soil good early growth and dry conditions late in the season, and the best yielding treatment being the combination of the two (30kg/ha by 60 cm row spacing) (Blackwell 2006).

As already mentioned, much of the reduction often associated with widening row spacing comes from a reduction and plant density (Amjad and Anderson 2006) and head density (Lafond 1994; Lafond and Derksen 1996; Tompkins et al. 1991). One might assume that this could be overcome by increasing seeding rate, given that increased plant density often results in increased head density, to a point (Anderson et al. 2004). However, this creates more intra-row competition, which limits growth, tillering and yield past a point (Puckridge and Donald 1967). Although there is limited literature on the topic in Australia, based on work in other

locations it would appear that seeding rate is unlikely to affect yield to the same extent in wide rows as in narrow rows. The only suggestion of an interaction in the literature is narrow row spacing may respond more to increased seeding rate, as in Tompkins et al. (1991).

Nitrogen

Wide use of applied nitrogen in Western Australian cereal production began in the late 1960's and early 1970's (Mason 1975). At the time legume pasture/cereal based ley farming was common practice and much of the required N was supplied by the pasture phase of the rotation. However, as both cropping intensity and grain yield have increased, applied N has become an increasingly important management tool for wheat farmers.

Applied nitrogen can affect numerous yield components that contribute to grain yield. The number of heads per m^2 is increased through increased tillering (Darwinkel 1983; Halse et al. 1969; Spiertz and De Vos 1983) and survival of ear-bearing tillers (Spiertz and De Vos 1983), and grains set per head can also be increased through increased spikelets per head (Langer and Liew 1973) and grains per spikelet (Darwinkel 1983; Spiertz and De Vos 1983; van Herwaarden et al. 1998). Grain size can be affected either negatively or positively by additional nitrogen, depending on soil water availability at grainfill (van Herwaarden et al. 1998).

Increased nitrogen availability can result in greater vegetative growth, leaf area index, and photosynthetic area, mostly as a result of increased tillering (Spiertz and De Vos 1983). While increased N supply increases the number of ears and grains as well as dry matter supply to the grains (through increased biomass and LAI at anthesis), the downside is the risk of exacerbating late season water deficit stress. The greater canopy size induced can result in greater ET (Norton and Wachsmann 2006) and hence any water stresses late in the season are accentuated because less water is available and the rate at which the crop will use any rainfall is greater (van Herwaarden et al. 1998).

Nitrogen supply that exceeds crop demand to build grain yield (when yield is limited by water) can increase grain protein. Therefore if N supply is well matched or less than demand for yield, additional N applied late in the season (after anthesis) can increase grain protein and attract a quality premium for the grower (Bly and Woodard 2003).

2.3.3 Genetics

A study of the genetic increase in grain yield of wheat cultivars grown in southwest Australia up to 1982, versus introductions and selections made before 1900, was conducted by Perry and D'Antuono (1989). Four years of experiments involving 20 field trials in the southwest Australian wheatbelt suggested a genetic increase in grain yield of 5.8 kg/ha.year or 0.57 percent per year from 1884 to 1982, while the total increase during that period is estimated to

be 20.2 kg/ha.year (Anderson et al. 2005). That is 30 percent of the annual yield increase was due to genetic improvement.

Phenology

Change in phenology has been one of the most important factors in yield increase in Australia due to the role it plays in matching crop water demand to soil water supply through rainfall (Loss and Siddique 1994). The matching of crop life cycle to seasonal conditions has already been discussed in section 2.3.2. Crop phenology interacts very much with time of sowing, making cultivar choice matched to start of season rainfall a very important decision for growers (Sharma et al. 2008).

Loss and Siddique (1994) reviewed key differences in the phenology between old and modern varieties. They concluded that modern varieties tended to have shorter thermal requirement to 'double ridge' (Kirby et al. 1989; Perry and D'Antuono 1989) and produce fewer leaves on the main stem (Kirby et al. 1989). Under the right vernalising conditions, old varieties have shorter durations between double ridge and terminal spikelet than modern varieties, however, in warmer conditions modern varieties tend to develop faster in this phase also (Kirby et al. 1989). Thermal time between terminal spikelet and anthesis hasn't changed considerably over the years of wheat breeding in Australia, but has been considered by breeders to increase fertile florets (Miralles et al. 2000). Thermal duration of grain filling has increased in modern cultivars (Loss et al. 1989).

Harvest Index

Another key area of yield improvement has come from increased harvest index; that is the proportion of grain weight produced compared to total biomass. Perry and D'Antuono (1989) suggested that 80 percent of the increase in yield of cultivars from 1884 to 1982 was a result of increased harvest index. This is partly due to more effective partitioning of assimilates into ear production (Siddique et al. 1989). Siddique et al. (1989) suggested that modern varieties are better able to convert PAR into dry matter, which resulted in great biomass at anthesis and slightly more biomass at maturity. Perry and D'Antuono (1989) recorded differences final biomass when comparing very old varieties (Purple Straw and Nabawa) to their successors.

Improvements in harvest index have also arisen from an increase in the proportion of soil water used after anthesis relative to before, due to reduced duration to anthesis in modern cultivars (Siddique et al. 1990). The introduction of the Rht gene to Australia wheat genetics in the 1970s was an important step in improving harvest index (Perry and D'Antuono 1989).

2.3.4 Interactions

Both genetic and agronomic approaches have been used to increase the grain yield of wheat. However, it is difficult to disaggregate and quantify the contribution of genetic improvement,

agronomy and the interaction of the two. Figure 2.6 shows the wheat yield increase in southwest Australia by decade from the period 1950-1999 and the corresponding management practices responsible for the increase in yield according to Anderson et al. (2005). The authors used Australian Bureau of Statistics data to estimate that the yield increase from 1950-1989 was 12 kg/ha.year while the jump during the 1990's was far greater at ~55 kg/ha.year. Perry and D'Antuono (1989) compared grain yield of modern (for the time) and historical cultivars in southwest Australia and found the yield increase due to genetics between 1860 and 1982 was 5.8 kg/ha per year, while Anderson et al. (2005) estimated that the total yield increase for the same time and rainfall was 20.2 kg/ha.year. Anderson et al. therefore concluded that the remaining 14.4 kg/ha.year of the yield increase can be attributed to management and the interaction of genetics with management. This of course ignores any change in the environment (particularly CO_2 and rainfall) that might have occurred over the period. Turner (2004) suggests that the recent surge in yield, as illustrated by Figure 2.6, can be attributed to genetics and management at similar levels as suggested by Anderson et al. (2005) for the preceding period, with genetics being responsible for one third of the increase, and management and the management interaction with genetics, two thirds. He explains that the increase is probably the result of appropriate agronomic packages matched to new cultivars and the ability of modern cultivars to respond to increased agronomic inputs. Often the increase in yield resulting from such interactions is the result of a reduction in water loss outside of crop transpiration (Turner 2004) and the more efficient use of water due to better timing of water use by the crop (Angus and van Herwaarden 2001).

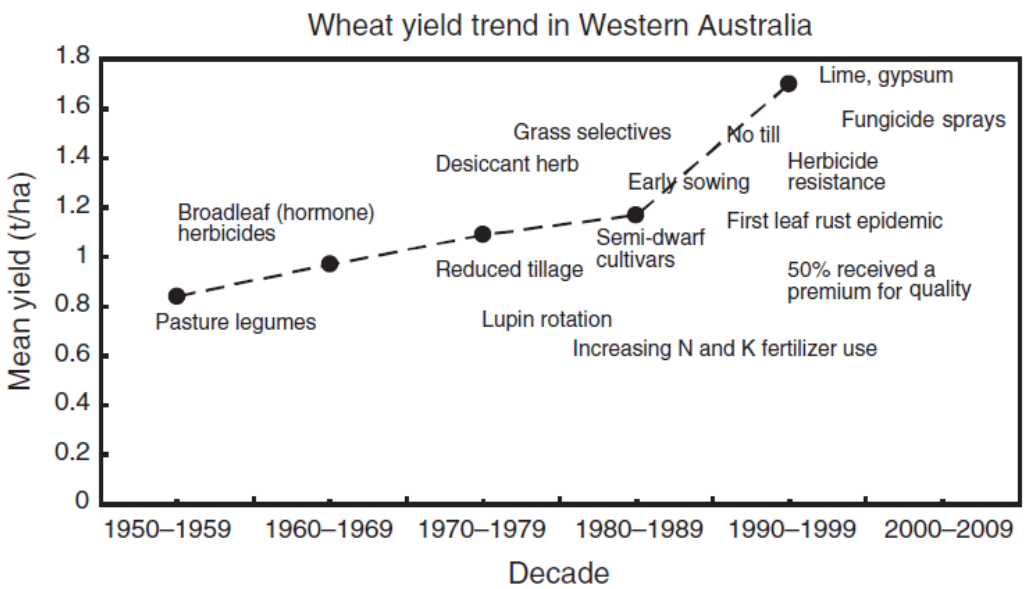


Figure 2.6: Average wheat yields in Western Australia by decade 1950-59/1990-1999, showing varying management practices adopted over the period (Anderson et al. 2005)

One common example of a positive interaction can be seen between high-yielding modern varieties and an increase in agronomic inputs such as major nutrients, as well as environmental factors such as water, CO_2 and solar radiation (Fischer 2009). For example; a higher-yielding modern variety will increase its grain yield in response to a given rate of N fertiliser more than an older lower-yielding variety (Fischer 2009). Even amongst modern varieties there can be G x N (nitrogen fertiliser) interactions due to variations in N uptake efficiency (net uptake as a percentage of applied N) (Anderson and Hoyle 1999).

Of great importance in the season to season management of a wheat crop is the interaction of sowing time with cultivar phenology which together determine flowering time. Ideally flowering time will occur at a time when frost risk is low but grain filling isn't exposed to the arid and hot conditions of late spring. This has already been covered in sections 2.3.2 and 2.3.3 . Another important crop trait that can interact with pre-crop management, such as summer weed control and other factors contributing to pre-crop water storage is a long coleoptile that allows deeper sowing and earlier crop establishment in some seasons than would otherwise be possible. A simulation study by Kirkegaard and Hunt (2010) demonstrated that grain yield could increase from 1.6 t/ha to 4.5 t/ha in certain circumstances.

Literature on G by plant density and row spacing interactions is less common. Del Cima, D'Antuono, and Anderson (2004) found genotypes to have different optimal seed rates in lower-yielding, late sown experiments, while Anderson et al. (2004) found evidence of G by plant density in higher yielding environments (grain yield over 2.5 t/ha and growing season rainfall over 205 mm). Amjad and Anderson (2006) found that cultivars of varying phenology interacted with row spacing due to longer-seasoned cultivars having greater biomass and better weed suppression in wider rows. In maize, there is a positive interaction between high yielding modern hybrid varieties and plant density, thought to be the result (at least in part) of changes in root architecture where increased root angle results in greater use of deep soil water (Hammer et al. 2009).

Discussed above are the environmental, management and genetic factors that contribute to wheat production in southwest Australia. What follows is discussion on recorded and predicted changes in the environment component that may affect wheat production in the area.

2.4 Historical and predicted climate change in southwest Australia

2.4.1 Rainfall

In September 2002, the Indian Ocean Climate Initiative (ICOI) released a report titled 'Climate variability and change in the south west of Western Australia'. The report found that the winter rainfall for southwest Australia had declined substantially since the mid-20th

century. The largest proportional decline was in early winter (May-July). In particular, a sudden drop-off in winter rainfall in the range of 15-20 percent was observed in the mid-1970s.

Figure 2.7 shows the trend in annual rainfall from 1970-2009 (BOM 2010), which is consistent with the IOCI (2002) report for southwest Australia. Little of the southwest wheatbelt actually lies within the south west of WA as defined by IOCI. Figure 2.7 suggests that some of the cereal growing region has actually increased in rainfall from 1970 to 2008, particularly in eastern and south eastern parts of the wheatbelt.

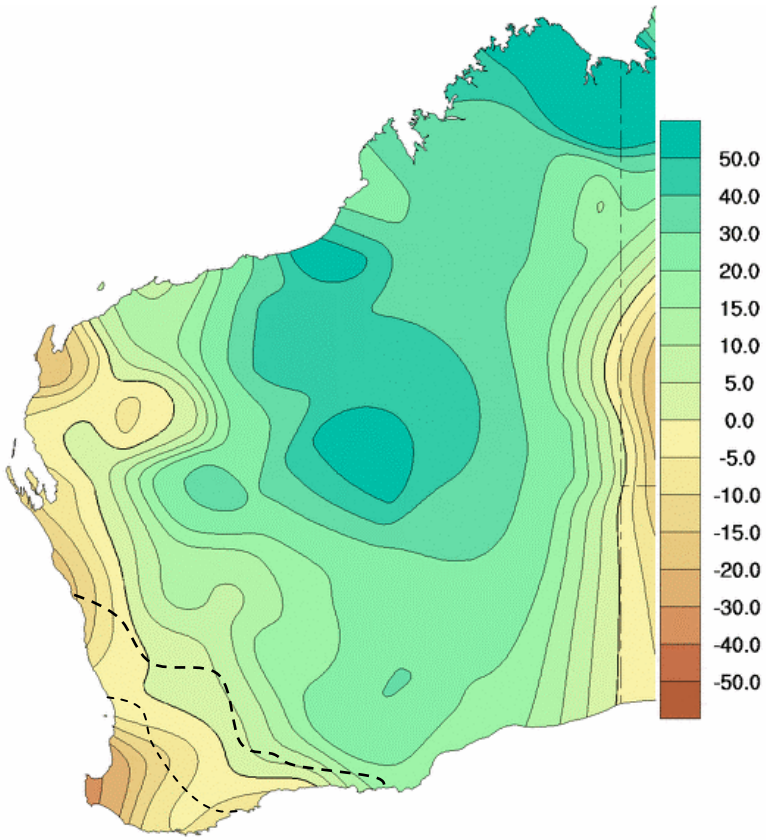


Figure 2.7: Trend in annual total rainfall 1970-2008 for Western Australia measured in mm/10yrs (BOM 2010). Traditional cereal cropping region indicated between dotted lines.

When the trend in rainfall in various parts of the year is considered over the same historical period we can see that the largest change has been in the summer months. Within the summer months the increase in rainfall is greatest in the eastern and southern parts of the wheatbelt. Trends in other seasons have been subtle in comparison but there has been a general decreasing trend in winter and spring rainfall from 1970-2009.

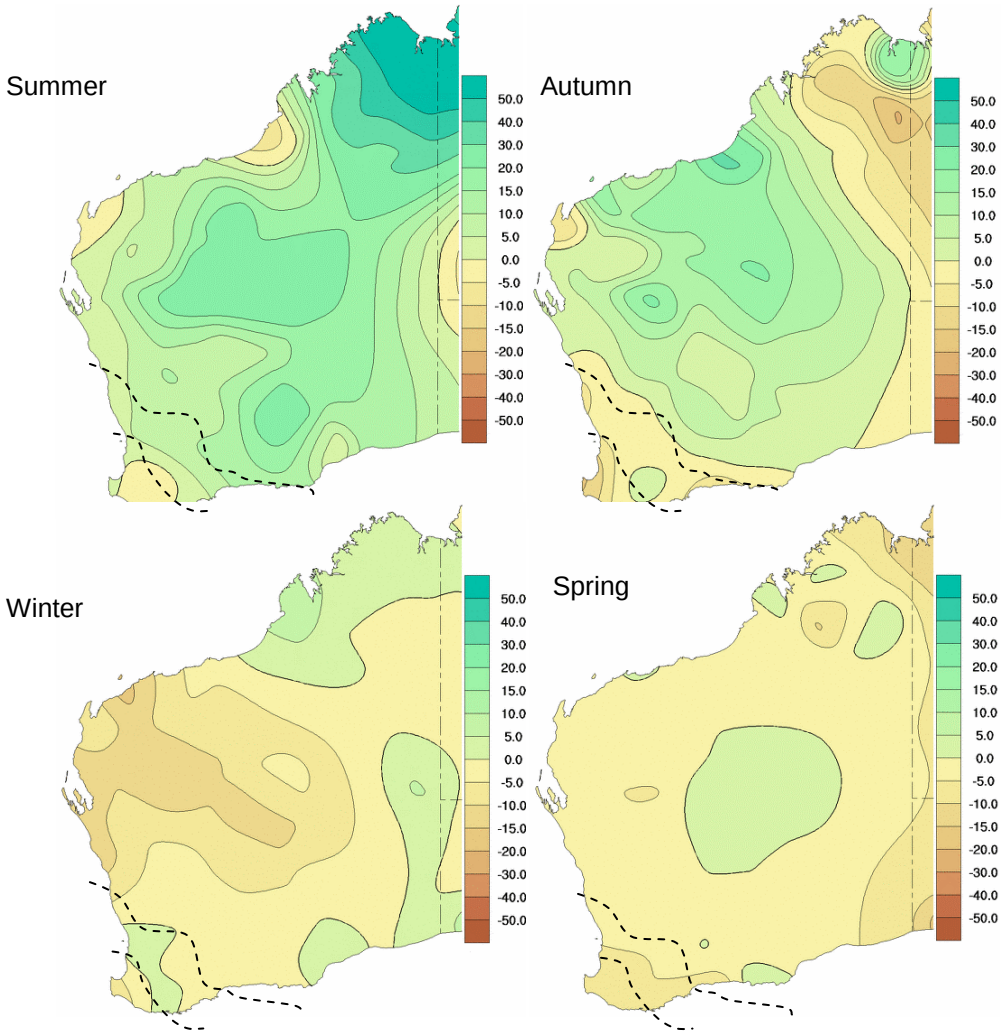


Figure 2.8: Trend in summer, autumn, winter and spring total rainfall 1970-2009 measured in mm/10yrs (BOM 2010). Dotted lines indicate the southwest Australian wheatbelt.

Using Australian Bureau of Meteorology (BOM) rainfall data, growing season rainfall (GSR) (May-Oct) and out of season rainfall (OSR - rainfall outside of growing season), for eight locations in the low rainfall, eastern edge of the Western Australian wheatbelt, were analysed for the periods 1945-1974 and 1975-2009, to determine whether there had been a shift in rainfall distribution. The locations ranged from Mullewa in the north to Salmon Gums in the south and are illustrated in Figure 2.9.

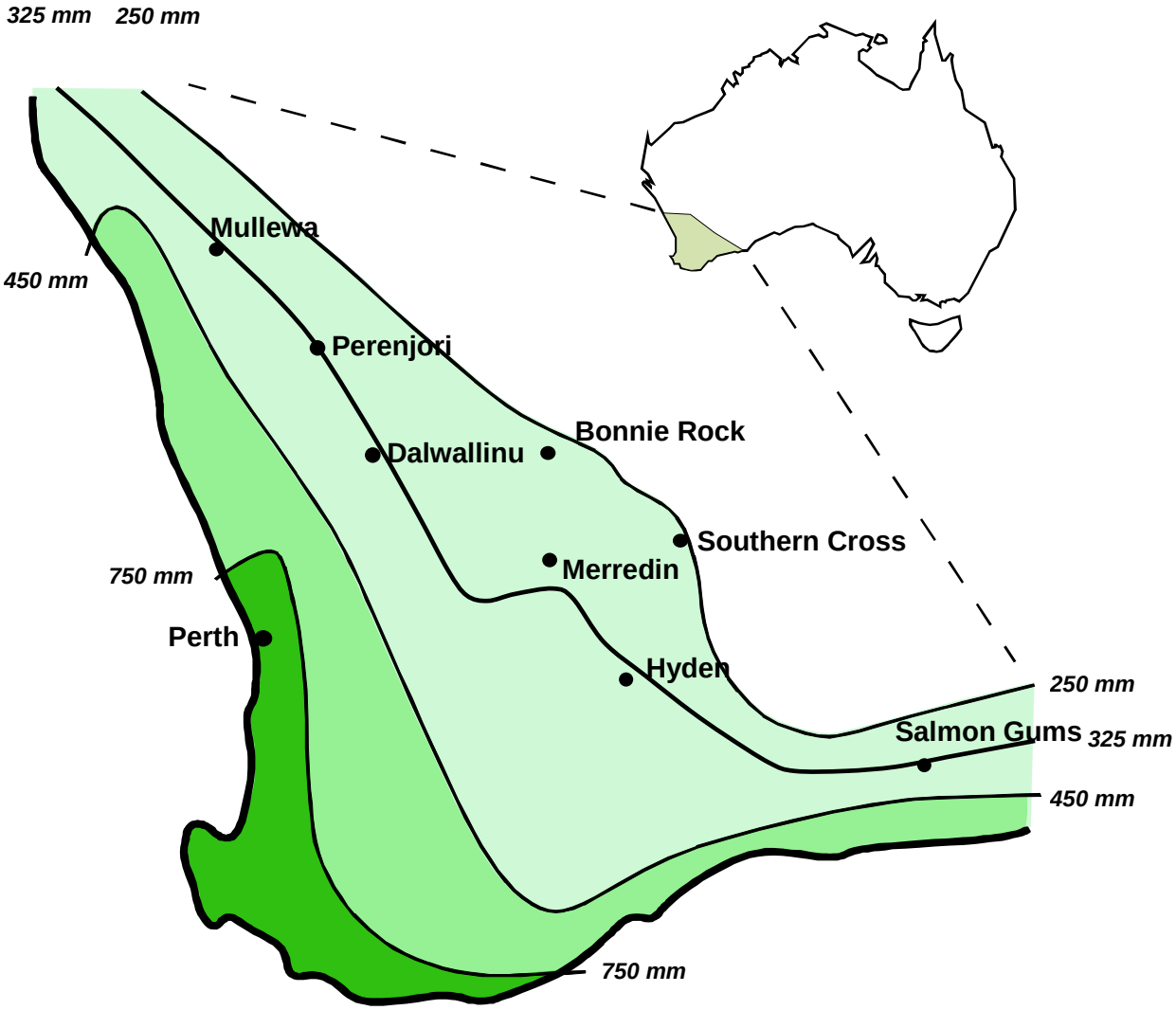


Figure 2.9: Map of southwest Australia showing the eight study sites for rainfall distribution analysis. Lines indicate rainfall isohyets. The wheatbelt of southwest Australia lies between the 250mm and 450mm isohyets.

The locations can be grouped based their geography; northern (Mullewa and Perenjori), central (Dalwallinu and Merredin), eastern (Bonnie Rock and Southern Cross) and southern (Hyden and Salmon Gums). Locations show similar trends in rainfall distribution over time as the other locations within their group (Figure 2.10, Figure 2.11 and Table 2.1). The northern group have seen a decrease in GSR and very little change in OSR. The central locations have also experienced a drop in GSR but had a slight increase in OSR. In eastern parts GSR has not changed substantially but OSR has increased, while both southern locations have also seen little movement in GSR and an increase in OSR, particularly in the more eastern location of Salmon Gums.

Table 2.1: Changes in growing season (May to October) and out of season rainfall between 1940-1974 and 1975-2009 for eight locations in the low rainfall (≤ 325mm) parts of the southwest Australian wheatbelt.

Location	Change in growing season rainfall			Change in out of season rainfall		
	mm	**%**	**Sig.**	**mm**	**%**	**Sig.**
Mullewa	-28	-11	N.S.	-3	-3	N.S.
Perenjori	-51	-20	P < 0.01	11	12	N.S.
Avg. Northern	***-39***	***-15***		***4***	***5***	
Dalwallinu	-36	-13	P < 0.05	22	25	N.S.
Merredin	-32	-13	P < 0.05	26	29	P < 0.1
Avg. Central	***-34***	***-13***		***24***	***27***	
Bonnie Rock	-17	-9	N.S.	47	51	P < 0.05
Southern Cross	-7	-3	N.S.	39	38	P < 0.05
Avg. Eastern	***-12***	***-6***		***43***	***45***	
Hyden	0	0	N.S.	22	22	N.S.
Salmon Gums	-14	-7	N.S.	36	29	P < 0.05
Avg. Southern	***-7***	***-3***		***29***	***26***	

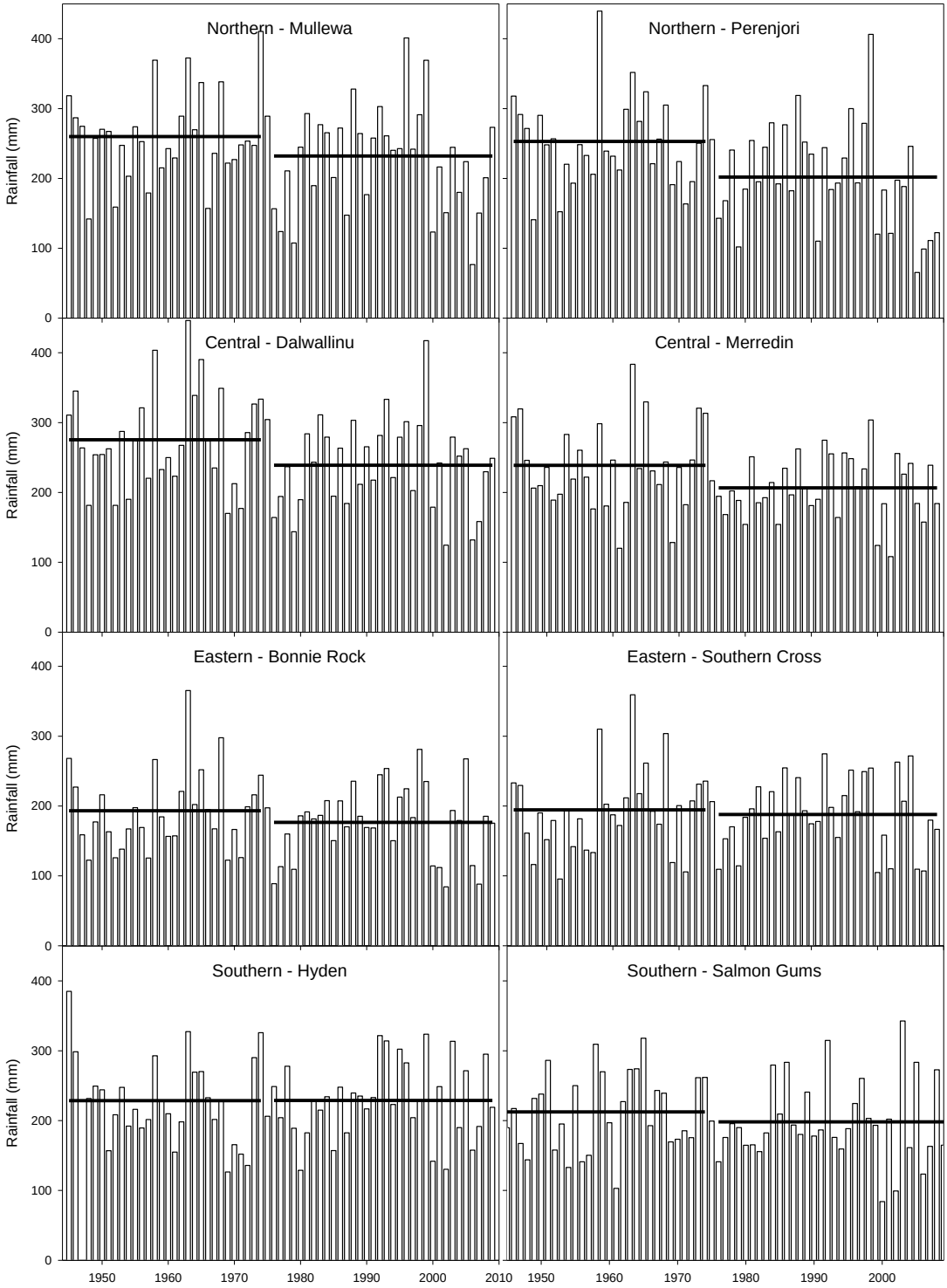


Figure 2.10: Time series of growing season rainfall (May to October) for eight locations within the low rainfall part of the southwest Australian wheatbelt. Lines indicate the average growing season rainfall for the 1940-1974 and 1975-2009 periods. Data source (BOM 2011)

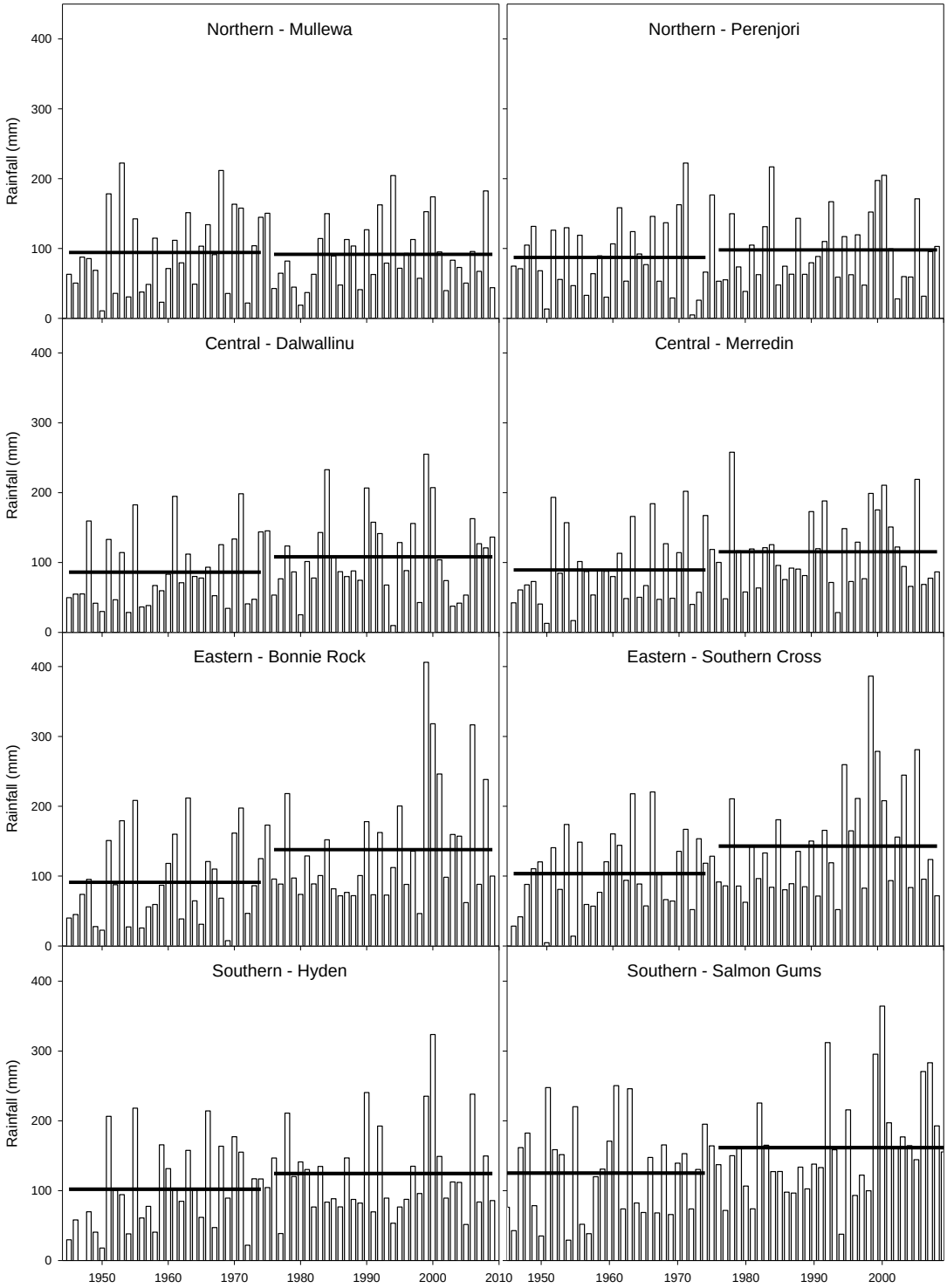


Figure 2.11: Time series of out of season rainfall (Dec to April) for eight locations within the low rainfall part of the southwest Australian wheatbelt. Lines indicate the average out of season rainfall for the 1940-1974 and 1975-2009 periods. Data source (BOM 2011)

Ludwig et al. (2009) also looked at rainfall data for nine sites in the Western Australian wheatbelt from 1945-1974 and 1975-2004. Southern Cross was the only site in the analysis to have an increasing trend in total annual rainfall. The biggest change in rainfall for all sites was in June and July with a decline of 18 percent in Southern Cross. The other sites in their analysis (Binnu, Tenindewa, Mingenew, Buntine, Wongan Hills, Northam, Cunderdin and Kellerberrin) all had declining trends in annual rainfall, growing season rainfall and June + July rainfall. Their sites generally have higher average annual rainfall than those in my analysis above.

So far, this section has focused on trends in rainfall over the past seventy or so years. Are these trends likely to continue into the future? The CSIRO together with the Australian Bureau of Meteorology have developed projections for rainfall (and other climatic components) using outputs from combined climate models (BOM and CSIRO 2010). Rainfall projections under climate change are less certain than those for temperature and atmospheric CO_2 (Howden, Gifford, and Meinke 2010). Figure 2.12 shows the 50th percentile of model outputs for the year 2030 for different periods of the year in Western Australia. Low, medium and high emission scenarios are included, according to the Intergovernmental Panel on Climate Change (IPCC) (2007). The maps suggest that the declining trend in winter and spring rainfall discussed earlier will continue with a reduction in the order of 5-20 percent by 2030 in the southwest of Australia. Contrary to the trends exhibited in historical rainfall data over the past seventy years, the projections also suggest a 2-5 percent decline in summer and autumn rainfall**.**

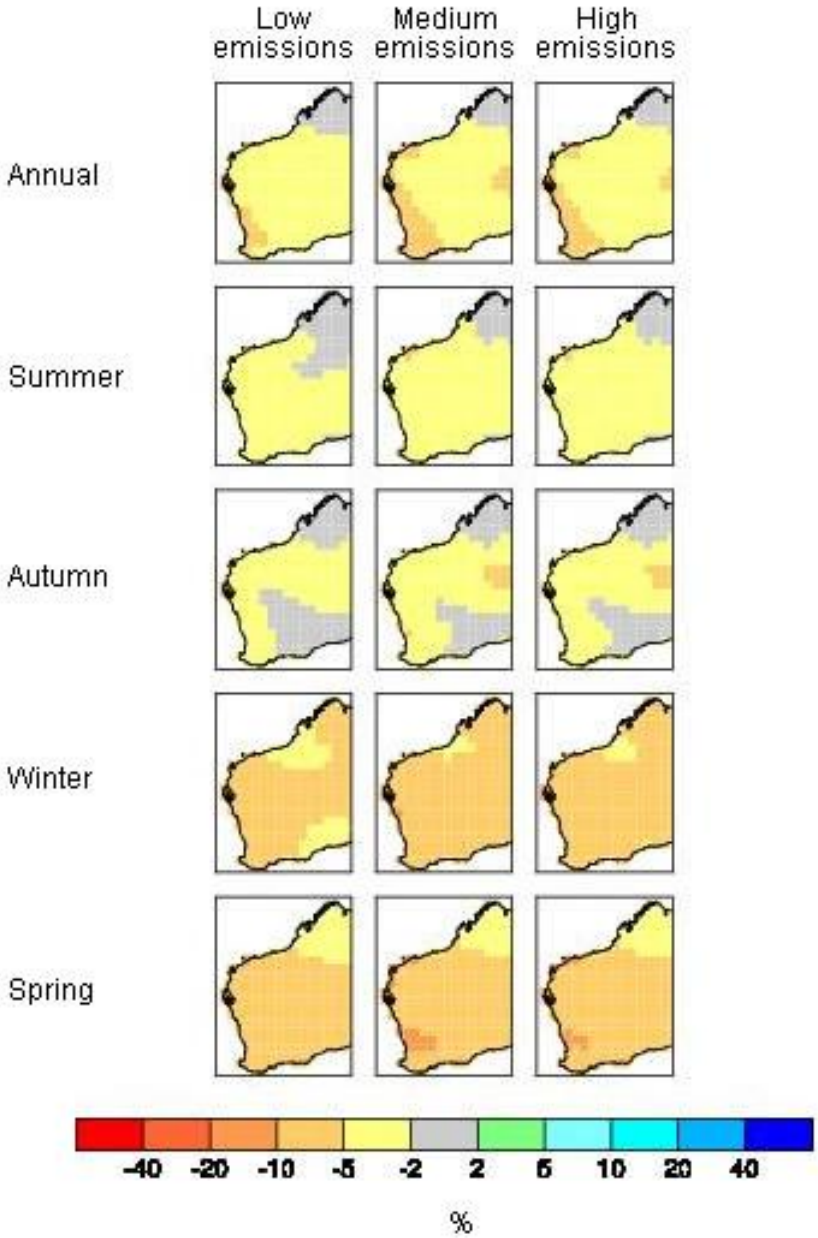


Figure 2.12: Projected change in Western Australian rainfall, at 50th percentile, by 2030 using the period 1980-1999 as a base (CSIRO and BOM 2010).

2.4.2 Temperature

Both maximum and minimum temperatures have increased in Australia since the 1950's with minimum temperatures increasing faster than maximum (Torok and Nicholls 1996). Maps have been developed by CSIRO and BOM for predicted temperatures for the year 2030. A 0.6 to1^{o}C increase in temperature is expected for southwest Australia by 2030 (Figure 2.13).

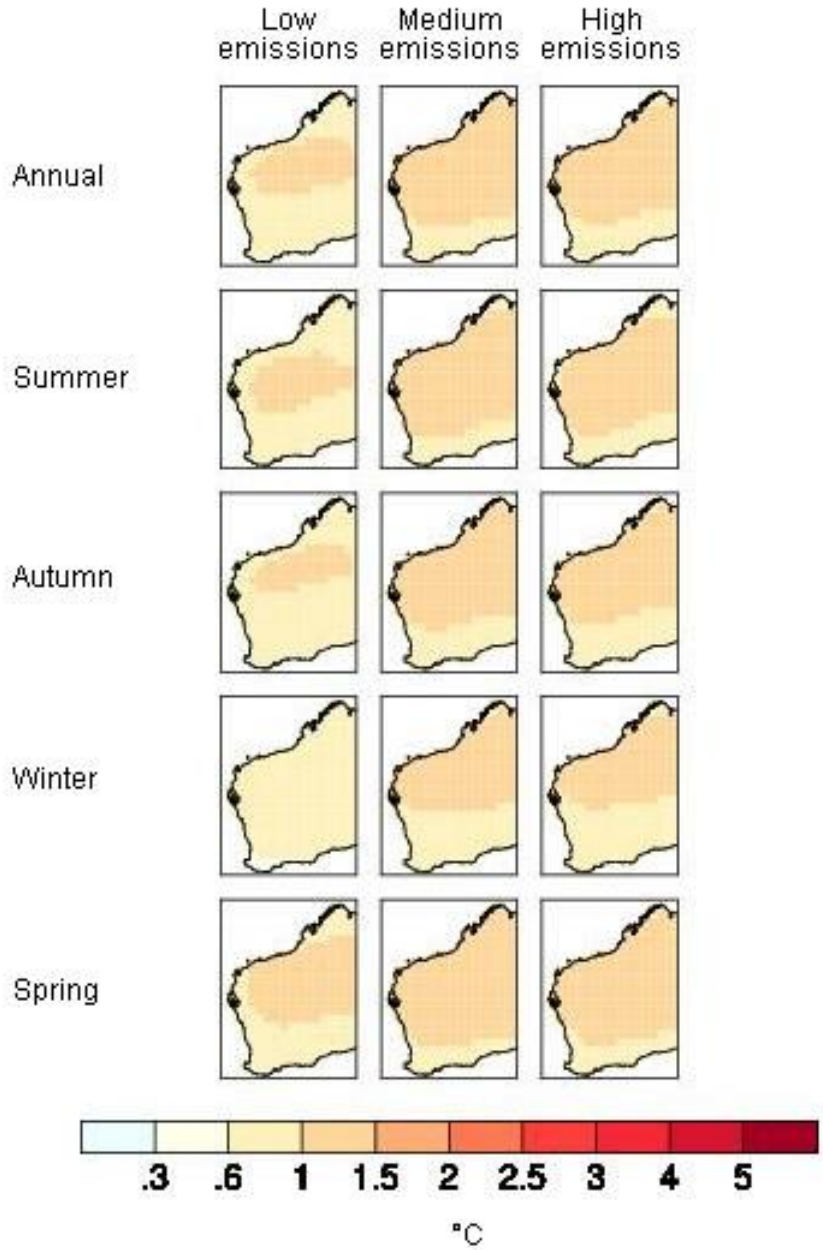


Figure 2.13: Projected change in Western Australian temperature, at 50th percentile, by 2030 using the period 1980-1999 as a base (CSIRO and BOM 2010).

2.4.3 Solar Radiation

Projected changes in solar radiation by the CSIRO and BOM are only expected for the winter months. Small changes in the order of one to two percent may occur in winter in southwest Australia by 2030 (Figure 2.14).

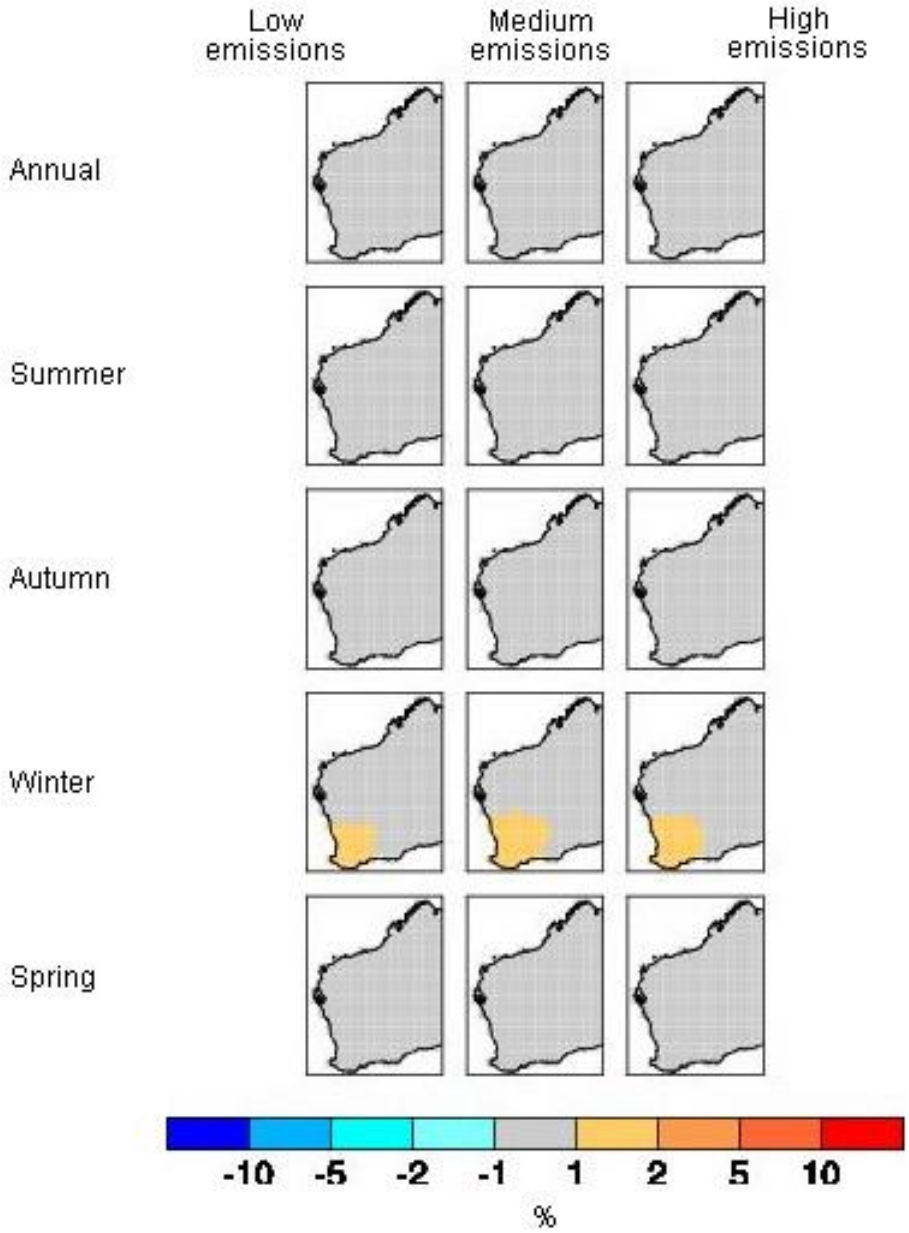


Figure 2.14: Projected change in Western Australian solar radiation, at 50th percentile, by 2030 using the period 1980-1999 as a base (CSIRO and BOM 2010).

2.4.4 Potential evapotranspiration

Potential evapotranspiration is generally forecasted to remain at 1980-1999 levels until 2030 in all seasons with the exception of winter, which is predicted to have a four to eight precent increase (Figure 2.15). Increases in potential evapotranspiration might be contested as pan evaporation rates actually declined during the period 1970 to 2002 (Roderick and Farquhar 2004). However, this was thought to be due to two reasons; firstly, temperature and humidly regimes haven't changed enough to affect pan evaporation rates, and secondly, there has been a decrease in wind speed and some regional decreases in solar irradiance that have resulted in the decrease in pan evaporation (Roderick et al. 2007). Therefore, it may be still possible that potential evapotranspiration will rise with increasing temperatures.

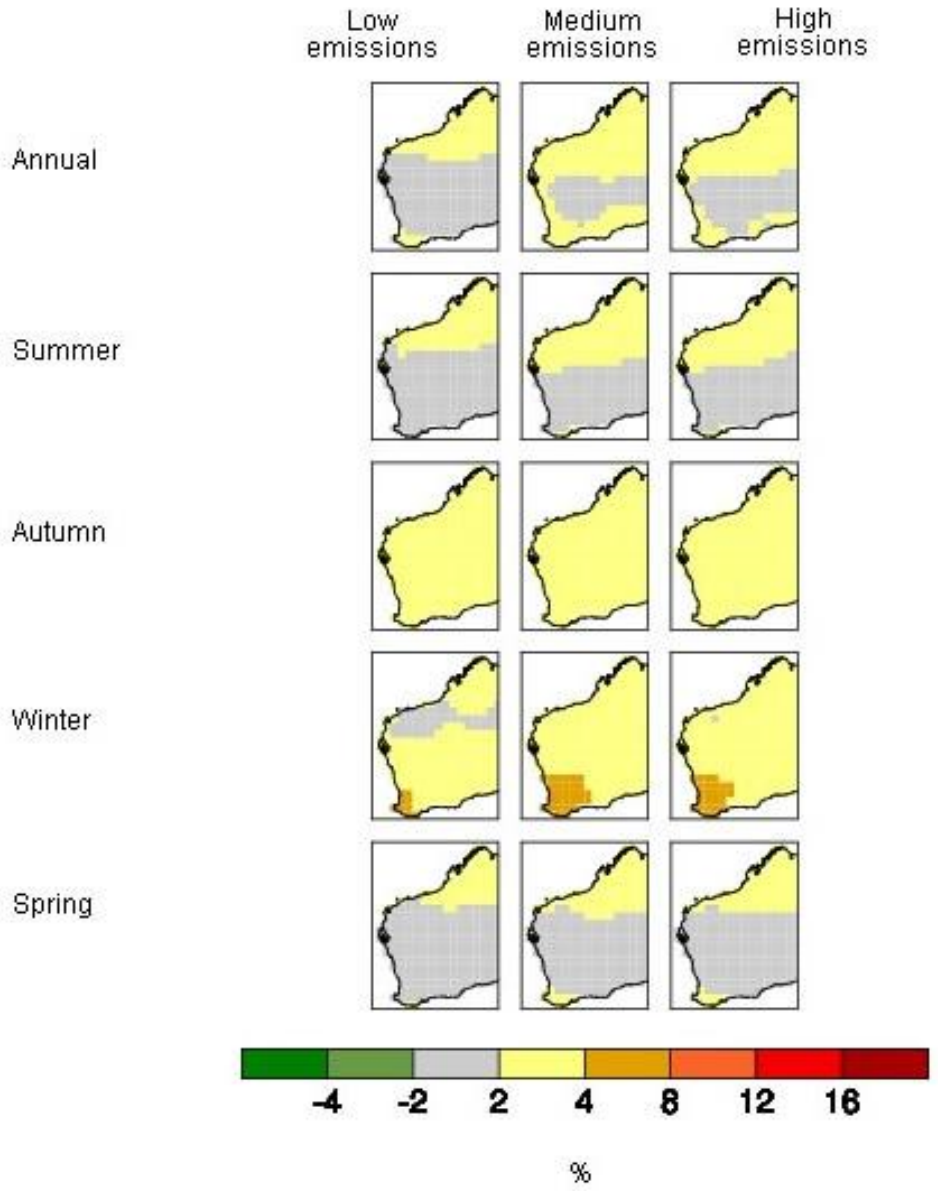


Figure 2.15: Projected change in Western Australian potential evapotranspiration, at 50th percentile, by 2030 using the period 1980-1999 as a base (CSIRO and BOM 2010).

2.5 Likely effect of predicted climate change on environment, management and genetic factors that drive wheat production in southwest Australia

2.5.1 Environment

Climate predictions indicate that Australia is likely to be impacted by combinations of higher levels of CO_2, increased temperatures and changes in rainfall, in order of diminishing confidence (Howden, Gifford, and Meinke 2010). Modelling suggests that without adaptation to the wheat production system and genotypes, there is likely to be a decline in yield in most parts of the Australian growing region (Howden and Jones 2004).

Increased atmospheric carbon dioxide

Unlike precipitation and temperature, atmospheric CO_2 is markedly uniform over the globe so there is no consistent spatial variation on which to gauge yield response to changes in CO_2 (Long et al. 2006). Most of the research on the effects of elevated CO_2 on plant growth has been conducted in enclosed experiments on a small scale (Ainsworth and Long 2005). In simple terms, the results indicate that crops become more resource efficient under elevated CO_2 conditions; more water efficient due to a reduction in stomatal conductance and transpiration per unit of CO_2 assimilated, and more light efficient due to increased rates of photosynthesis (Drake, Gonzalez-Meler, and Long 1997). These physiological changes in the plant result in what is commonly called the CO_2 fertilisation effect. In recent years Free-Air CO_2 Enrichment (FACE) experiments have been designed and conducted to determine whether crops respond to elevated CO_2 levels in open field conditions in the same way as in enclosed experiments. A review by Long et al. (2006) comparing enclosed studies to that of 15 years of FACE studies showed that the experiments carried out in an environment closer to field conditions resulted in lower percentage increases, in photosynthesis (13 versus 21 percent), biomass (10 versus 24 percent), and yield (13 versus 19 to 31percent) as a result of elevated atmospheric CO_2 (550 µmol mol^{-1} versus ambient). However, there is some conjecture as to the findings of these results with Tubiello et al. (2007) believing FACE results to indeed match those of enclosed experiments. These authors suggest that the analysis of Long et al. (2006) involved technical inconsistencies and lacked statistical significance. This difference in opinion on exactly how much elevated atmospheric CO_2 levels will increase crop growth and yield highlights the need for better research and methodologies. Also required is research into the interaction of elevated CO_2 with other climate components that affect crop growth that could be affected by climate change (temperature and rainfall through soil water) and also the interaction with different management and genotypes. The interactive effects of elevated atmospheric CO_2 concentration and limited water supply were tested in FACE experiments at Arizona, USA (Kimball et al. 1995). Elevated CO_2 levels

increase net canopy photosynthesis by 19 percent in the wet plots and 44 percent in the dry plots, and resulted in an eight percent increase in yield in the wet plots and 20 percent increase in the dry plots. In southeast Australia, Tausz-Posch et al. (2012) has compared the response of the wheat cultivar 'Drysdale' (selected for increased transpiration efficiency) to 'Hartog' (recurrent parent) in elevated atmospheric CO_2 conditions. While Hartog exhibited better early growth than Drysdale under elevated CO_2, grain yield was 19 percent greater in Drysdale, whereas under ambient CO_2 the yield different was only two percent. The authors concluded that wheat lines selected for transpiration efficiency (see section 2.5.3) will continue to be successful under elevated atmospheric CO_2.

FACE experiments by Kimball et al. (2001) suggested that the elevated atmospheric CO_2 will exacerbate the negative effects of low N on grain quality due to the dilution of N concentration, while the effects are expected to be minor when N is adequate. Crop modelling approaches have suggested similar results (Asseng et al. 2004; Luo et al. 2003; van Ittersum, Howden, and Asseng 2003).

Increased mean temperature

During the winter months in southwest Australia, when wheat crops do much of their vegetative growth, mean temperatures are typically below the optimum for photosynthesis (see section 2.3.1), so an increase in temperature would increase crop growth rates during this period. However, during the spring months when crops are typically setting grain, an increase in temperature could be detrimental to grain production. An increased incidence of days over 30°C during grain filling will reduce yields (Panozzo and Eagles 1999) but could increase grain protein (Panozzo and Eagles 2000). A review by Warlaw and Wrigley (1994) suggested that above optimum temperatures in Australia and the USA likely results in 10-15 percent decrease in grain yield. Using simulation modelling Asseng et al. (2011) found that variation in average growing season temperature of ± 2°C can reduce grain yields by 50 percent for a given yield level (same rainfall, management and soil N).

An increase in temperature will also result in faster development of wheat cultivars (Angus et al. 1981). Changes to the phenology of cultivars may be required so that the accumulated thermal time required by the crop between growth stages is increased so that under increased temperatures, optimal flowering dates are still achieved. Lack of adaptation in phenology could result in flowering dates coinciding with increased chances of frost events (however, the effect of climate change on frost in southwest Australia is not yet known). Furthermore, if crop development accelerates severely, there may be insufficient time for the crop to produce tillers, intercept photosynthetically active radiation and build biomass, which in turn will both reduce sink size and the capacity to fill grain (Fischer 1999).

Vapour pressure deficit (VPD) has a close association with minimum and maximum temperatures (Tanner and Sinclair 1983). Therefore, If minimum and maximum temperatures are to rise then there will be an increase in VPD. This will both increase transpiration demand and reduce transpiration efficiency of wheat crops (Monteith 1986). However, historical records show that minimum temperatures have risen faster than maximum temperatures since the 1950s (Torok and Nicholls 1996) and also that vapour pressure deficit has remained near constant between 1970 and 2002 (Roderick and Farquhar 2004). Therefore it is hard to say with accuracy, what the likely change in VPD, and its effect on wheat production, will be.

The effect of predicted temperature increases on evaporation rates is difficult to gauge as there are interactions with day-time versus night-time temperature change, wind speeds and global atmospheric humidity. Increased evaporation rates could reduce the amount of soil water available for transpiration by the crop assuming that the management of soil surface cover remains similar to current practises. However, if the current decreasing trend in wind speed continues and vapour pressure doesn't change with increasing temperature then there is likely to be little change to evaporation (Roderick and Farquhar 2004).

Decreased and variable rainfall

The change in rainfall is the least certain of the climate changes affecting wheat production, while it has the potential to have the greatest impact. Farre et al. (2007) used a higher-resolution nested model of the CSIRO Global Climate Model MK3 called the Cubic Conformic model and downscaled it to provide daily climatic data for the period 1976-2005 and 2035-2064, and then used the crop simulation model APSIM (Keating et al. 2003) to estimate wheat yields for eight locations in the southwest Australian wheatbelt. Generally wheat yields were simulated to be lower for the 2035-2064 period with generally lower growing season rainfall and a predicted atmospheric CO_2 level of 440 ppm (350 ppm was used for 1976-2005). The exception to this pattern occurred in waterlogging prone soils in high rainfall locations, where grain yields were simulated to increase.

On the other hand Ludwig et al. (2009) simulated wheat yields for the nine sites mentioned on page 51 for the periods 1945-74 and 1975-2004 and their associated differences in rainfall. Grain yields generated by APSIM resulted in no real differences pre and post 1975 and there were even benefits of less drainage and nitrate leaching post 1975. Most of the change in rainfall occurred in June and July, in which the greatest amount of rainfall occurs while evaporative and crop demand are low. During these months, once the soil has reached saturation, excess water moves out of the soil profile resulting in nitrate leaching and drainage.

A feature of the 2000s in southwest Australia has been the variability in rainfall (Figure 2.10 and Figure 2.11). The importance of rainfall to wheat yield in southwest Australia has already been outlined and the effect of this recent variability is clearly illustrated in Figure 2.3. The locations where the effect of decreasing growing season rainfall on wheat production is likely to be largest is in those areas where rainfall and soil water is historically the most limiting to production – in the marginal, low rainfall cropping regions with a long term average annual rainfall of 325 mm or less. Previous studies looking at the effect of climate change in southwest Australia, both historical (Ludwig, Milroy, and Asseng 2009) and projected (Farre, Foster, and Charles 2007), have concentrated on medium and higher rainfall locations, with little research being conducted for the most vulnerable areas on the low rainfall margins of the wheatbelt.

2.5.2 Management

Time of sowing

Time of sowing of wheat in Australia during the 1980s got earlier at the rate of a day per year, with the greatest changes occurring in southwest Australian and Queensland (Stephens and Lyons 1998b). This coincides with the adoption of reduced tillage techniques and the development of new herbicides for better post and pre-seeding control of weeds (Kerr, Siddique, and Delane 1992). Given the importance of May rainfall on time of sowing and therefore grain yield in southwest Australia (Stephens and Lyons 1998a), changes in rainfall in this month could have the largest impact on grain yields.

Row spacing

The impact of row spacing on wheat growth and yield has been discussed in a historical context. But is there likely to be a different response to row spacing in a future climate?

In southwest Australia, Blackwell, Pottier and Bowden (2006) found a positive grain yield response to increased row spacing on a shallow but fertile soil. In this instance autumn rainfall filled the soil profile with water, seasonal rainfall was low and the crop was sown early. Grain yield was increased from 1.5 t/ha to 1.9 t/ha when row spacing was increased from 30 cm to 60 cm. The growing conditions experienced in this experiment were similar to what is expected under projected rainfall patterns under climate change in southwest Australia (reduced growing season rainfall but more stored soil water at sowing).

Some growers in southwest Australia have responded to variable and unreliable seasons in recent times by extending the fallow period in order to store soil water before sowing and thus lower production risk (Oliver, Robertson, and Weeks 2010). Sowing crops after time has been allowed for soil water storage is a common practice in northern parts of eastern Australia (where rainfall is summer dominant), so it is worthwhile discussing cropping systems there in

relation to row spacing. Routley et al. (2003) looked at sorghum in Queensland and northern New South Wales, where crops largely depend on stored soil moisture for growth; they compared solid plantings to skip row (every third row not planted) and double skip row (two rows planted and two not planted) configurations. Planting arrangements were on a different scale to what is used in wheat in southern Australia with 1m row spacings used as a base. Findings from the research suggested that grain yields under skip row are equal to or greater than solid row plantings when yield levels are below about 2.5 t/ha i.e. when in season rainfall is low. Modelling using APSIM suggested that double skip planting arrangements could be beneficial in lower rainfall areas, where it was predicted that the frequency of crop failures would decrease, averaged grain yield would increase and grain yield would be generally less variable (McLean et al. 2003).

Based on this information and climate trends and projections, widening row spacing may be a useful technique for lowering production risk for wheat producers in low rainfall regions of southwest Australia. There are practical advantages to wider row spacings: seeding implements can typically be wider for the same cost, crops can be sown in thicker stubble loads and the seeding operation can be conducted at higher speeds, improving the timeliness of sowing (Jones and O'Halloran 2006). Anecdotal evidence suggests that row spacing has already widened over the past decades with the adoption of no-till (GRDC 2011).

2.5.3 Genetics

Water deficit stress is likely to be an increasing issue in southwest Australia if climate change projections prove to be correct. Wheat physiologists and breeders have been working for a number of years to develop wheat genotypes with improved drought tolerance either through escaping water deficit or having increased tolerance to water deficit stress at different stages of the growing season. However, there has been little plant physiological research and pre-breeding effort filtering through breeding programs to result in widely grown varieties, and the majority of cultivars grown commercially today are the result of empirical breeding programs (Richards 2006). This is partly due to the complexity of drought tolerance making it difficult to distinguish one or two physiological traits that will be beneficial in water scarce environments (Chaves et al. 2002; Araus et al. 2002), and the effectiveness of selection for yield potential in increasing yield in both stress-free and stressful environments (Araus et al. 2002; Fischer and Maurer 1978; Cattivelli et al. 2008; Dodig et al. 2008; Richards 1996). Also confounding breeding efforts is the requirement of breeders to select for other factors such as disease resistance and grain quality. However, it is becoming more likely that pre-breeding efforts will shape released cultivars as more genetic material filters through to breeding programs and knowledge of plant physiological processes (particularly those

affecting yield potential and response to abiotic stress) become central to the effective use of molecular breeding techniques (Araus et al. 2002).

Below is a summary of literature on genetic approaches to increasing drought tolerance in wheat in light of the three key areas of increasing yield in water scarce environments (increased water use, water use efficiency and harvest index) (Passioura 1977).

Limited tillering

The rationale for producing wheat plants with limited tillering stems back to the Donald crop ideotype. Donald (1968) postulated that a weak competitor with a short strong stem, erect leaves, few small leaves, a large and erect ear, the presence of awns, and a single culm would be a successful crop ideotype under ideal conditions. Donald could also see advantages in dry wheat growing environments as less water and assimilates would be lost on infertile tillers. Donald (Donald 1979) produced barley lines with traits consistent with his ideotype, in that they were uniculm and had a high harvest index. The lines didn't possess the desired short, erect leaves of the ideotype. Converse to what might have been hypothesised; Donald's high yielding uniculm performed comparatively better in wetter seasons than in drought years.

In light of Donald's ideotype Richards (1988) bred and tested wheats possessing a recessive tiller inhibition gene, designated *tin*, found in a wheat line from Israel. Duggan et al. (2005) tested wheat lines with the *tin* gene against their near isogenic sister lines in terminal drought and found yields to be similar across lines but with the highest yielding genotype across four experiments containing the *tin* gene. To date, there have been no intentional releases of *tin* varieties in Australia, but breeding companies Longreach and Australian Grain Technology (AGT) are known to have *tin* sources in their crossing programs (G. Rebetzke, personal communication June 1, 2011).

Breeding wheat cultivars with limited tillering has been done against the background of the Donald ideotype. Donald (1968) also stressed that consideration must be given to the environment in which the ideotype is grown, i.e. it is unlikely to be successful in wide rows with low seeding rates.

Osmotic adjustment

When leaf water potential is reduced by soil or atmospheric water deficits, osmotic adjustment or solute accumulation can help maintain leaf turgor and water content (Morgan and Condon 1986). Therefore, plants exhibiting osmotic adjustment are more likely to convert biomass into grain in cases of severe drought due to sustained cell and tissue activity and the maintenance of root activity (Serraj and Sinclair 2002). There have been numerous studies touting osmotic adjustment in wheat as being beneficial under water deficit stress (Blum and Pnuel 1990; Blum, Zhang, and Nguyen 1999; Morgan and Condon 1986; Morgan, Hare, and

Fletcher 1986; Quarrie, Stojanovic, and Pekic 1999) while others argue that the trait is of little benefit to growers because it is only beneficial under extreme drought conditions when yields are so low that a small percentage increase in yield results in little extra grain (Munns 1988; Serraj and Sinclair 2002).

Stem stored water soluble carbohydrates

Accumulation of water soluble carbohydrates (WSC) in the stem of a wheat plant prior to anthesis is reputed as being beneficial for grain filling when water becomes limiting after anthesis (Blum 1998; Davidson and Birch 1978; Foulkes et al. 2007), while being unimportant when post-anthesis water deficit doesn't occur (Blum and Pnuel 1990). Carbohydrates are translocated from the stem into the grain when the plant is stressed and unable to effectively produce assimilates for grain filling. Ruuska et al. (2006) measured genotypic differences in the amount of water soluble carbohydrates in wheat across nine site years and 22 genotypes and found that mean WSC across environments ranged from 108 to 203 mg g^{-1} dry weight, and mean genotype WSC ranged from 112 to 213 mg g^{-1} dry weight. The contribution of WSC to crop yield is hard to quantify due to inadequate methods and large seasonal variability, so Asseng and van Herwaarden (2003) attempted to quantify it using the crop model APSIM, which they compared with field experiments. They estimated that assimilates stored before anthesis could contribute between 5-90 percent of grain yield over a number of locations and seasons. The simulations also suggested that an increase of 20 percent in the capacity to accumulate pre-grain filling assimilates increased yield by up to 12 percent in a moderate season with terminal drought but had little effect in very poor and very wet seasons when factors effecting carbohydrate storage rather than storage capacity limited yield.

Early vigour

Early vigour in wheat is suggested to increase water use efficiency by capturing more of the limited water supply. In theory, a plant with greater early vigour will shade more of the soil and therefore, a) reduce evaporation from the soil surface, and b) increase competitiveness of the crop against weeds that might result in less soil water used by weeds. Interest in the trait also arises from the yield advantage of barley over wheat that has been attributed to early vigour (Richards 1996). There have been numerous journal articles discussing the benefit of early vigour to wheat production (Dodig et al. 2008; Quarrie, Stojanovic, and Pekic 1999; Reynolds, Majeeb-Kazi, and Sawkins 2005; Richards 1996; Richards et al. 2002; Richards, Watt, and Rebetzke 2007), and research has suggested that genetic advancement in this area is possible (Rebetzke et al. 2004; Rebetzke et al. 2007; Richards et al. 2002).

Increased soil surface shading early in the season should aid in greater partitioning of evapotranspiration to transpiration. However, greater biomass accumulation early in the

season may also result in increased water demand and usage and reduce the amount of soil water available after anthesis, which can have an adverse effect on harvest index and grain yield (Passioura 1977; van Herwaarden et al. 1998). Richards (1983) investigated the effect of leaf area on grain yield in wheat with post anthesis drought by removing tillers and leaves and found that reducing leaf area reduced water use and increased grain yield. Field testing of early vigour in southwest Australia was conducted by Botwright et al. (2002), using two methods. Firstly, a locally grown cultivar (Amery) was backcrossed with a high vigour donor and three high vigour lines resulting from the cross were compared to three low vigour sister lines at two locations in two seasons. The high vigour lines resulted in a 12 percent increase in grain yield in the wetter year, when averaged across both locations. In the drier season there was no significant difference in grain yield. The second method used was to manipulate early vigour through varying grain size of Amery. Larger grain size resulted in increased early vigour, biomass production and grain yield in one of four experiments. Nicolas and Turner (1987) compared 22 wheat lines in southwest Australia and found a positive relationship between early vigour and grain yield on a light textured soil.

Root depth and growth

An obvious method to increase water availability to the plant for transpiration is to have a root system that takes up more water from the soil. This can be achieved by a deeper root system, which in effect increases the size of the 'bucket' the crop has access to. Another approach is a more efficient root system that extracts more water from the same soil space. Hamblin and Tennant (1987) found that rooting depth is better correlated with water use than root length per unit ground area. Unfortunately knowledge in this field is limited due to the difficult nature of the research so genetic differences are hard to identify. Kirkegaard and Lilley (2007) analysed rooting depth data from 36 agronomic experiments in eastern Australia and found little difference in root penetration rates (RPR) between genotypes, and that soil type had a much larger effect on RPR. However, root systems are often restricted by factors that can interact with genotype (such as cereal cyst nematode, soil acidity and soil salinity) and the effect of these constraints could be lessened through breeding and selection (Richards 2008).

Plant roots can also play a role in converting the biomass produced more efficiently into grain by extracting water at times critical for grain production. One concern of increased RPR is that soil water supplies will be exhausted faster leading to increased post-anthesis drought and decreased harvest index (Delroy and Bowden 1986). The extent of this is likely to vary depending on sowing time, soil type and rainfall distribution. Lilley and Kirkegaard (2010) simulated the effects of increased RPR (by 20 percent) at four locations (with different soil types), including a deep yellow sand at Wongan Hills in southwest Australia, and found that

the median benefit was 0.1 t/ha at Wongan Hills (with a median yield of 3.8 t/ha) but the benefit was increased in time limited crops when sowing was delayed (median benefit of 0.2 t/ha). The same study found that increased efficiency of extracting water at depth (>1 m) had a larger benefit to yield than increased RPR at other locations in eastern Australia, but had a similar benefit at Wongan Hills.

Axial Resistance

In an attempt to conserve more soil water for post anthesis use, Passioura (1983) proposed that breeding efforts should be made to increase axial resistance to water movement through reducing the diameter of xylem vessels in seminal roots. Richards and Passioura (1989) developed a backcross breeding program to test this idea and found that the narrow vessel selections showed a 3-11 percent increase in grain yield in dry seasons when wheat was grown on stored soil water from fallow. There was little difference in grain yield in wet seasons.

Transpiration efficiency

The ability to turn more of the water transpired by a plant into increased biomass (carbon fixation) would clearly be beneficial in crops grown in water-limited environments. In the fixation of carbon through photosynthesis plants discriminate against the naturally occurring stable isotope ^{13}C, i.e. plants contain a smaller ratio of ^{13}C to ^{12}C than does CO_2 in the air (Farquhar and Richards 1984). Farquhar and Richards (1984) discovered that wheat lines that show less discrimination against ^{13}C in the atmosphere are more transpiration use efficient. Rebetzke et al. (2002) demonstrated that selecting for this trait can result in increased grain yield (average 5.8 percent), particularly in low rainfall environments. Selection for reduced carbon discrimination resulted in commercial cultivars Rees and Drysdale being released and grown in the eastern states of Australia (Condon et al. 2004).

2.6 Conclusions

Compared to other major wheat growing regions in the world the low rainfall regions of southwest Australia have many environmental constraints on production, the most important of which is water. Hot and dry finishes to the growing season often lower the harvest index of wheat crops, so care must be taken by farmers to manage the crop so as to not use too much soil water before anthesis which can result in small grain size and reduced yields.

Predicted climate change suggests increased atmospheric CO_2 levels, increased temperatures and a shift towards reduced growing season rainfall and perhaps increased out of season rainfall for southwest Australia. If this occurs, wheat producers will need to adapt their wheat production systems. Increased atmospheric CO_2 is likely to aid production in making wheat plants more water and radiation use efficient. Increased temperatures may increase crop water

demand and evaporation hampering grain filling in the already hotter months of the growing season. A decline in growing season rainfall could be detrimental to wheat production in already low rainfall regions. There will be greater reliance on out of season rainfall and producers may lengthen fallow periods to store more soil water before sowing and lower production risk. Management and genetic approaches are required to manage water use throughout the growing season so as to increase water use efficiency in a changing climate.

This literature review has discussed the factors that currently drive wheat production in southwest Australia and how projected climate change may affect them. Of the management factors discussed, row spacing and nitrogen supply show potential for manipulating the pattern of water usage as both are proven methods that can be used to slow water use by a wheat crop. However, with slower water use and canopy growth, evaporation from the soil can increase and yield potential can decline so research is required into changes in these factors and how they affect grain yield and yield stability. There has also been limited research into the interaction of genotypes with row spacing that could affect crop water use and grain yield.

Experiments and modelling studies described in this thesis were designed and conducted to determine if there is a G (cultivar) by M (row spacing and timing of nitrogen) by E (rainfall distribution) interaction that can be exploited to improve water-use-efficiency and productivity of wheat in a changing climate, particularly in the low rainfall parts of southwest Australia.

The following hypotheses will be tested:

I. *Increased out of season rainfall and decreased growing season rainfall will result in reduced wheat yields due to reduced individual grain size.*

II. *Growing wheat on wide row spacings will reduce biomass and evapotranspiration before anthesis resulting in increased individual grain weight and yield when the degree of reliance on out of season rainfall is increased.*

III. *Wheat genotypes will respond differently to wide row spacings according to their early vigour and tillering ability under competition (more plants per metre row).*

Chapter three

Materials and methods

"If I have seen farther it is by standing on the shoulders of giants"

- Isaac Newton

3. Materials and Methods

3.1 Introduction

The purpose of this chapter is to cover materials and methods used that were common to the two experiments in 2008 and 2009 that are covered in Chapters 4 and 5. The experiments were conducted on the same site using the same method of altering 'rainfall' distribution through rainout shelters and irrigation. The same techniques for measuring soil water and calculating growing season evapotranspiration and water-use-efficiency were used across experiments and the same weather station was used to collect climatic data.

3.2 Experimental site

The experiments were conducted in paddock 9A at the Department of Agriculture and Food, Western Australia's (DAFWA) Merredin Research Station (31.50°S, 118.22°E, mean annual rainfall 313 mm). The soil type is locally described as Sandy Salmon Gum or medium-heavy land and classified according to Isbell (1993) as a Sodic Hypocalcic Yellow Chromosol. A characterisation completed at the site (Russell 2005) described the first 8 cm as dark brown clayey sand, 8-50 cm as dark red sandy loam and 50-190 cm as brown sandy clay with calcite flecks. The physical properties and pH can be viewed in Table 3.1 and soil description of different layers, as described by Russell (2005), in Table 3.2. Figure 3.1shows the driest and wettest soil profiles in the 1993 growing season as measured by Russell (2005).

Table 3.1: Particle size distribution and pH with depth for the soil at the Merredin experimental site as described in Russell (2005)

Soil Depth (cm)	Physical properties (%)				pH_{ca}
	Clay	Silt	Sand	Gravel	
0	10.8	4.4	84.4	0.4	5.4
10	23.4	4.8	71.8	0.7	6.5
20	30.5	4.2	65.2	2	6.7
30	34.5	4.4	61	0.8	7
40	38.1	4.8	57.1	1.4	
50	40.8	5.7	53.4	1.4	7.3
70	35.4	5.6	59	10.1	7.7
90	31.8	4.9	63.3	6.8	7.9

Table 3.2: Description of the soil profile used at the Merredin experimental site (Russell 2005)

Horizon	Depth (cm)	Description
Ap	0-5	Light brown (7.5YR 6/4) dark brown (7.5TY 3/2, moist), whole coloured; weakly humose, clayey fine to medium sand; massive, apedal; dry, firm, hardsetting; clay dispersive after remoulding; sandy fabric; abundant roots; abundant coarse white sand grain; clear boundary to
Bw	5-25	Reddish yellow (5YR 6/6 dry), light red (2.5YR 6/6, moist), whole coloured; clayey fine to coarse sand; massive, apedal; dry, firm, hard setting; clay dispersive after remoulding; sand fabric; frequent fine roots; abundant white coarse sand grains; clear boundary to
B21t	25-45	Reddish yellow (5YR 6/6, dry and moist), whole coloured; coarse sand clay loam, subplastic increasing to sandy medium clay; medium to fine blocky grading into massive structure, dry, tough to hard consistence; smooth fabric, grading to rough fabric; sporadic ironstone gravel and abundant quartz grains; clay dispersive after remoulding, rare fine roots; clear boundary to
B22t	45-100	Reddish yellow (7.5YR 6/6, dry), reddish yellow (5YR 6/6, moist), whole coloured; gritty medium clay; massive to coarse rocky, occasionally plate; dry tough consistence; rough fabric; sporadic lime segregation in fine earth; rare roots; clear boundary to
2b2gt	100-120+	Very pale brown (10YR 7/4, dry, pale brown (10YR 6/3, moist 50%), reddish yellow (7.5YR 6/6, dry) reddish yellow (5YR 6/6, moist, 50%), mottled; fine sandy medium clay; massive to coarse blocky; dry, tough consistence; smooth and rough fabric; sporadic lime segregation in fine earth; rare roots

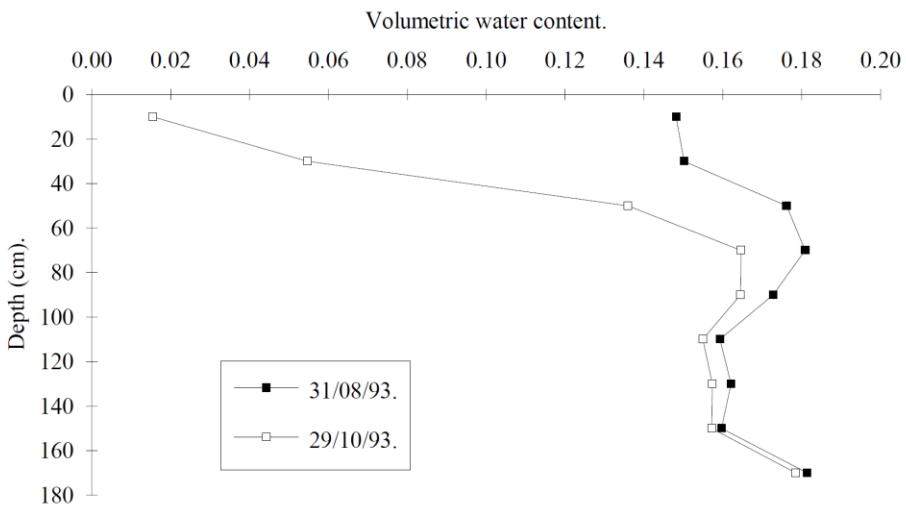


Figure 3.1: Wettest and driest volumetric water content (cm^3 cm^{-3}) by depth at experimental site in 1993 growing season as measured by Russell (2005)

The experimental site had been set up approximately 20 years ago to conduct similar experiments where rainfall needed to be controlled with rainout shelters and irrigation systems. The site has anchor points for securing two rainout shelters. Access tubes for neutron probe soil moisture measurement run down the centre of the shelter site, with tubes spaced 2.14 m (equivalent to the width of the cone seeder at the research station) apart. Adjacent to each of the rainout shelter site are a set of access tubes for plots grown outside the rainout shelters. The pre-existing layout created some limitations to the experimental design and randomisation. Due to these limitations, the experimental designs were a factorialised, incomplete randomized block design. The experiment layouts can be viewed in Appendix 1and Appendix 2.

Limitations to the design were as follows:

- All plots of the same 'rainfall distribution' treatment are located in the same block; either in the rainout shelters or in the adjacent 'open' blocks
- Due to the proximity of the rainout shelter sites and their adjacent open blocks, the cone seeder doesn't have room to turn around between them. This means the cone seeder must seed both blocks in the same 'run' and results in the same crop row spacing treatment in line across both blocks.

Before the shelters were installed the experimental plots were sown using a cone seeder. The dimensions of the shelters were 32 m by 6 m, which allowed room for 14 plots running across the shelter on 2.14 m centres with buffer plots at the extremities. Trenches were dug at the edges of the shelter so that water running off the canvas would flow away from the plots (Plate 3.2). Once the shelters were installed it was possible to cover the experimental plots when rain was imminent to enforce the out of season dominant rainfall treatment.

3.3 Rainout shelters and irrigation

Rain distribution treatments (either growing season dominant [GSD], or out of season dominant [OSD]) were achieved through a combination of rainout shelters and irrigation systems. The rainout shelters consisted of a series of steel cables held in position by steel frames and tensioned on anchor points buried in the ground. Canvas covers were then positioned on the cables on clips attached to the runners so that the covers could either be extended over the entire plot area or pushed to one side so that no plots are protected (Plate 3.1). Covers were only closed in the likelihood of an undesired rain event, otherwise leaving plots exposed to ambient conditions.

Plate 3.1: Rainout shelter; cables, frames and covers

Plate 3.2: Establishment of 2008 experiment before rainout shelters were installed showing side trenches for water control and wooden walkways to limit damage to plots

To simulate out of season rainfall (OSD) a modified boomspray was used. This had high volume nozzles attached to a scheme water standpoint and pulled by a low geared tractor capable of very slow speeds. Depending on the scheme water pressure and the speed of the tractor at the time of application, each pass applied between 9 and 18 mm of water. The amount of water applied was monitored by a series of rain gauges placed under the boom. To keep rainfall off GSD treatments before the growing season, the area was covered in black plastic.

To create the rainfall needed for the GSD treatment plots, the irrigation system was constructed based on thin wall dripper lines (Streamline™ 16080 by Netafim™) running perpendicular to plots and spaced 36 cm apart (with drippers spaced 20 cm apart in the lines) to achieve uniform distribution of water in the soil profile. The dripper lines were fed by a custom made system of PVC manifolds feeding three dripper lines each (Plate 3.3), which in turn were fed by 50 mm header pipe, which was fitted with a pressure regulator and water meter (Plate 3.4). The irrigation system was attached to a scheme water standpoint by a 64 mm flexi pipe. Water was supplied at sufficient pressure to ensure that water along the length of the dripper lines was uniform (Abrecht and Calder 1994).

Plate 3.3: Streamline™ 16080 thin walled dripper line (left) and PVC manifolds (right)

Plate 3.4: Header pipe and PVC manifolds

3.4 Soil water measurements

As indicated earlier, neutron probe access tubes had been installed up the centre of the shelters. Walkway planks were manufactured so that the tubes could be accessed without damaging the surrounding plants (Plate 3.5). This set-up was identical for the all plots.

Soil moisture was measured with a Campbell Pacific Nuclear (CPN) Hydroprobe. This reading was then calibrated against known soil moisture levels in the soil profile as calculated by Russell (2005):

0-20 cm $\theta_v = (pcount - 0.14)/1.9537$

20-40 cm $\theta_v = (pcount - 0.3619)/1.3112$

Below 40 cm $\theta_v = (pcount - 0.389)/0.9611$

Where θ_v is volumetric water content and *pcount* is proportional counts, that is the neutron reading for a given soil layer divided by the mean of ten neutron readings taken in 100 percent water on the same day.

PVC access tubes were 2m deep. Soil moisture was measured at 20 cm increments starting at 10 cm below the soil surface. The crop rows were planted so that the tubes were in the centre of the interrow (Plate 3.2). In 2009 additional tubes were installed so that one tube was positioned in the row and another in the centre of the interrow of the 60 cm row spacing treatment plots.

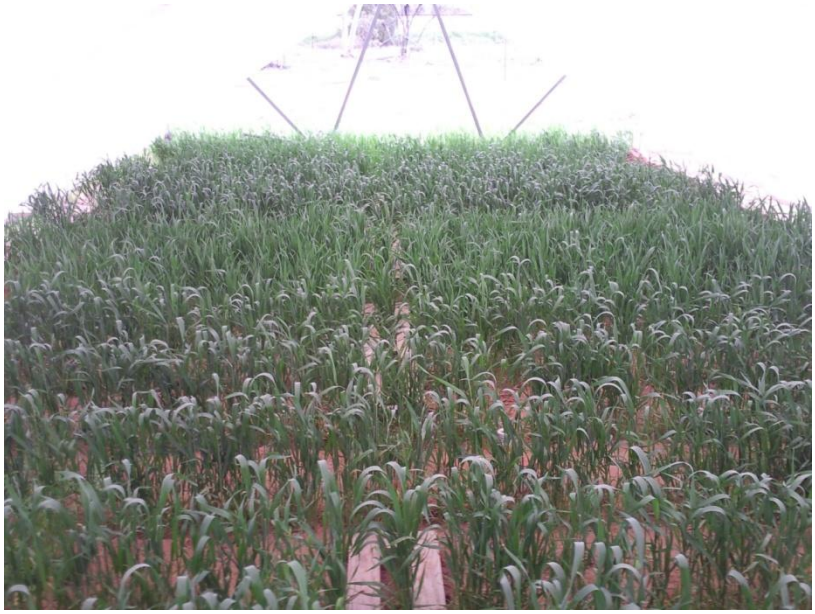


Plate 3.5: Walkway planks used to access neutron probe access tubes without damaging experimental plots

Crop lower limit (CLL) and drain upper limit (DUL) were determined by driest and wettest profiles for each soil layer over the two seasons of observations (Figure 3.2) and tested against soil water infiltration and extraction rates in the APSIM crop model (see Appendices 3-6). The depth of extraction (90 cm) and driest profile is similar to that in the 1993 season as recorded by Russell (2005). The DUL was generally lower in the 1993, suggesting the profile wasn't 'wet-up' to capacity in that season. Also, the DUL presented in Figure 3.2 was determined by the wettest recording for each individual depth (which could have been on different days), rather than the wettest recording for the whole profile.

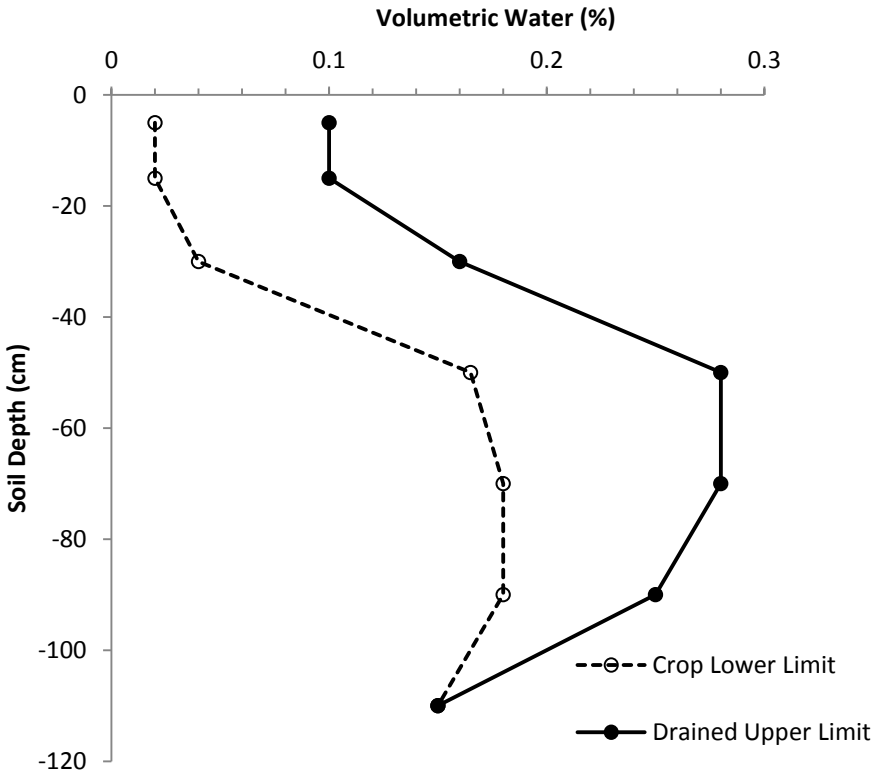


Figure 3.2: Crop lower limit and drained upper limit of experimental site as determined by driest and wettest profiles over two experimental seasons and tested against soil water infiltration and extraction rates in the crop model APSIM

Water-use-efficiency (WUE) was calculated using total evapotranspiration throughout the growing season. The formula of French and Schultz (1984) was used:

$$WUE = \frac{GY}{ET}$$

Where GY is grain yield and ET is evapotranspiration calculated using the following formula:

$$ET = (Soil\ water\ at\ sowing - Soil\ water\ at\ end\ of\ season) + rainfall\ from\ sowing\ to\ maturity$$

Partitioning of E and T was estimated using the technique outlined by Jones (2009). Total transpiration is calculated by dividing the maximum biomass by an estimate of transpiration efficiency – 50 kg/ha.mm, as suggested by French and Schultz (1984). Total evaporation (E) is calculated as ET minus total transpiration (T).

3.5 Cone seeder

The Merredin Research Station cone seeder was used to seed both experiments. The seeder had no-till seeding tines with knife points and press wheels. Fertiliser applied at seeding is placed 2 cm below the seed to avoid toxicity to the seed. Because the varieties differed in

average grain weight, seeding rates (g/plot) were varied between varieties to give the same seed number per unit area. This aimed at achieving a similar plant density for each variety.

3.6 Weather

Meteorological data was recorded by the Department of Agriculture and Food, Western Australia's (DAFWA) Merredin Research Station weather station on the research station, located about 300 m from the trial site. A rain gauge was also maintained at the site.

The weather station recorded the following measurements:

- Air temperature at 1.25 m, using a platinum RTD element.
- Relative humidity at 1.25 m, using a Vaisala Humitter 50 element.
- Soil temperature at 4 cm below ground level, using a platinum RTD element
- Solar radiation at 3m, using a Li-Cor LI200S pyranometer.
- Rainfall at 0.3 m, using a Rimco rain gauge.
- Pan evaporation, calculated using a modified Penman-Monteith equation.
- Wind speed at 3m, using a Met-one 014A sensor
- Wind Direction at 3m, using a Met-one 024A sensor

Chapter four

Response of five genotypes to rainfall distribution and row spacing

"Science is built of facts the way a house is built of bricks; but an accumulation of facts is no more science than a pile of bricks is a house"

- Henri Poincare

4. Response of five genotypes to rainfall distribution and row spacing

4.1 Introduction

Changes in rainfall patterns and declining terms of trade have increased the need for more resilient cropping systems in the marginal wheat growing regions of southwest Australia. Up until the year 2000 wheat yields in the southwest Australian wheatbelt had steadily increased as a result of improved genotypes and agronomy (Anderson 2010). However, during the 2000s wheat yield became inconsistent from year to year due to increased variability of seasonal rainfall relative to the 1990s (Figure 4.1). While yields have tended to increase over the past three decades, rainfall in the southwest of Australia has trended the other way (Bates et al. 2008). In most parts of the wheatbelt there has been a declining trend in rainfall in winter and spring, when the crop is grown, and an increasing trend in summer rain (section 2.4.1). If these climate trends continue, wheat producers will need to implement genotype (G) and management (M) combinations that improve grain yield in this changing and variable environment (E).

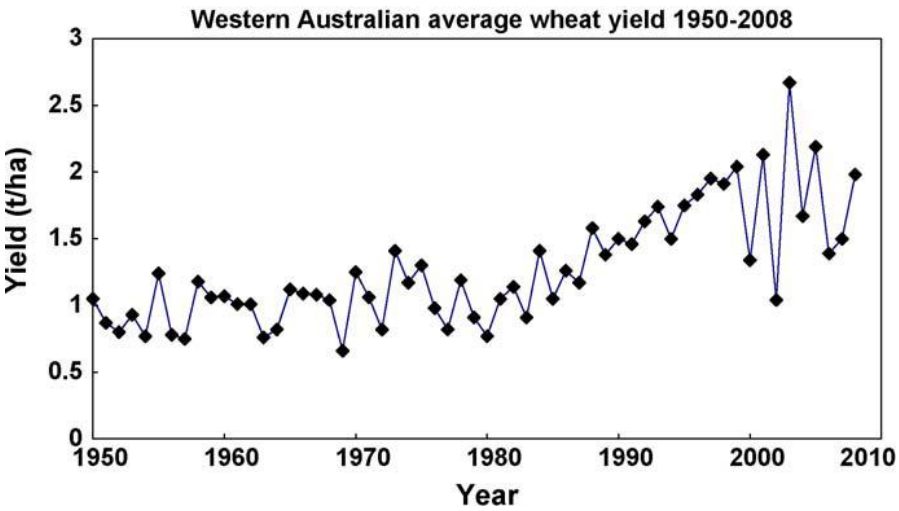


Figure 4.1: Average yield of wheat in southwest Australia 1950-2008. Data from Cooperative Bulk Handling Ltd (Anderson 2010)

Passioura (1977) discussed the importance of soil water reserves after anthesis to aid in grainfill, which becomes especially important in the typically hot and dry end to the growing season in mediterranean-type climates. Availability of soil water after anthesis is likely to become an even greater issue in a climate in which growing seasons start with stored soil water but there is more limited rainfall during the growth period. Kleemann and Gill (2010) showed that widening row spacing could slow down the transpiration rates of a wheat crop in southern Australia, a finding consistent with those in other parts of the world such as Mediterranean Syria (Eberbach and Pala 2005) and North America in winter wheat (Johnson, Witters, and Ciha 1981; Tompkins, Fowler, and

Wright 1991). In most instances increased row spacing results in decreased grain yield (Amjad and Anderson 2006; Shackley 2000; Tompkins, Fowler, and Wright 1991; Winter and Welch 1987), but Blackwell (2006) found in the northern parts of southwest Australia that increased row spacing could be beneficial to yield, particularly when the crop was grown largely from stored soil water and in a fertile shallow soil.

There is little written on the interaction of genotype with row spacing (RS) in wheat but Fischer (2009) postulated that genotypes suited to wider rows would require rapid canopy expansion to fill the interrow to reduce evaporation from the soil and increase weed suppression. Amjad and Anderson (2006) in southwest Australia found that there was a tendency for longer-seasoned genotypes to perform better in wider rows than shorter-seasoned genotypes due to greater competition with weeds and more biomass late in the season. There have been some studies on plant density (altered mainly through seeding rate) that suggest the interaction of genotype and plant density in wheat is small. In a summary of 32 experiments conducted in southwest Australia, Anderson et al. (2004) concluded that genotype by plant density interactions only occurred when grain yield exceeded 2.5 t/ha. In maize, modern high yielding hybrid genotypes respond more to high density canopies (greater seeding rates and narrower row spacing) than older, conventional genotypes (Evans and Fischer 1999). This is thought to be a mostly a result of reduced root angle, resulting in more deep extraction of soil water (Hammer et al. 2009).

Donald (1979) attempted to exploit the genotype by plant density interaction when he found a positive grain yield relationship between a single culm ideotype and increased plant density in barley. Whilst early stages of this research were promising, they failed to have a commercial impact. Later work has been conducted in wheat with the use of wheat lines containing the tiller inhibition gene (*tin*) with similar results; genotypes with reduced tillering showed a stronger response to plant density (Duggan et al. 2005).

The aim of the experiment reported here was to investigate the effects on crop performance of the interaction between management (wheat canopy manipulated by altering row spacing [RS]), genotype [G]) and rainfall distribution [E]. The environment (E) component of G*E studies can involve one site over multiple seasons, multiple sites in one season, or more commonly, a combination of the two. The aim of the experiment discussed in this chapter is to investigate G*E*RS interactions within one site and one season by manipulating water availability to different treatments. To test for the reproducibility of effects across years a similar experiment was conducted at the same site in 2009 (Chapter 5).

4.2 Materials and methods

4.2.1 Experimental design and trial management

An experiment was conducted on the Department of Agriculture and Food, Western Australia (DAFWA) Merredin Research Station during the 2008 growing season (May to October). The details of the soil type and sheltering and irrigation of the trial can be found in the Materials and Methods chapter (Chapter 3). Experimental treatments consisted of two 'rainfall distributions', five genotypes and two crop row spacings, arranged factorially. Details of the treatments are given in Table 4.1.

The experiment investigated crop water use, growth and grain yield under two contrasting rainfall distributions; out of season dominant, and growing season dominant. Also tested were a conventional row spacing (23 cm) and a wide row spacing treatment (60 cm) to determine how they interact with rainfall distribution. Five genotypes were used in this experiment to determine whether differences in canopy architecture would result in an interaction with row spacing. Also of interest was whether there would be an interaction with rainfall distribution given differences in the way the genotypes construct yield. Genotypes were selected based on reputed canopy traits. Wyalkatchem and Westonia are similar in phenology but Wyalkatchem is reputed to be shorter, have lower vigour and short erect leaves and is generally considered to be poor in competition with weeds, which has led to the use of the cultivar in weed competition studies; e.g. Zerner and Gill (2010). Silverstar was introduced to compare to a near isogenic line with the tiller inhibition gene (*tin*). Halberd is an older and taller cultivar with a reputation for plasticity and tolerance to drought that allows it to adapt to different seasons.

Table 4.2 provides a list of the management operations carried out on the experiment. Table 4.3 details the sampling dates conducted for data collection.

Table 4.1: Treatment type, labels and description of Merredin 2008 experiment

Treatment	Labels	Description
Rain Distribution	Out of Season dominant (OSD)	Decile 9 out of season rainfall with reduced growing season rainfall to finish the growing season (end of October) at Decile 5 total rainfall (Figure 4.4)
	Growing Season dominant (GSD)	Decile 1 out of season rainfall with increased growing season rainfall to finish the growing season (end of October) at Decile 5 total rainfall (Figure 4.4)
Genotypes	Wyalkatchem	Maturity: early Canopy: low vigour (compared to Westonia)
	Silverstar	Maturity: very early Canopy: high tillering (compared to Silverstar (*tin*)
	Silverstar (*tin*)	Maturity: very early Canopy: reduced tillering (compared to Silverstar)
	Westonia	Maturity: early Canopy: more vigorous that Wyalkatchem
	Halberd	Maturity: mid-late Canopy: taller than all other genotypes
Crop row spacing	60cm	60 cm from middle of crop row to the middle of neighbouring row
	23cm	23 cm from middle of crop row to the middle of neighbouring row

Table 4.2: Management operations applied to 2008 experiment at Merredin

Activity	Rate	Product	Date	Treatments
Irrigation	112 mm	Water	Early-Mid April	OSD
Summer weed control	2 L/ha	Hammer (240 g/L Carfentrazone-ethyl)	24 Apr	OSD
	2 L/ha	Roundup Powermax (540 g/L Glyphosate)		
Pre-sowing Herbicides	2 L/ha	Sprayseed (135 g/L Paraquat, 115 g/L Diquat)	11 Jun	All
Sowing (target plant density 120/m^2)	55 kg/ha 53 kg/ha 58 kg/ha 46 kg/ha 44 kg/ha	Seed	11 Jun	Halberd Westonia Wyalkatchem Silverstar Silverstar (*tin*)
Fertiliser	120 kg/ha	Agras (16.1N, 9.1P, 14.3S)	11 Jun	All

Table 4.3: Sampling dates and measurement for Merredin 2008 experiment

Activity	Date/s	Measured
Stem elongation sampling	Aug 23	Leaf Area Index (LAI), total dry matter, dry matter partitioning
Anthesis sampling	Sep 23	LAI, flag leaf disease rating, total dry matter, dry matter partitioning
Soil water measurement	Jun 6 Jun 30 Jul 14 Jul 29 Aug 11 Sep 10 Sep 22 Oct 6 Nov 4 Nov 17	Soil water content at 20cm intervals from 10-110cm depth
Harvest sampling	Nov 25	Grain yield, total dry matter, yield components, grain protein

4.2.2 Measurements

Weather, soil water, evapotranspiration and water-use-efficiency

See Materials and Methods chapter (Chapter 3) for details.

Light interception

Photosynthetically active radiation (PAR) measurements were taken above and below the crop canopy using an AccuPAR Linear PAR/LAI ceptometer (model PAR-80, Decagon Devices Inc.) between 1100 and 1400 hours, at stem elongation (Zadoks growth stage 30) and anthesis (Zadoks growth stage 65). A spot reading was taken above the canopy before and after three below canopy readings in three separate parts of each plot. Each below canopy reading was taken over 10 seconds with one reading taken per second and then averaged. The amount of intercepted PAR was calculated by the average of the two above canopy spot readings and the three below canopy readings.

The ceptometer was angled across crop rows so that mid inter-row to mid inter-row was measured (Figure 4.2) in both row spacing treatments.

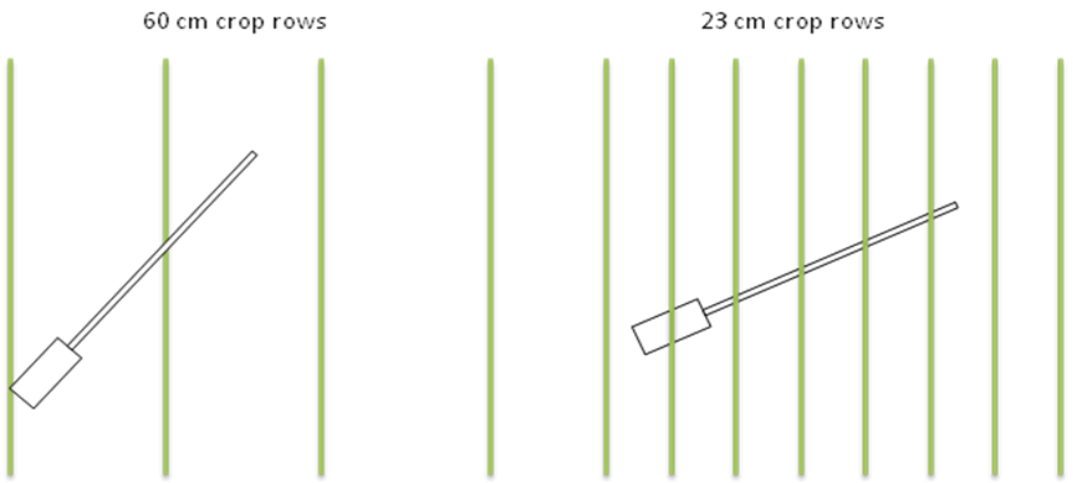


Figure 4.2: Positioning of ceptometer across varying row spacings

Dry matter accumulation and partitioning

Plants were removed from the field three times in the growing season (Table 4.3), when the crop was at Zadoks stage 30 (stem elongation), 65 (anthesis) and at maturity (harvest). For the first two sampling dates four rows, each 0.5 m in length, were taken from the RS_{23} plots and two rows, each 0.5 m long, from the RS_{60} plots. Two samples were taken from each plot for the harvest sampling. One sample was the same size as those taken at the other sampling dates and the other was larger with 1 m of row taken of the same number of rows.

Sampled plants were counted and 10 representative plants were selected for subsampling. The subsample was partitioned into stems and leaves at stem elongation sampling; infertile stems, stems, leaves and heads at anthesis sampling; and grain, husks and chaff at maturity, and dried at 70°C for 70 hours.

All plants not included in subsampling were dried the same way and used in calculating total dry matter.

Grain yield, yield components and harvest index

Grain yield and harvest index were calculated from the harvest samples. All heads within the samples were removed and counted. Twenty median heads were removed from the larger harvest samples and ten from the smaller samples for further yield component measurements.

The bulk of the heads were threshed using a VRS-1 Venables Small Seed Thresher (L.T. Venables Pty. Ltd., Wembley, Western Australia) and the grain was weighed to derive grain yield. The husks were also collected and dried for 70 hours at 70°C, as was the straw. Harvest index was calculated by dividing the grain weight by the total weight of grain, husks and straw.

Each subsample head had spikelets counted and was threshed. Subsampled grains were counted using a Count-A-Pak Model 77 (FMC Corporation, Pennsylvania, USA) as were the grains threshed from the bulk heads.

Grain protein

Grain protein percentage was indirectly estimated by Near Infrared Spectroscopy (NIRS) on a Foss near-infra-red NIRS6500 spectrometer (Foss, Höganäs, Sweden) using calibrations developed at the Department of Agriculture and Food Western Australia, South Perth.

4.2.3 Statistics

A Restricted Maximum Likelihood (REML) procedure, developed in conjunction with Department of Agriculture and Food, Western Australia biometrician Mario D'Antuono, was used to analyse the dataset for significant differences using the GenStat program.

4.3 Results

4.3.1 Weather

'Rainfall' in this experiment was considered as that occurring naturally as well as irrigation to create the two rainfall distribution treatments. The out of season dominant (OSD) treatment received 112 mm of boom irrigation in early April, but a great deal of runoff and evaporation occurred and water storage was minimal compared to water supplied (26 mm extra stored in OSD treatment at sowing). The hard-setting and dispersive nature of the soil (Chapter 3) together with lack of stubble cover due to the poor season the year before, meant infiltration was slow. Growing season dominant (GSD) rainfall tracked at decile one until August due to extremely low rainfall. After August a combination of natural rainfall and irrigation elevated GSD to greater than OSD in cumulative rainfall. OSD finished the growing season at about decile five while GSD was decile six (Figure 4.4).

Daily maximum air temperature tended to be slightly warmer than average in the early parts of the growing season and slightly cooler than average in the latter, which reflected the rainfall in 2008 (drier than average early and wetter than average later) (Figure 4.4). The cooler finish to the season meant days of 30°C or more did not occur until the end of October. Daily minimum temperatures were similar to the average and while temperatures reached sub-zero on three occasions there was no sign of frost damage.

Solar radiation and pan evaporation levels were similar to the average with the exception of August which tended to have higher levels in 2008 than the long term average (Figure 4.4).

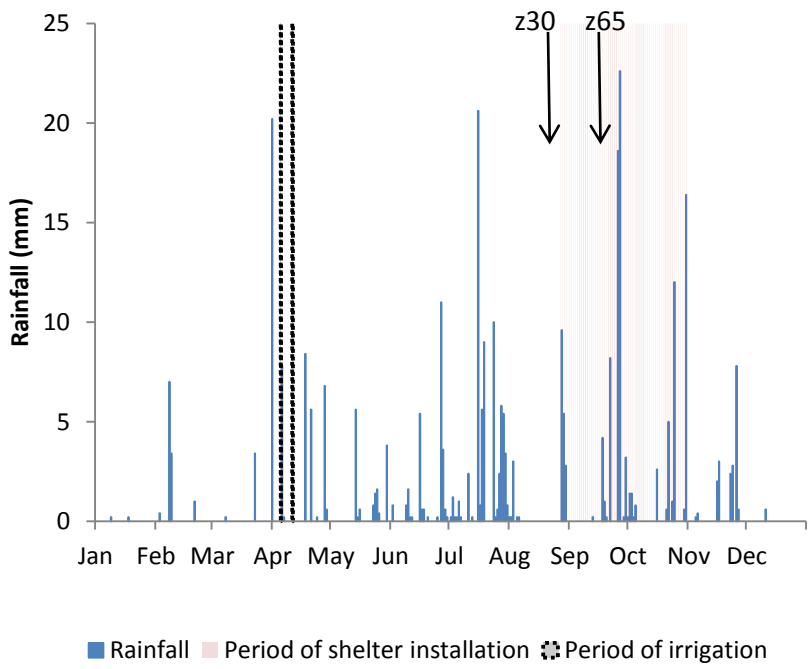


Figure 4.3: Periods of irrigation, rainout shelter installation (when OSD plots were covered on rainy days), days and amount of rain, and key development dates

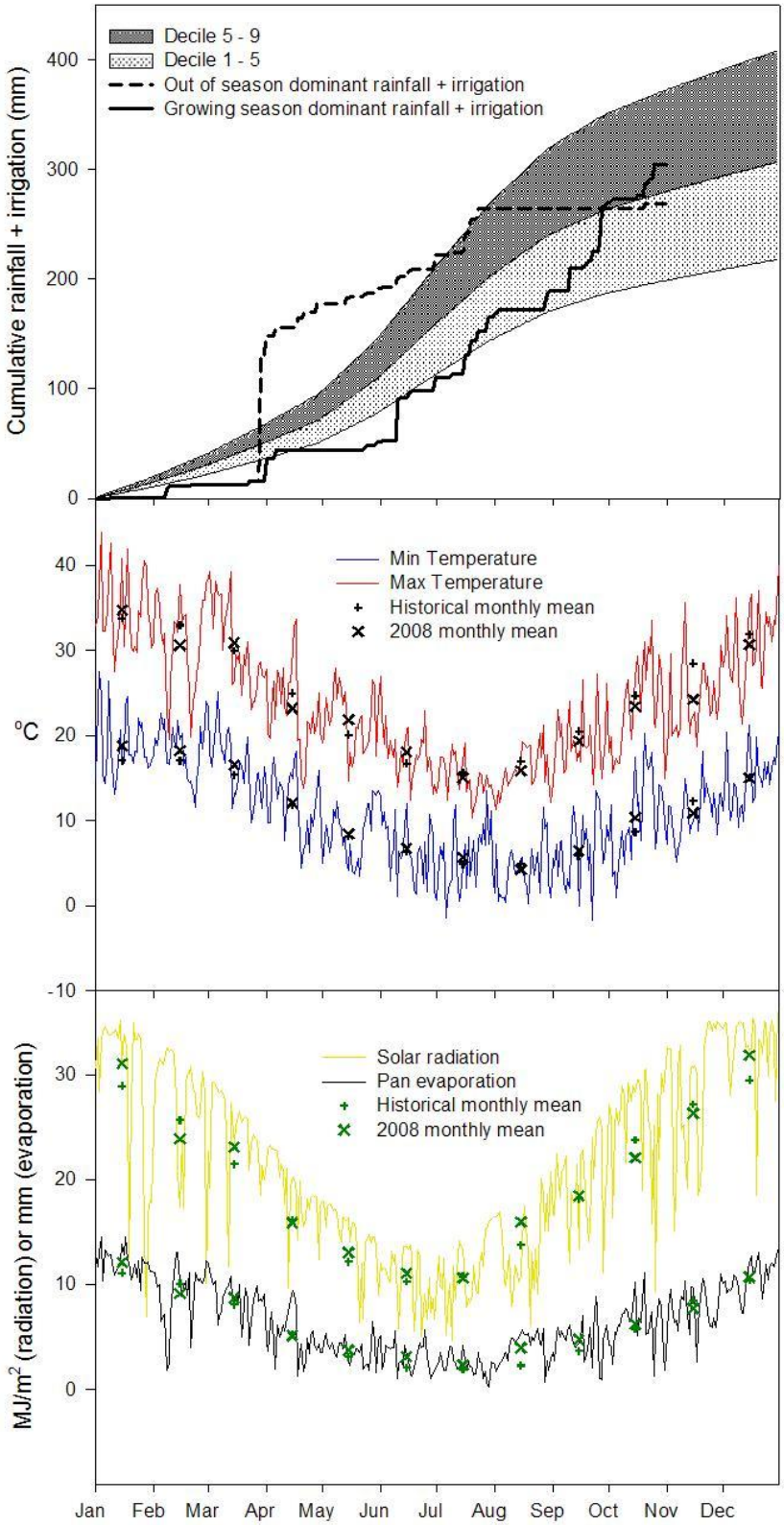


Figure 4.4: Cumulative rainfall, daily minimum and maximum temperatures, solar radiation and pan evaporation for the Merredin experimental site in 2008

4.3.2 Water use

Soil water storage in relation to rainfall distribution

Averaged across all genotypes and row spacings, profile (i.e. 0-100 cm) soil water storage as a result of boom irrigation in the OSD treatment resulted in 26 mm extra in that treatment (not significant due to variation) (Figure 4.6). The OSD treatment had significantly greater soil water than in the GSD treatment in the 10 cm and 50 cm soil zone depths at the first sampling date, on June 18, a week after sowing (Figure 4.5). By July 29 soil water content for the two rainfall distributions treatments was equal at all soil depths. They remained the same until September 10 when more soil water was measured at 30 cm in the GSD treatment. By September 22 the rainfall distribution treatments reached parity again before more rainfall in GSD resulted in that treatment having more soil water at 10, 30 and 50 cm for the remainder of the growing season.

Total evapotranspiration for the season was significantly affected by both rainfall distribution and row spacing ($P < 0.05$) (Table 4.4). Total ET for the GSD treatment was 209 mm compared to only 98 in OSD and the narrow row spacing treatment RS_{23} used 23 mm more than RS_{60} (165 mm to 142 mm). Estimated transpiration, calculated as outlined in the Materials and Methods chapter, was 75 mm for the GSD treatment compared to just 30 in OSD (Table 4.5).

Row spacing

The impact of row spacing on soil water content throughout the year was quite similar for both rainfall distribution treatments. The row spacing treatments started with the same soil water at all depths, and remained similar until September when less water was being extracted from RS_{60} (measurements taken from inter-row space), which resulted in that treatment having more soil water at 10 and 30 cm in GSD and 10, 30 and 50 cm in OSD. The next two sampling dates saw differences in the GSD treatment with more soil water also present at the 50 cm depth in RS_{60}. Towards the end of the season rainfall brought the row spacing treatments back to parity. In the OSD treatment where rain was excluded the differential continued until the end of the season. At this stage, there was no difference at 10 and 30 cm but RS_{60} finished with an extra 14 mm residual soil water at 50 cm and 7 mm at 70 cm (Figure 4.7).

No differences in water use were identified between genotypes.

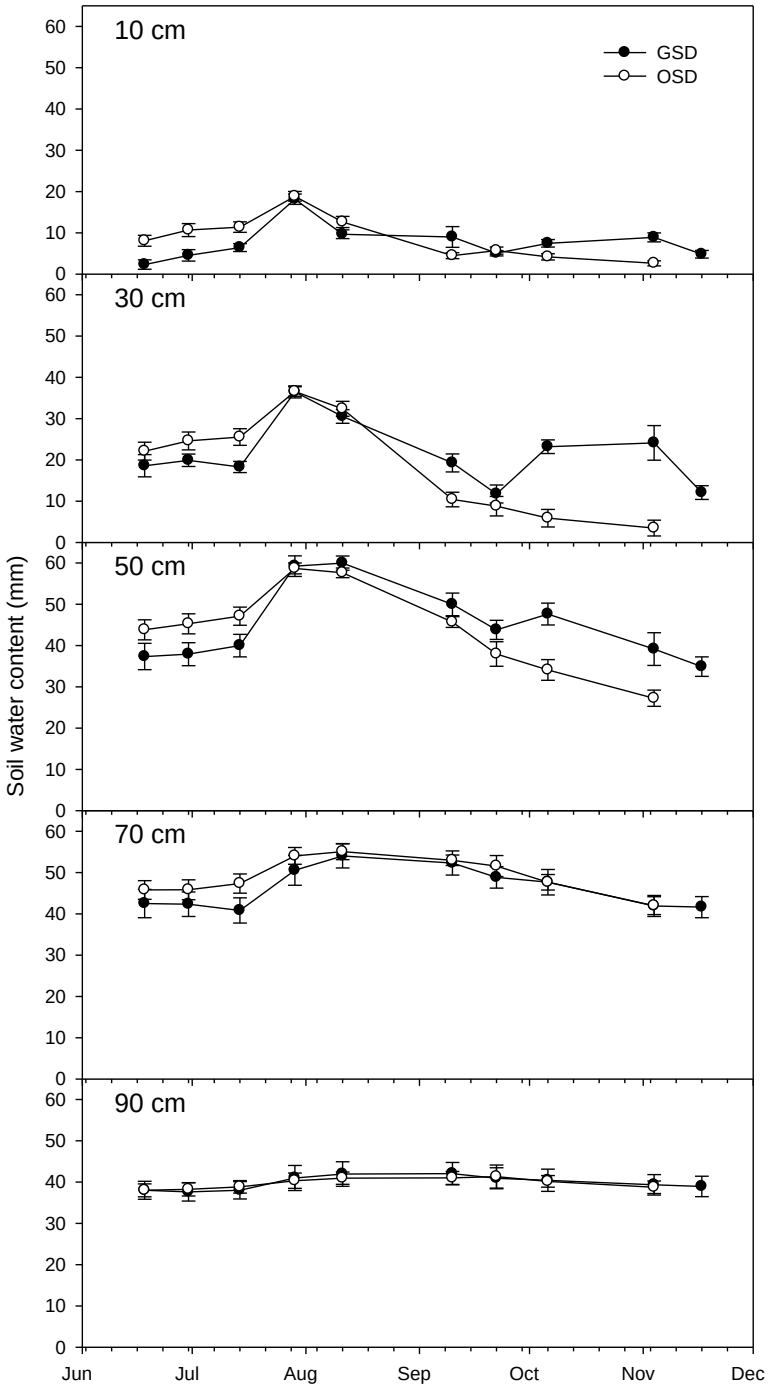


Figure 4.5: Soil water content at 10, 30, 50, 70 and 90 cm depth as affected by rainfall distribution (RS_{23} row spacing treatment). Merredin 2008.

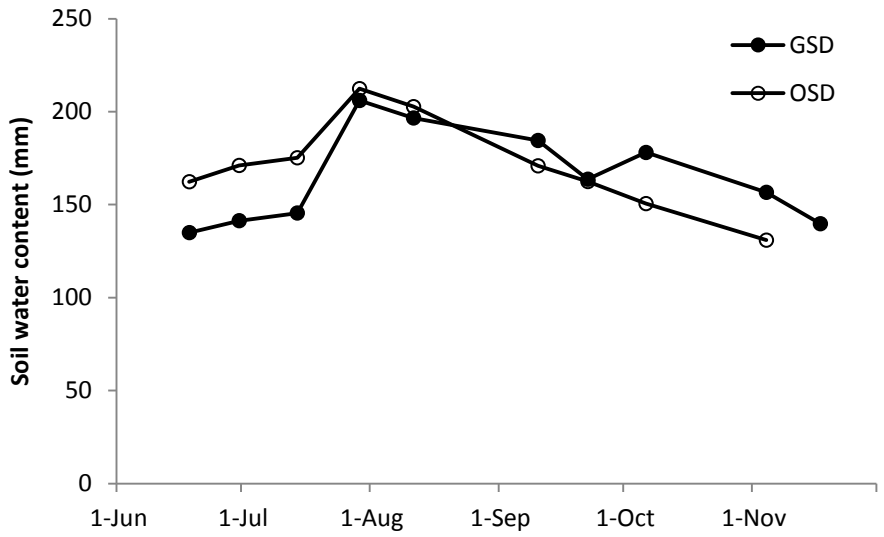


Figure 4.6: Total soil water content as affected by rainfall distributions. Merredin 2008.

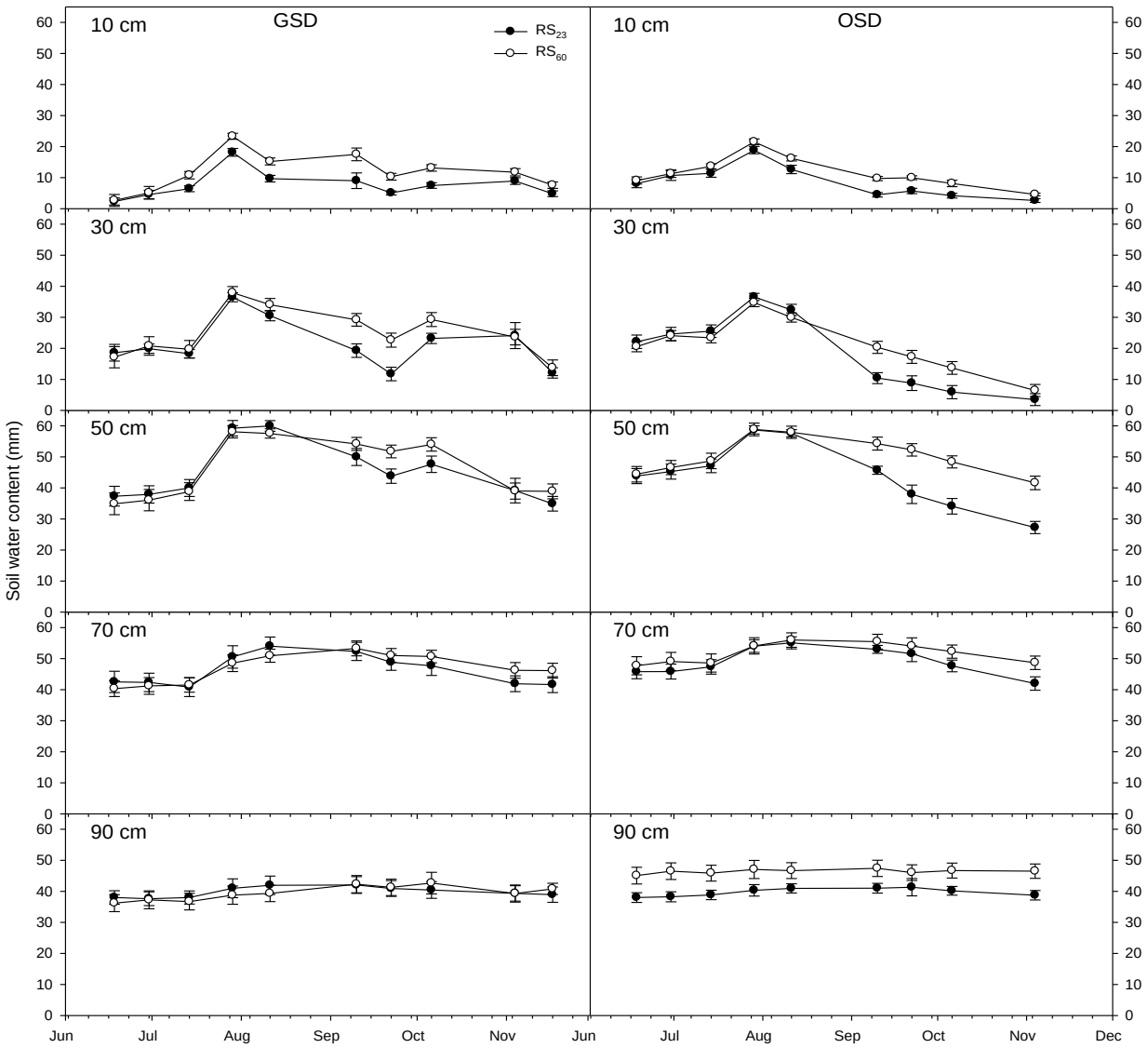


Figure 4.7: Soil water content at 20 cm intervals as affected by rainfall distribution treatment and row spacing. Merredin 2008.

Table 4.4: Effect of rainfall distribution and row spacing on soil water (SW) content over the growing season, and evapotranspiration. Merredin 2008. WUE = water use efficiency

Rain treatment	Row Spacing	Starting SW	Finishing SW	Rainfall	Evapotranspiration	Grain yield t/ha	WUE
		a	b	c	d = (a-b) + c	e	e*1000/d
GSD	23	139	134	214	219	2.04	9.5
	60	133	147	214	200	1.56	8.1
Mean		**136**	**141**	**214**	**209**	**1.80**	**8.8**
OSD	23	158	114	67	111	0.75	7.0
	60	166	148	67	85	0.54	6.8
Mean		**162**	**131**	**67**	**98**	**0.65**	**6.9**
	23 Mean	**148**	**124**	**140**	**165**	**1.40**	**8.3**
	60 Mean	**150**	**148**	**140**	**142**	**1.05**	**7.4**
Rainfall		n.s.	n.s.	n/a	**	***	*
Row Spacing		n.s.	***	n/a	***	***	n.s.
Rainfall*row spacing		n.s.	n.s.	n/a	n.s.	**	n.s.

n.s.	not significant
*	P < 0.1
**	P < 0.05
***	P < 0.01

Table 4.5:Effect of rainfall distribution and row spacing on final dry matter and estimated transpiration and evaporation

Rain treatment	Row Spacing	Evapotranspiration	DM Yield t/ha	Transpiration	Evaporation	% Trans.
		a	b	c=b*1000/50	a-c	c/a
GSD	23	219	4.29	86	133	39%
	60	200	3.19	64	136	32%
Mean		**209**	**3.74**	75	134	36%
OSD	23	111	1.79	36	75	32%
	60	85	1.25	25	60	29%
Mean		**98**	**1.52**	30	68	31%
	23 Mean	**165**	**3.04**	61	104	37%
	60 Mean	**142**	**2.22**	44	98	31%

4.3.3 Phenology

At the stem elongation sampling, the genotypes differed in development (P < 0.001). Wyalkatchem and Halberd were close to Zadoks growth stage 30 with the average number of nodes per plant being 0.7 and 0.6 respectively. Westonia and the Silverstar genotypes averaged 1.4 nodes per plant or Zadoks 31. At the anthesis sampling there was no distinguishable difference in phenology between Wyalkatchem, Westonia and the Silverstar genotypes, which all averaged close to Zadoks 70. Halberd, however, was behind in development (P < 0.001) at Zadoks 66. As anthesis cuts were taken to the laboratory before they were assessed for phenology there was some difficulty in determining the presence of anthers on samples as they were prone to falling off. Therefore the difference in phenology may have been slightly greater than that recorded. This is not thought to have affected the interpretation of yield results.

4.3.4 Plant density

Rainfall distribution had a significant effect on plant density at stem elongation (P < 0.01) and a marginally significant effect at anthesis (P < 0.1). At stem elongation the GSD treatment averaged 122 plants per m^2 compared to 94 in OSD (Table 4.6) and there was little change in the average densities in either rainfall treatment between stem elongation and anthesis (data not presented).

Table 4.6: Effect of rainfall distribution, genotype and row spacing on plant density, biomass and light interception at stem elongation, and biomass and light interception at anthesis. Merredin 2008.

Treatment	Label	Stem Elongation (z30)			Anthesis (z65)	
		Plant Count	Biomass (t/ha)	Intercepted light	Biomass (t/ha)	Intercepted light
Rainfall distribution	GSD	122	0.82	32%	2.52	52%
	OSD	94	0.55	26%	1.36	33%
		***	*n.s.*	*n.s.*	**	*n.s.*
Genotype	Halberd	104	0.70	35%	1.95	49%
	Silverstar	93	0.57	29%	1.91	41%
	Silverstar (tin)	112	0.52	20%	1.74	43%
	Westonia	110	0.80	33%	2.03	45%
	Wyalkatchem	121	0.83	27%	2.07	34%
	Indicative L.s.d.	23	0.16	5%	0.30	11%
		n.s.	***	***	n.s.	***
Row Spacing	23 cm	108	0.8	37%	2.2	49%
	60 cm	108	0.6	21%	1.7	36%
		n.s.	***	***	***	***

n.s.	not significant
*	P < 0.1
**	P < 0.05
***	P < 0.01

Table 4.7: Effect of rainfall treatment, genotype and row spacing on plant density, biomass and light intercept at stem elongation, and biomass and light interception at anthesis. Merredin 2008.

Rain Treatment	Genotype	Row Spacing (cm)	Stem Elongation (z30) Plant Density	Stem Elongation (z30) Biomass (t/ha)	Stem Elongation (z30) Intercepted light	Anthesis (z65) Biomass (t/ha)	Anthesis (z65) Intercepted light
GSD	Halberd	23	132	1.02	49%	2.80	65%
		60	102	0.49	28%	2.22	54%
	Silverstar	23	103	0.93	39%	2.88	64%
		60	110	0.51	26%	2.04	43%
	Silverstar (tin)	23	131	0.72	33%	2.94	53%
		60	113	0.56	13%	1.69	42%
	Westonia	23	122	1.15	44%	2.75	55%
		60	142	0.77	27%	2.32	52%
	Wyalkatchem	23	145	1.33	37%	3.36	60%
		60	118	0.74	21%	2.24	35%
Means		23	126	1.03	41%	2.94	59%
		60	117	0.61	23%	2.10	45%
OSD	Halberd	23	97	0.82	40%	1.54	44%
		60	85	0.49	25%	1.25	34%
	Silverstar	23	75	0.47	30%	1.60	37%
		60	86	0.38	22%	1.12	21%
	Silverstar (tin)	23	84	0.38	24%	1.17	41%
		60	119	0.43	9%	1.17	35%
	Westonia	23	88	0.71	36%	1.77	39%
		60	89	0.58	25%	1.29	33%
	Wyalkatchem	23	104	0.66	33%	1.32	27%
		60	116	0.60	19%	1.38	14%
Means		23	90	0.61	32%	1.48	38%
		60	99	0.50	20%	1.24	27%
Lsd within the same Rainfall Treatment			45	0.32	11%	0.60	21%
	Cultivar		46	0.40	12%	0.63	35%
	Row spacing		46	0.38	12%	0.62	33%

4.3.5 Canopy development and growth

In the early parts of the growing season rainfall distribution had no significant effect on dry matter accumulation (Table 4.7) though GSD tended to be greater. Row spacing had an impact on dry matter from early stages with RS_{23} (0.82 t/ha) producing greater amounts of biomass than RS_{60} (0.56 t/ha) at stem elongation ($P < 0.001$). There was an interaction between rainfall distribution and row spacing at stem elongation with RS_{23} producing comparatively greater biomass in the GSD treatment than in the OSD (Figure 4.8).

By anthesis GSD had led to greater production of biomass than OSD ($P < 0.05$), RS_{23} maintained greater biomass than RS_{60} ($P < 0.001$) and the interaction between rainfall treatment and row spacing was still present showing the same trend of comparatively greater biomass of the narrow row spacing in the better growing conditions of the GSD treatment (Figure 4.8).

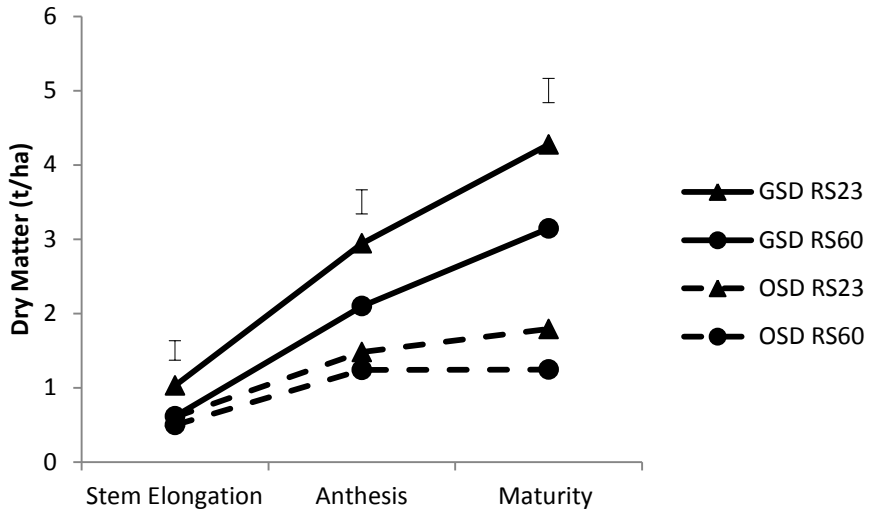


Figure 4.8: Effect of row spacing and rainfall distribution on dry matter accumulation at stem elongation, anthesis and maturity. Vertical bars indicate least significant difference (5%). Merredin 2008.

At maturity, rainfall distribution had a large impact on total biomass ($P < 0.01$) with GSD (3.7 t/ha) producing substantially greater dry matter than OSD (1.5 t/ha) when averaged across all other treatments. Crops grown at the narrow row spacing produced greater biomass (3.0 t/ha) than the wide (2.2 t/ha) on average although there was a significant interaction with genotype ($P < 0.1$) that suggested Westonia and Halberd produced comparatively more biomass under wide rows than Silverstar, Silverstar (*tin*) and Wyalkatchem (Figure 4.9). Genotype also interacted with rainfall distribution ($P < 0.05$). Under the OSD rainfall there was very little difference between genotypes, but under GSD where productivity was higher and rainfall less limiting in the latter parts of the growing season, differences in total biomass were evident between genotypes. Silverstar (*tin*) had significantly lower harvest biomass than Halberd, Westonia and Wyalkatchem, and Silverstar had significantly lower biomass than Halberd and Westonia (Figure 4.9). The interaction between rainfall distribution

and row spacing at harvest was large (P < 0.001) and showed the same patterns as at other sampling times; greater increase in biomass in RS_{23} compared to RS_{60} in the GSD rainfall distribution treatment (Figure 4.8).

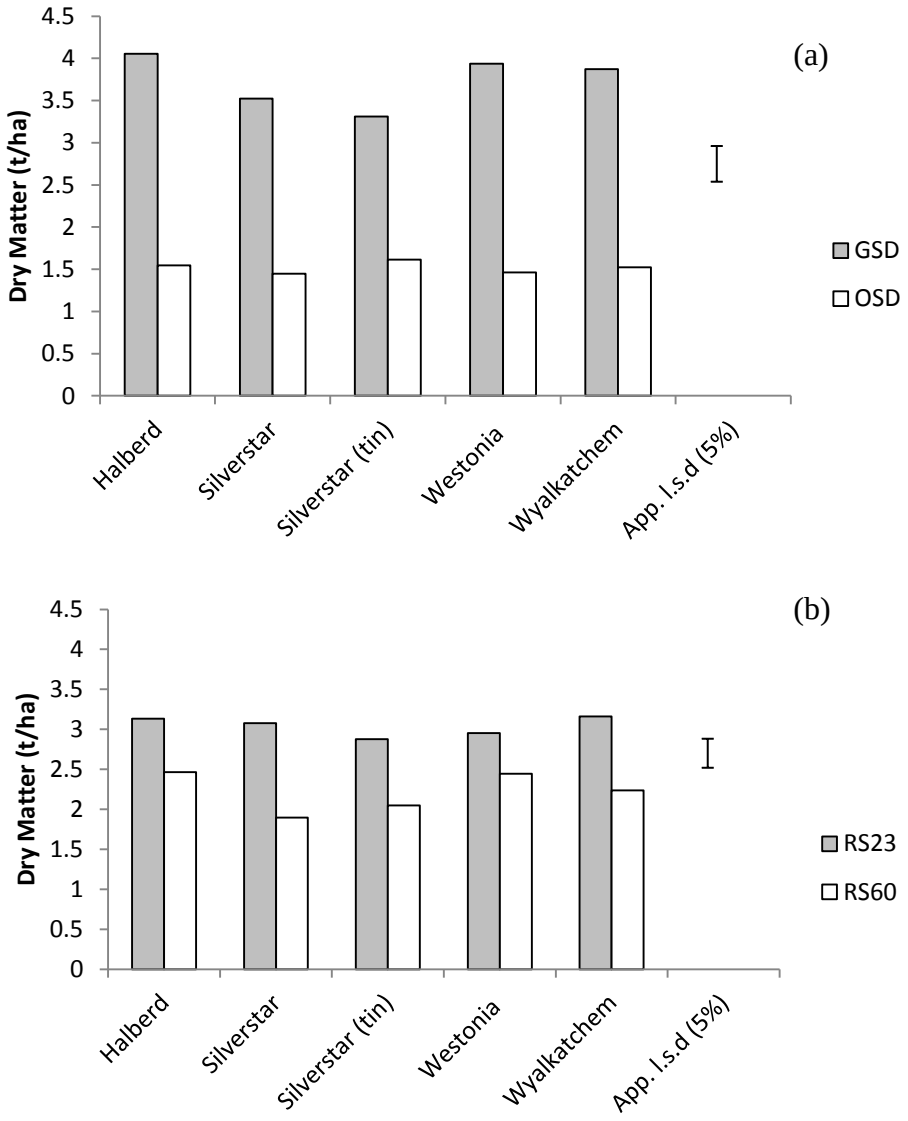


Figure 4.9: Interaction effects of genotype with row spacing (a) and genotype with rainfall distribution (b) on dry matter production at harvest. Merredin 2008.

Light interception by the canopy had similar patterns to dry matter accumulation. At stem elongation there was no difference between the rainfall treatments. Row spacing had a large effect when averaged across other treatments (P < 0.001) with RS_{23} intercepting 36 percent of photosynthetically active radiation (PAR) compared to only 21 percent by RS_{60}. There was a large genotype effect (P < 0.001) that did not show up in the dry matter measurements indicating that morphology was playing a

role in light interception (Table 4.8). At stem elongation the taller genotype Halberd had greater PAR interception than the shorter Silverstar genotypes and Wyalkatchem. Westonia, which was chosen for its reputed greater vigour than Wyalkatchem, had greater interception than Wyalkatchem. Silverstar (*tin*) had significantly lower light interception than all other genotypes.

By anthesis the varietal effect was still significant ($P < 0.001$) but light interception appeared to be more uniform across genotypes, with the exception of Wyalkatchem which was intercepting less PAR than Halberd but statistically similar amounts to all other genotypes (Table 4.8). By anthesis some tillers and leaves had senesced. Dry weights were taken of infertile tillers (those without heads), many of which had senesced. Silverstar (*tin*) had put about a third less of it's assimilates into infertile tillers than the other genotypes.

Table 4.8: Genotype effect on light interception at stem elongation and anthesis. Merredin 2008

Genotype	Stem Elongation		Anthesis	
Halberd	36%	a	49%	a
Westonia	33%	ab	45%	ab
Silverstar	29%	bc	41%	ab
Wyalkatchem	27%	c	34%	b
Silverstar (*tin*)	20%	d	43%	ab

* Genotypes with the same letter are not significantly different

The crops grown on the narrower row spacing were still intercepting more light than at the wide spacing at anthesis ($P < 0.001$), even though RS_{23} had allocated more assimilate into infertile tillers ($P < 0.01$).

The interaction that existed between rainfall treatment and row spacing for dry matter accumulation was also reflected in light interception data at stem elongation ($P < 0.1$). The same trend existed in the higher producing GSD treatment, where the differential between RS_{23} (41 percent) and RS_{60} (23 percent) was larger than in OSD (32 percent for RS_{23} and 20 percent for RS_{60}). The interaction ceased to exist at anthesis. By anthesis a rainfall distribution by genotype interaction had developed. While all genotypes showed reduced light interception in the OSD treatment, some did so more than others, particularly Wyalkatchem and Silverstar. Interestingly, Silverstar (*tin*) performed similarly in the two rainfall treatments when compared to its near-isogenic counterpart without tiller inhibition (Figure 4.10). It is important to note that error terms in the readings taken at anthesis were high due to cloudy conditions resulting in only half of each rainfall distribution treatment being recorded.

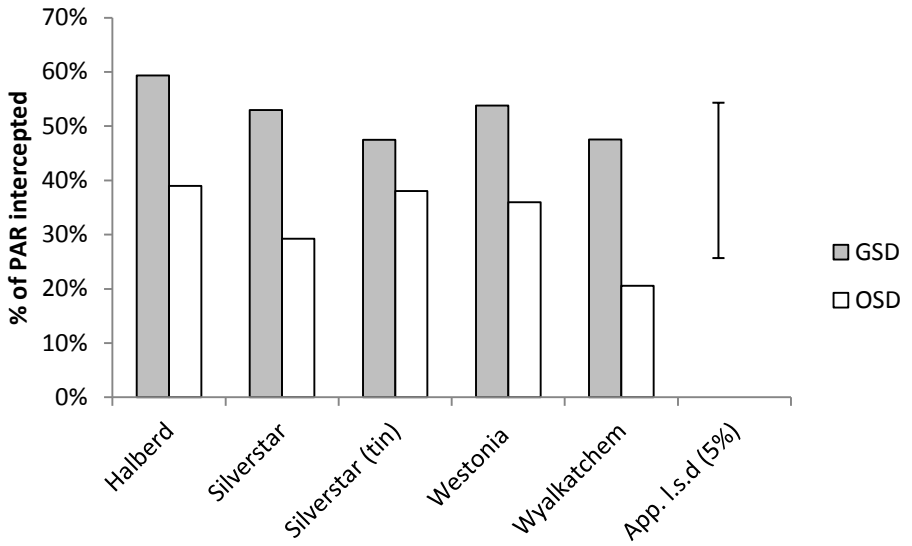


Figure 4.10: Light interception of two rainfall distribution treatments and five genotypes at anthesis. Merredin 2008.

4.3.6 Grain yield, harvest index and yield components

When averaged across all genotypes and row spacings, rainfall distribution had a significant effect on grain yield (1.80 t/ha for GSD, to 0.64 t/ha for OSD) (Table 4.9). All yield components as well as harvest index were significantly affected by rainfall distribution. Across both row spacings and all genotypes, head density was the most important component in constructing yield, particularly in the GSD treatment. This is demonstrated by the correlation between grain yield and head density (Figure 4.11).

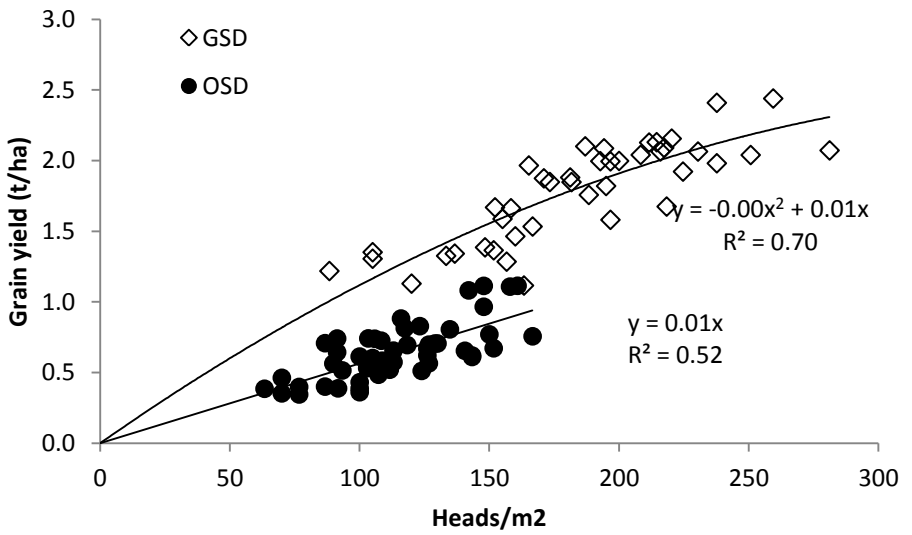


Figure 4.11: Effect of head density on grain yield in GSD and OSD treatments. Merredin 2008.

Overall there were no grain yield differences between the genotypes (Table 4.9). However, there was considerable variation between genotypes in the way that grain yield was constructed, and in harvest index. Silverstar and Silverstar (*tin*) tended to have fewer heads but more grains in each head, to the point they had more grains m^{-2} than Wyalkatchem and Westonia. Wyalkatchem compensated by having a higher individual grain weight than all other genotypes. Westonia had a greater individual grain weight than all other genotypes except Wyalkatchem, and Halberd had greater grain weight than the two Silverstar entries.

Grain yield was lower in the wide row spacing treatment when averaged across all other treatments (Table 4.9). A lower head density (131 versus 168 heads/m^2) was the primary reason for RS_{60} having fewer grains per square metre (3829 versus 5226).

There was a genotype by row spacing interaction ($P<0.05$) in respect to grain yield (Figure 4.12). Halberd and Westonia showed least difference in grain yield between the two row spacing treatments while Silverstar and Silverstar (*tin*) had the greatest reduction yield (41 and 30 percent respectively) (Figure 4.12). Silverstar had the highest grain yield (numerically) under the RS_{23} treatment and was statistically higher than Westonia. Under RS_{60} Silverstar yielded the lowest and was significantly lower than Westonia.

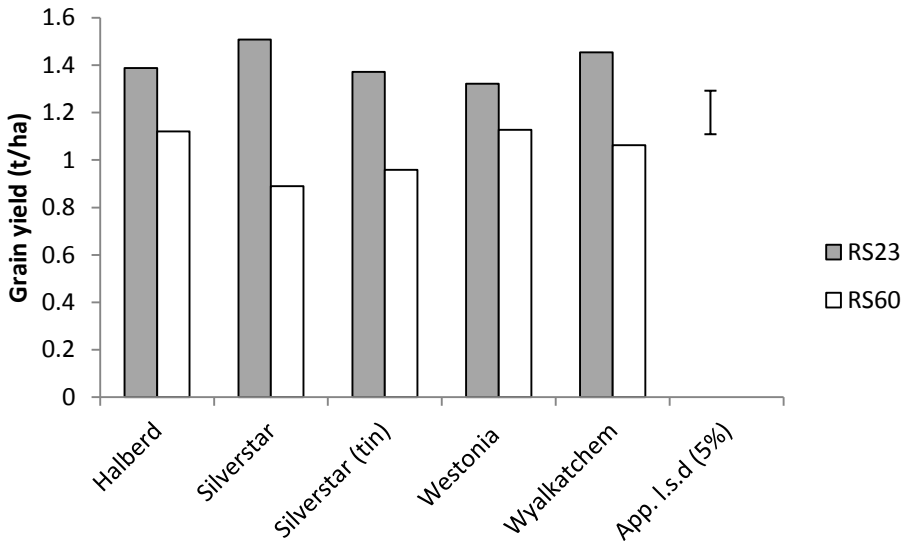


Figure 4.12: Grain yield as affected by genotype and row spacing averaged across both rainfall treatments. Merredin 2008.

The large yield reduction in Silverstar in response to increased row spacing was due to a reduction in head density, grains per head and subsequently grains per metre square. Silverstar had the largest decline in each of these components with 30, 15 and 41 percent declines respectively (Figure 4.13). Westonia exhibited no significant differences in these components between the two row spacings. Further, Silverstar was the only cultivar that suffered a significant decline in grains per head.

Table 4.9: Effect of rainfall distribution, genotype and row spacing on grain yield and yield components. Merredin 2008.

Treatment		Grain yield t/ha	Heads /m2	Grains /head	Spikelets /head	Grains /Spikelet	Grains /m2	Grain Wgt (mg)	Harvest Index
Rainfall distribution	Growing season dominant	1.80	186	34.34	16.78	2.06	6251	34.90	0.48
	Out of season dominant	0.64	113	24.66	15.87	1.55	2804	28.89	0.37
		***	**	***	*	**	**	*	***
Cultivar	Halberd	1.25	166	25.87	16.17	1.60	4503	31.72	0.41
	Silverstar	1.20	141	33.42	15.73	2.10	4894	29.12	0.44
	Silverstar (tin)	1.16	136	36.12	16.75	2.16	4981	28.03	0.43
	Westonia	1.23	151	25.85	16.63	1.55	4065	33.67	0.41
	Wyalkatchem	1.26	155	26.22	16.36	1.60	4195	36.95	0.43
	Lsd	*0.12*	*16*	*2.01*	*0.42*	*0.11*	*590*	*1.15*	*0.02*
		n.s.	***	***	***	***	**	***	***
Row Spacing	23 cm	1.41	168	30.43	16.97	1.80	5226	31.75	0.43
	60 cm	1.03	131	28.56	15.68	1.81	3829	32.05	0.42
		***	***	n.s.	***	n.s.	***	n.s.	n.s.

n.s. not significant
* P < 0.1
** P < 0.05
*** P < 0.01

There was a rainfall distribution by row spacing interaction ($P < 0.001$) that reflected the same interaction in harvest biomass. In the more productive GSD treatment the narrower row spacing treatment RS_{23} had a larger yield advantage over RS_{60} (0.5 t/ha in GSD compared to 0.25 t/ha in OSD) (Table 4.10). However, the percentage decrease in yield between row spacing treatments was quite similar between rainfall distribution treatments (25 percent in GSD and 32 percent in OSD).

The interaction between rainfall distribution and genotype with respect to yield was not statistically significant ($P = 0.104$) but did reflect total biomass at harvest. Grain yields in the OSD treatment were very similar between genotypes but there were significances in the higher yielding GSD treatment. Halberd (1.90 t/ha) had a greater grain yield in GSD than Silverstar (*tin*) (1.62 t/ha)

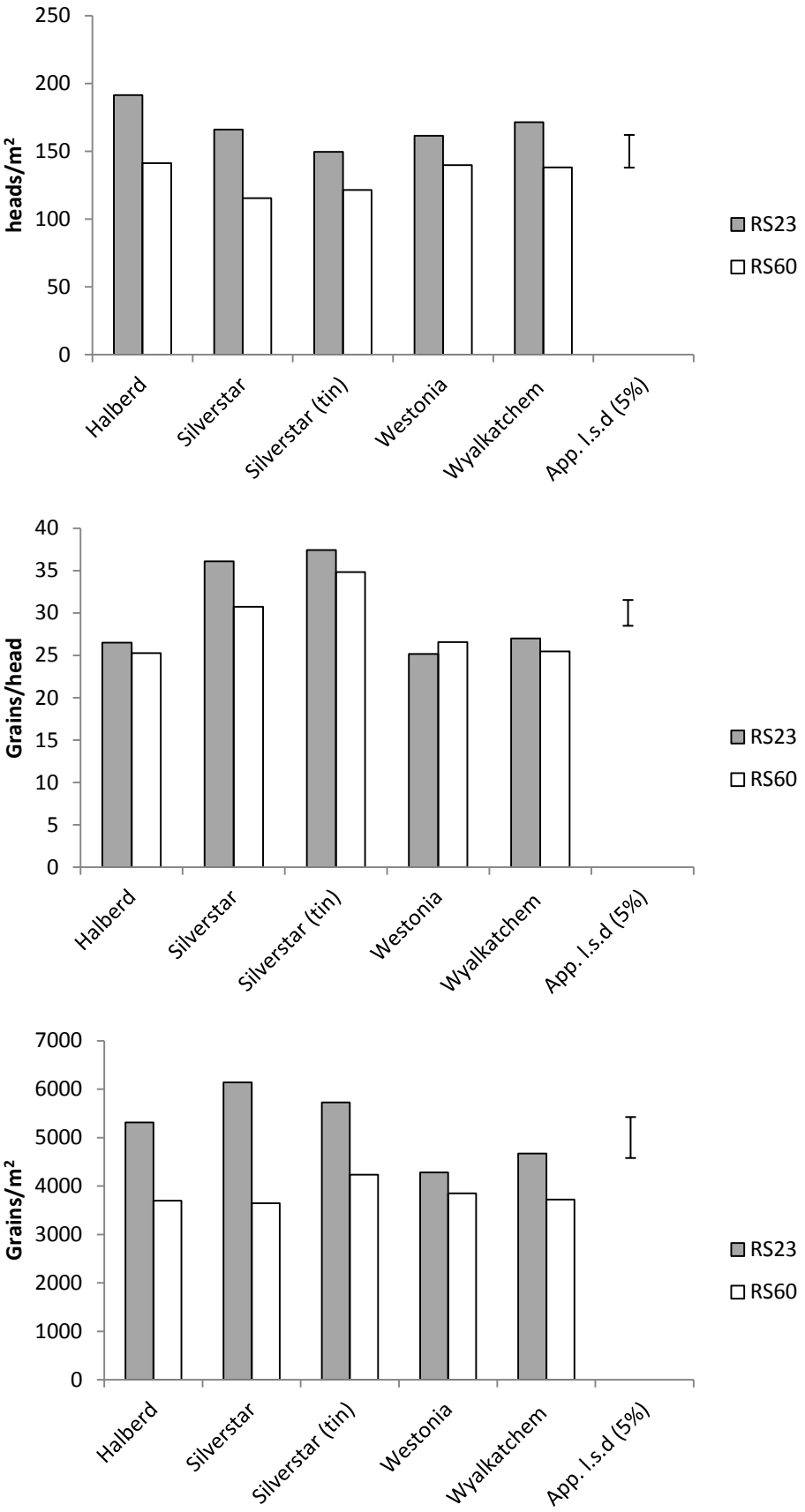


Figure 4.13: Effect of genotype and row spacing on heads per metre square, grains per head, and grains per metre square. Error bars indicate least significant difference . Merredin 2008.

Table 4.10: Effect of rainfall treatment, genotype and row spacing interactions on grain yield, yield components and harvest index. Merredin 2008.

Rain Treatment	Genotype	Row spacing (cm)	Grain yield t/ha	Heads /m2	Grains /head	Spikelets /head	Grains /Spikelet	Grains /m2	Grain Wgt (mg)	Harvest Index
GSD	Halberd	23	2.09	248	32.63	17.77	1.87	7858	33.57	0.46
		60	1.71	174	30.52	16.18	1.87	5264	34.92	0.48
			1.90	**211**	**31.58**	**16.98**	**1.87**	**6561**	**34.25**	**0.47**
	Silverstar	23	2.12	201	43.14	17.05	2.55	8439	32.33	0.51
		60	1.41	150	34.89	14.93	2.29	5188	32.36	0.51
			1.77	**176**	**39.02**	**15.99**	**2.42**	**6814**	**32.35**	**0.51**
	Silverstar (tin)	23	1.91	181	40.01	17.47	2.31	7319	31.36	0.49
		60	1.33	134	42.69	16.16	2.63	5576	29.90	0.49
			1.62	**157**	**41.35**	**16.82**	**2.47**	**6448**	**30.63**	**0.49**
	Westonia	23	2.03	210	28.59	17.50	1.62	6044	37.05	0.46
		60	1.66	163	33.11	17.64	1.89	5286	36.16	0.49
			1.84	**186**	**30.85**	**17.57**	**1.76**	**5665**	**36.61**	**0.48**
	Wyalkatchem	23	2.09	214	28.40	17.27	1.65	6067	40.62	0.46
		60	1.61	187	29.41	15.88	1.86	5465	40.77	0.48
			1.85	**200**	**28.91**	**16.58**	**1.76**	**5766**	**40.70**	**0.47**
Means		**23**	**2.05**	**211**	**34.55**	**17.41**	**2.00**	**7145**	**34.99**	**0.48**
		60	**1.55**	**161**	**34.12**	**16.16**	**2.11**	**5356**	**34.82**	**0.49**

Continued...

Rain Treatment	Genotype	Row spacing	Grain yield t/ha	Heads /m2	Grains /head	Spikelets /head	Grains /Spikelet	Grains /m2	Grain Wgt (mg)	Harvest Index
OSD	Halberd	23	0.68	135	20.35	16.50	1.26	2764	29.30	0.35
		60	0.53	109	20.00	14.24	1.38	2127	29.09	0.35
			0.61	**122**	**20.18**	**15.37**	**1.32**	**2446**	**29.20**	**0.35**
	Silverstar	23	0.90	131	29.06	15.94	1.82	3841	26.08	0.40
		60	0.37	81	26.58	15.01	1.76	2107	25.70	0.36
			0.63	**106**	**27.82**	**15.48**	**1.79**	**2974**	**25.89**	**0.38**
	Silverstar (tin)	23	0.84	118	34.85	16.97	2.05	4136	25.06	0.39
		60	0.58	109	26.92	16.38	1.63	2893	25.81	0.37
			0.71	**114**	**30.89**	**16.68**	**1.84**	**3515**	**25.44**	**0.38**
	Westonia	23	0.62	113	21.70	16.55	1.33	2517	30.39	0.34
		60	0.60	116	20.00	14.83	1.36	2413	31.09	0.34
			0.61	**115**	**20.85**	**15.69**	**1.34**	**2465**	**30.74**	**0.34**
	Wyalkatchem	23	0.81	129	25.59	16.71	1.52	3275	31.74	0.39
		60	0.51	90	21.49	15.59	1.39	1972	34.66	0.38
			0.66	**110**	**23.54**	**16.15**	**1.45**	**2624**	**33.20**	**0.38**
Means		**23**	**0.77**	**125**	**26.31**	**16.53**	**1.59**	**3307**	**28.51**	**0.37**
		60	**0.52**	**101**	**23.00**	**15.21**	**1.50**	**2302**	**29.27**	**0.36**
Indicative Lsd (5%)within the same Rainfall Treatment										
	Genotype		0.18	15	1.99	0.63	0.11	546	1.75	0.02
	Row spacing		0.12	24	3.04	0.43	0.16	855	1.19	0.02
	Genotype*Row spacing		0.26	34	4.26	0.89	0.23	1204	2.46	0.03

4.3.7 Water use efficiency

Rainfall distribution had a significant effect on WUE ($P < 0.1$) with the GSD treatment (8.8 kg/ha.mm) recording a higher WUE than the OSD treatment (6.9 kg/ha.mm) across all other treatments. Table 4.4 shows the means of these treatments as well as the factorial with row spacing. There were no other significant effects on WUE.

4.4 Discussion

This discussion will consider the main effects and interaction of rainfall distribution, row spacing and genotype on wheat water use, grain yield and the relationship between the two (water-use-efficiency). Also discussed are issues with the experiment that may have affected the results.

4.4.1 Effect of rainfall distribution and total

The results from the 2008 experiment showed a large yield advantage when rainfall was distributed predominantly in the growing season (1.8 to 0.65 t/ha). The reason for this was in part due to the extra and late rainfall in the GSD treatment that resulted in large grain sizes (34.9 to 28.9 mg/grain) and high harvest index (0.48 to 0.37). The other reason was the lack of soil water storage from pre-sowing irrigation in the OSD treatment. Despite 112mm of irrigation applied in March, little of that water found its way into the soil profile and about a week after sowing soil water measurement showed that OSD had only 26 mm more than GSD. This result highlights the importance of effectively capturing and storing rain that occurs out of season. Conservation tillage and stubble retention have been proven to aid in water infiltration and reducing runoff (Zhang et al. 2007).

The crop on GSD rainfall used water more efficiently than that on OSD rainfall (8.8 to 6.9 kg/ha.mm). A part of this was greater access to solar radiation (no rainout shelter) and high harvest index due to good rainfall after anthesis. Water used by the crop after anthesis has been found to be very efficient in being converted into grain (up to 59 kg/ha per millimetre of water used) (Kirkegaard et al. 2007). For more information on the effect of the rainout shelter on light interception see section 4.4.6.

4.4.2 Effect of row spacing

The wider row spacing had a negative effect on grain yield (1.4 to 1.05 t/ha), consistent with other studies (Amjad and Anderson 2006; Shackley 2000; Tompkins, Fowler, and Wright 1991; Winter and Welch 1987). Some of the difference in grain yield between the row spacing treatments can be explained by the reduction in water-use at the wider spacing. Plants grown at the wider spacing (RS_{60}) used 19 mm less in the GSD treatment and 26 mm less in OSD than in the narrower spacing (Table 4.4) (water measurements taken in the inter-row). The WUE of wheat growing in RS_{60} tended to be lower than RS_{23} but the difference was not significant. Given the lower light interception of the wide rows throughout the season it is reasonable to suggest that soil evaporation could have been higher in

the treatment due to more radiation reaching the soil surface (Passioura 2002). Estimates of transpiration and evaporation suggested that the narrow row spacing used 37% of water for transpiration while the wide row spacing only used 31%. In a study by Eberbach and Pala (2005) using microlysimetry, evaporation from soil was found to be greater in 30 cm rows when compared to 17 cm row spacing. By contrast, the results of Yunusa et al. (1993), at the same location as this study and on a similar soil type, found no difference in evaporation (measured with microlysimetry) in row spacings ranging from 9 cm to 36 cm in sparse canopies. However, the year of Yunusa's experiment was dry and 41 percent of a total of 127 mm between seeding and harvest fell the week after sowing, when the canopy would not have affected evaporation. At this stage the canopies were very small and would not have influenced evaporation (Ritchie 1983). Studies that measured the difference in biomass accumulation between varying row spacings often find that the narrower row spacing produce greater biomass due to increased light interception (Eberbach and Pala 2005; Johnson, Witters, and Ciha 1981; Tompkins, Fowler, and Wright 1991). Consistent with this, the current experiment showed large differences in biomass and light interception. The larger canopies produced a greater number of heads (168 versus 131), which has been a common finding among row spacing studies (Chen et al. 2008; Doyle 1980; Johnson, Witters, and Ciha 1981; Tompkins, Fowler, and Wright 1991). Narrow rows also had more spikelets per head (16.8 to 15.7), likely due to less access to water and N in wide rows at the time of spikelet development. The number of grains per spikelet was equal between row spacing treatments, which resulted in the narrow row spacing treatment having more grains per m^2 (5226 versus 3829), consistent with other studies (Chen et al. 2008; Johnson, Witters, and Ciha 1981; Kleemann and Gill 2010; Tompkins, Fowler, and Wright 1991). This large increase in sink size resulted in the greater grain yields (1.41 versus 1.03 t/ha when averaged across all genotypes and rainfall distribution treatments) as individual grain weight was not statistically different between row spacing treatments.

4.4.3 Effect of rainfall distribution and the interaction with row spacing

It was hypothesised at the start of this thesis that wider rows would perform comparatively better when rainfall was out of season dominant. Statistically, there was an interaction between rainfall distribution and row spacing because the yield decline in the wider rows in the GSD treatment was numerically greater than in OSD, however, the percentage yield decline was similar. Widening row spacing had the desired effect of slower water use by the crop and conserved more soil water for after anthesis use. However, the crop failed to make use of this water even though the small grain sizes and the visual appearance of the plants suggested that the crop experienced water deficit stress after anthesis. At maturity, the RS_{60} treatment had 34 mm more residual water than RS_{23} and used 26 mm less water in the growing season. This may have been due to the root system not being able to access inter-row soil water due to late sowing and exacerbated by external factors as mentioned in section 4.4.6.

4.4.4 Effect of genotype interaction with rainfall distribution

There was no decisive evidence to suggest that any of the genotypes used in this study were better than others in the heavily water stressed OSD treatment. When the grain yield of genotypes was averaged across both row spacings, the range was 100 kg/ha between the highest and lowest yielding genotypes. There was greater variation between genotypes in the higher yielding GSD rainfall treatment. This is to be expected as interactions with genotype (both management and environmental) tend to occur more as yield increases (Anderson et al. 2004; Fischer 2009).

Wheat traits that are put forward as providing drought tolerance are likely to be more useful if they aid, or at least don't hinder, grain yield in average and good years as well as providing a benefit in poor ones. Osmotic adjustment, for example, allows a plant to continue functioning through sustained cell and tissue activity in extreme drought conditions, but is unlikely to make much difference in average and good seasons (Munns 1988; Serraj and Sinclair 2002). The relocation of water soluble carbohydrates (Blum 1998), on the other hand, may contribute to yield in the event of a dry finish to the growing season, which is a common occurrence in mediterranean-type climates (Nix 1975), and therefore maybe of value even in reasonable seasons with good early growth and post anthesis drought. Early vigour is likely to work well with wide row spacing as it should both provide greater competition with weeds and reduce soil evaporation. However, in crops on narrow rows, that have a greater risk of drought stress after anthesis, the added leaf area of a genotype exhibiting early vigour will result in greater transpiration by the crop (Ritchie 1974) and may amplify the risk of lower individual grain weights and even grain yield if water after anthesis is limiting (Richards 1983).

4.4.5 Effect of row spacing interaction with genotype

There was a row spacing by genotype interaction in this experiment that has not often been recorded in the literature. The two genotypes that had a smaller yield decline in the wider row spacing were those that also showed greater vigour through increased light interception at stem elongation: Halberd and Westonia. Halberd (released in 1969) was intercepting 35 percent of incoming solar radiation at stem elongation, which was more than all other genotypes except Westonia. Other than increased radiation interception for photosynthesis, there are two reasons why a more vigorous canopy might perform better in wide rows. The first is that a larger canopy will shade more of the inter-row between wide rows which reduces water loss through evaporation, leaving more for plant transpiration (Passioura 2002). The second is that the more competitive canopy results in less competition for resources from weeds, which otherwise exploit the bare inter-row space of wide rows (Borger, Hashem, and Pathan 2010).

While the experiment was treated a number of times to control weeds, both chemically and by hand, they were hard to control during the latter part of the season when rainfall kept the soil moist. The inter-row space inherent in wide row spacings can provide ideal resources for weed production and

the management of those weeds is a paramount consideration in any wide row cropping system (Peltzer et al. 2009).

4.4.6 Issues with experiment

One of the factors contributing to low WUE for the crop in the OSD rainfall treatment was the reduced radiation available to the OSD on rainy days after July due to the covering of the rainout shelter. This will be discussed in detail in Chapter 5.

Another factor might have been 'spray drift' damage observed early in the season. The extra soil water available to plants in the wider row spacing treatment late in the season should have resulted in increased grain weight in the OSD treatment, where soil water was very limited and grain weights were severely reduced. The light dose of Glyphosate early in the life of the crop may have reduced root growth, which meant plants grown on wide row spacing could not access excess water at the end of the season. The effect was more noticeable in the OSD plots as establishment numbers were lower in this treatment and the extra rainfall and radiation in the GSD plots seemingly allowed the crop to recover better.

4.5 Conclusions

This experiment investigated rainfall distribution by row spacing by genotype interactions on a shallow Sodic Hypocalcic Yellow Chromosol soil with the use of rainout shelters and irrigation. Poor soil water storage in the out of season dominant rainfall distribution meant grain yields were very low compared to when rainfall was growing season dominant.

This study revealed crop responses not previously described in the literature. A row spacing by genotype interaction was seen throughout the growing season and resulted in some genotypes showing relatively less reduction in grain yields under wide row production than others. It appears that phenology and a competitive canopy are beneficial to yield at wide row spacings. Widening row spacing from 23 cm to 60 cm slowed down water use by the crop, but did not benefit yield as increased individual grain weights (as might have been expected from more water remaining during grain filling) did not compensate for the lower number of grains per m^2. Future experiments should aim to investigate the effect of row spacing on grain yield when sink size is less limiting. To increase biomass production and sink size, nitrogen fertiliser could be used in combination with greater early water availability especially in a treatment simulating greater out of season rainfall.

There were shortcomings of this experiment that result in the need for further investigation. The effect of chemical drift onto the trial site could not be quantified in terms of crop growth and yield, but is thought to be significant; a similar experiment is needed to see if results found in this experiment are repeatable. More care is needed in future experiments to ensure the rainfall distribution treatment that is based on out of season rainfall stores more soil water before the crop is planted to determine the

true effect of a change in distribution in rainfall. Also greater consideration needs to be given to weed control, especially in wide rows, to ensure soil water and nutrient resources are used by non-crop plants. Earlier sowing would better match industry practice and allow more growth for treatment differences.

Chapter five

Response of two genotypes to rainfall distribution, row spacing and timing of nitrogen fertilisation

"The significant problems of our time cannot be solved by the same level of thinking that created them"

- Albert Einstein

5. Response of two genotypes to rainfall distribution, row spacing and timing of nitrogen fertilisation

5.1 Introduction

Managing soil water is an important part of wheat production in low-rainfall growing regions of Australia, and particularly in mediterranean-type climates, where hot and dry spring conditions negatively affect grain filling (Nix 1975). With further drying to southwest Australia predicted (section 2.4.1), management of rainfall so that ample water is available during grain filling will become even more important. Trends in parts of the low rainfall region in southwest Australia suggest that out of season rainfall has increased while growing season rainfall has generally declined. If this trend continues, growers will be more reliant on soil water stored before seeding to grow their crop and will run the risk of increased terminal drought after anthesis. Passioura (1977) outlined the importance of having sufficient soil water available for grain filling and these projected changes in climate make that finding even more important. The literature suggests there are a number of factors that wheat producers can employ to reduce water use by the crop; for example, wheat producers in marginal (≤ 325mm annual rainfall) growing regions may wish to extend fallow periods in order to lower production risk by increasing the amount of stored water at seeding (Oliver, Robertson, and Weeks 2010).

Nitrogen fertiliser application has been shown to increase leaf area and biomass which in turn increases crop water demand (Norton and Wachsmann 2006). Van Herwaarden et al. (1998) found that excess nitrogen can be detrimental to wheat yield when severe terminal drought occurs, as might be expected in an out of season dominant rainfall distribution and in hot dry springs of a mediterranean-type climate. It is hypothesised in this chapter that delaying the second N application (the first being at seeding) until stem elongation (rather than at tillering) will reduce tillering and early season crop growth and will be beneficial to wheat grain yield when the crop is grown mainly from stored soil water and on narrow row spacings as the reduced canopy size will reduce water use and leave more water available for grain filling.

Widening row spacing has also been proven to slow water use in a crop (Eberbach and Pala 2005; Kleemann and Gill 2010) and when growth is vigorous and water demand high and soil water after anthesis is limited, wider rows can result in increased grain yield (Blackwell, Pottier, and Bowden 2006). A key finding from the previous experiment (Chapter 4) was that low head density in the wider rows was an important reason why yield declined in that treatment. Other research into head density in southwest Australia by Zhang et al. (2010)

suggests that head density is important to grain yield (R^2 = 0.75) in this growing region. It is hypothesised that N applied at tillering (rather than at stem elongation) will be more beneficial to crops grown in wider rows due to increased head density.

The aims of this experiment were; a) to confirm results from 2008 experiment (Chapter 4), and b) to explore nitrogen application timing interactions with row spacing and rainfall distribution. The same rainfall distribution treatments were used but with greater care to store more soil water in the out of season dominant rainfall treatment. The 2008 experiment showed more residual soil water in the wide rows than in the narrow, which was one of the main reasons for a yield penalty in the wide rows. This experiment includes the same two row spacing treatments to see if this result is repeated. Two genotypes from the 2008 experiment were used (Silverstar and Wyalkatchem) as they have similar phenology but showed different morphology and tillering habits, particular in wide rows. A nitrogen timing treatment was introduced to test for an interaction with row spacing and rainfall distribution (for the reasons discussed above). The same row spacing treatments as in the 2008 experiment were used.

5.2 Materials and methods

5.2.1 Experimental design and trial management

The experiment was conducted on the Department of Agriculture and Food, Western Australia (DAFWA) Merredin Research Station during the 2009 growing season (May to October). The site was the same as that used in the 2008 growing season and the details regarding the sheltering and irrigation of the trial can be found in the Materials and Methods Chapter (Chapter 3). Different 'seeding boots' were used on the cone seeder in 2009 than in 2008 in order to create a wider seeding furrow and reduce intra-row competition as this has been found to be beneficial to grain yield in wider rows (Amjad and Anderson 2006).

The experiment tests the sequential nature of two cropping systems; narrow row and wide row spacings. Row spacing treatments were placed on plots that were that same treatment in the 2008 season.

The experimental treatments were also similar to those in the previous year with factorialised treatments consisting of two rainfall distributions, two genotypes, two crop row spacings, and two timings of nitrogen fertiliser. Details of the treatments can be viewed in Table 5.1.

Table 5.1: Treatment type, labels and description of Merredin 2009 experiment

Treatment	Labels	Description
Rainfall Distribution	Out of Season dominant (OSD)	Decile 9 out of season rainfall with reduced growing season rainfall to finish the growing season at Decile 5 total rainfall (Figure 5.3)
	Growing Season dominant (GSD)	Decile 1 out of season rainfall with increased growing season rainfall to finish the growing season at Decile 5 total rainfall (Figure 5.3)
Genotype	Wyalkatchem	Maturity: early
	Silverstar	Maturity: very early
Crop row Spacing	60 cm (RS_{60})	60 cm from middle of crop row to the middle of neighbouring row
	23 cm (RS_{23})	23 cm from middle of crop row to the middle of neighbouring row
Nitrogen Timing	N @ Zadoks stage 15	16 kg/ha of N applied at growth stage Z15
	N @ Zadoks stage 31	16 kg/ha of N applied at growth stage Z31

Table 5.2: Management inputs to 2009 experiment at Merredin

Activity	Rate	Product	Date	Treatments
Irrigation	108 mm	Water	Late March	Out of season dominant
	40 mm	Water	Week before seeding	Out of season dominant
	20 mm	Water	Week before seeding	Growing season dominant
Summer weed control	2 L/ha	Roundup	May 11	Out of season dominant
Pre-sowing Herbicides	2 L/ha 1 L/ha	Sprayseed Treflan	May 19	All
Sowing	130 seeds/m^2	Silverstar, Wyalkatchem	May 19	All
Fertiliser	80 kg/ha 50 L/ha 50 L/ha	Agras Flexi-N Flexi-N	May 19 July 1 July 31	All N @ Tillering N @ Stem Elongation
Post-sowing Herbicides	100 g/ha 85 ml/ha 50 ml/ha 1 L/ha 1%	Lontrel Topic Uptake Decision DC-Trate	July 27 July 27 July 27 Aug 28 Aug 28	All
Post-sowing Fungicides	500 ml/ha	Tilt	Sep 15	All

Table 5.3: Sampling date according to growth stage and measurements for Merredin 2009 experiment

Activity	Date/s	Measured
Plant counts	15 Jul	Plant density
Stem elongation sampling	29 Jul	Leaf Area Index (LAI), total dry matter, dry matter partitioning
Anthesis sampling	19 Sep	LAI, flag leaf disease rating, total dry matter, dry matter partitioning
Soil water sampling	28 May 2 Jul 24 Jul 24 Aug 14 Sep 11 Nov	Soil water content at 20cm intervals from 10-110cm depth
Harvest sampling	10 Nov	Grain yield, total dry matter, yield components, grain protein

5.2.2 Measurements

Starting soil nitrogen

Soil cores were taken across the trial site (eight from each rainfall distribution treatment) to a depth of 60 cm. Soil was collected into plastic tubes and taken to a laboratory and divided into depths 0-10 cm, 10-20 cm, 20-30 cm and 30-60 cm before being packaged and taken to CSBP for soil analysis. A summary of results is provided in Table 5.4.

Table 5.4: CSBP Soil N results taken from experimental site before 2009 experiment at Merredin (mg/kg)

Depth	GSD Rainfall Treatment			OSD Rainfall Treatment		
	Total N	Nitrate	Ammonium	**Total N**	Nitrate	Ammonium
0-10 cm	**12.8**	9.8	3.0	**10.0**	7.0	3.0
10-20 cm	**7.3**	4.5	2.8	**3.8**	1.8	2.0
20 -30 cm	**4.0**	1.5	2.5	**3.8**	2.0	1.8
30-60 cm	**3.0**	1.8	1.3	**6.0**	4.5	1.5
Total	**27**	**17.5**	**9.5**	**23.5**	**15.2**	**8.2**

It's important to note that the soil cores were taken on April 1, about a month and a half before the crop was sown and irrigation was applied to the OSD treatment. Using the crop modelling software APSIM, an estimate of soil N at sowing in the OSD treatment was calculated and can be viewed in (Table 5.5). For more information on the APSIM model and the calibration of the model against experimental data see Chapter 6. The simulations suggested that nitrogen was not limiting to crop growth (data not presented).

Table 5.5: Estimate of soil N in OSD treatment at time of sowing (May 19) as provided by APSIM (mg/ka); Merredin 2009

Depth	OSD Rainfall Treatment		
	Total N	Nitrate	Ammonium
0-10 cm	**8.0**	7.0	0.9
10-20 cm	**10.7**	10.1	0.6
20 -60 cm	**6.9**	6.8	0.1
Total	**25.6**	**24.0**	**1.6**

Crop establishment

Plant counts were taken eight weeks after the crop was sown. In the RS_{23} row spacing treatment plants were counted both side of a metre rule at four locations in each plot. In the RS_{60} treatment plants were counted on one side of a metre rule at four locations in each plot.

Light interception

Delta-T solarimeter tubes were installed on August 19 and hourly readings logged on a Datataker DT500 for the remaining part of the growing season. Two tubes were placed in one plot for each of the treatments involving Wyalkatchem. Two tubes were placed above the canopy outside the rainout shelter and one was placed above the canopy inside the shelter. Percentage of intercepted radiation was calculated from readings taken daily between 0900 and 1700 hrs from the start of August to the end of October.

Water use

Soil water data was measured as described in the Materials and Methods chapter (Chapter 3). In early 2009 extra access tubes were installed in the plots designated for the 60 cm row spacing treatment, 30 cm from the existing tubes to provide one tube in the inter-row and one in the row.

Dry matter accumulation and partitioning

Samples were taken three times in the growing season (Table 5.3) when the crop was at Zadoks growth stage 30 (stem elongation), 65 (anthesis) and 100 (maturity). For the first two sampling dates four 0.5 m sections of the central rows were taken from the RS_{23} plots and two rows from the RS_{60} plots. Plants and near surface roots were removed and taken to the Muresk laboratories for processing. Two samples were taken from each plot at harvest. One sample was the same size as those taken at the other sampling dates and the other was larger with 1 m of row taken of the same number of rows.

Sampled plants were counted and 10 median plants were removed for sub-sampling. The subsample was partitioned into stems and leaves at stem elongation sampling; infertile stems, stems, leaves and heads at anthesis sampling; and grain, husks and chaff at maturity.

The remaining plants that weren't sub-sampled were dried for 70 hours at 70°C and were used in calculating total dry matter. Partitioned subsamples were dried for the same time and temperature.

Grain yield, yield components and harvest index

Grain yield and harvest index were calculated from the harvest samples. All heads within the samples were removed and counted. Twenty median heads were removed from the larger harvest samples and ten from the smaller samples for further yield component measurements.

The bulk of the heads were threshed using a VRS-1 Venables Small Seed Thresher (L.T. Venables Pty. Ltd., Wembley, Western Australia) and the grain was weighed. Harvest index was calculated by dividing the grain weight by the total weight of grain, husks and straw.

Each sub-sampled head had spikelets counted and was threshed. Sub-sampled grains were counted using a Count-A-Pak Model 77 (FMC Corporation, Pennsylvania, USA) as were the grains threshed from the bulk heads.

Grain protein

Grain protein percentage (%, db) was indirectly estimated on all harvest samples by Near Infrared Spectroscopy (NIRS) on a Foss near-infra-red NIRS6500 spectrometer (Foss, Höganäs, Sweden) using calibrations developed at the Department of Agriculture and Food Western Australia, South Perth.

Rainout shelters

In order to shield out-of-season dominant rainfall treatments from growing season rainfall, rainout shelters were installed and used as per the Materials and Methods chapter (Chapter 3). Shelters were only closed in the likely event of rainfall, but this still resulted in reduced radiation to the crop. Delta-t solarimeter tubes placed above the crop canopy, outside and inside the shelter, indicated that about 78 percent of incoming solar radiation was intercepted by the shelter when it was closed. It was possible to determine how many hours per day the shelters were closed by comparing the difference in recordings between above canopy tube solarimeters inside and outside the shelter. The APSIM model was used to quantify the impact that closing the shelters had on crop growth. The model was run twice. Firstly using the appropriate initial parameters and the standard weather file for the season and then again using a weather file in which the solar radiation was reduced by 78 percent for the duration of tunnel closure. Figure 5.1 shows the difference in simulated biomass accumulation and grain yield, with and without the reduction in radiation. To view the time the shelters were installed and the rain days occurring during that period, see Figure 5.2.

Fallow

At the end of each plot of block two (one of two growing season dominant rainfall distribution blocks) of the experiment, two metres of plot had been maintained as fallow from August 2008 (see Appendix 2). This resulted in about 9 months of fallow before the area was sown in May 2009. In 2009 this area was treated as per the growing season dominant treatment. Harvest cuts were the only samples taken from the area. There was not full replication for factorial treatments so N treatments were pooled. Standard errors were calculated on the row spacing by genotype interactions (of which there were three of four data points each).

Statistical analysis

A restricted maximum likelihood (REML) procedure, developed in conjunction with Mario D'Antuono, biometrician at the Department of Agriculture and Food, Western Australia, was used to analyse the dataset for significant differences using the GenStat program. Due the possibility of extra soil water in some plots analysis was conducted using soil water as a covariate. This analysis did not change the ranking or magnitude of the data, so was not used.

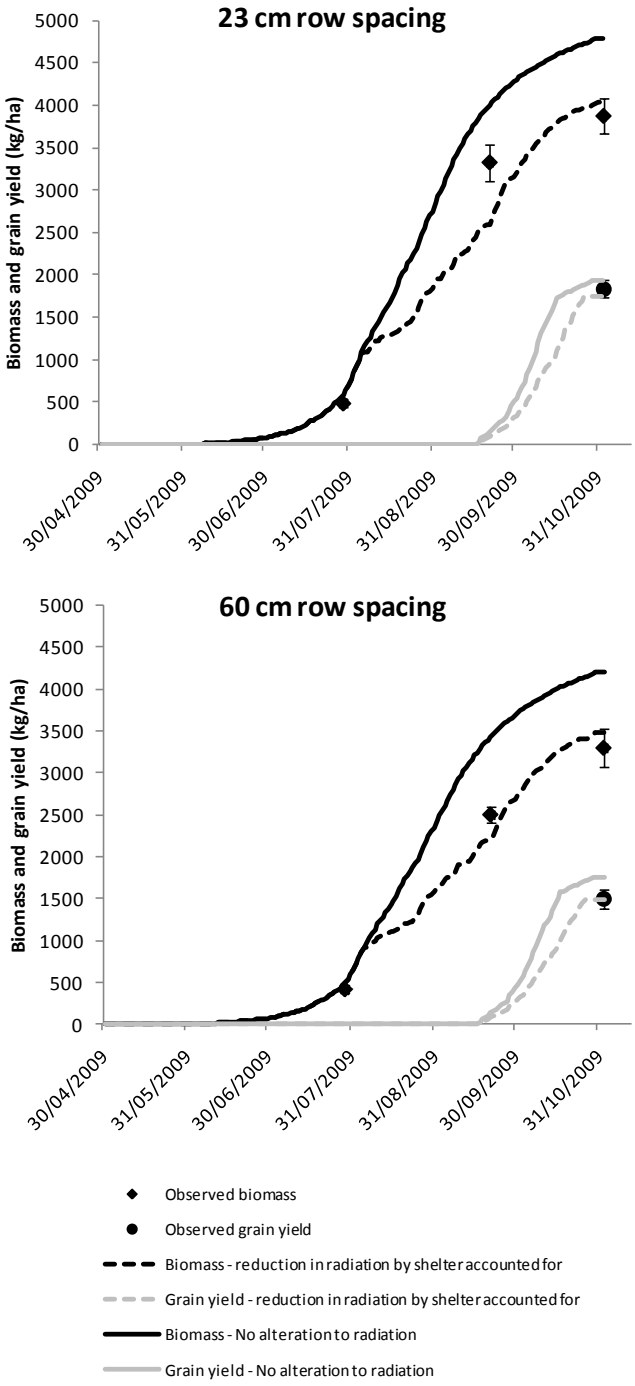


Figure 5.1: Simulated biomass and grain yield compared to observed data with and without interception of solar radiation by the rainout shelter. Merredin 2009.

5.3 Results

5.3.1 Weather

Natural rainfall was at decile one levels until July (112 mm from the start of the year for Merredin based on long term records) and finished the growing season at about decile five (279 mm) (Figure 5.3). The out of season dominant (OSD) rainfall treatment was irrigated before sowing so that 'rainfall' was above decile nine until mid-August (295 mm). After August the crop was sheltered during rainfall events so that the total cumulative rainfall after the growing season was about decile five – close to that of the growing season dominant treatment (GSD). The GSD treatment had 20 mm of boom irrigation in the week prior to seeding but no more irrigation after seeding.

The growing season involved some extreme temperatures. Nine times temperatures fell below 0°C (14 and 22 June, 14 and 26-29 July, 3 Sep, and 1 Oct) although there was no apparent frost damage in the crop. There were also three days in October that exceeded 30°C; the 10th (31°C), 18th (33°C) and 19th (35.8°C). Monthly minimum and maximum temperatures were generally consistent with long term averages, with the exception of September which tended to be colder in 2009. Daily pan evaporation rates were typically between two and five mm from May to August and between four and 10 mm in September and October. Solar radiation, measured by the nearby weather station, tended to be higher in 2009 than long-term averages from February to May, equal during the winter months then slightly higher during spring. Cumulative rainfall, daily min and max temperatures, solar radiation and pan evaporation can be viewed in Figure 5.3. Periods of irrigation and rainout shelter installation and days of rain compared to crop stem elongation and anthesis can be viewed in Figure 5.2.

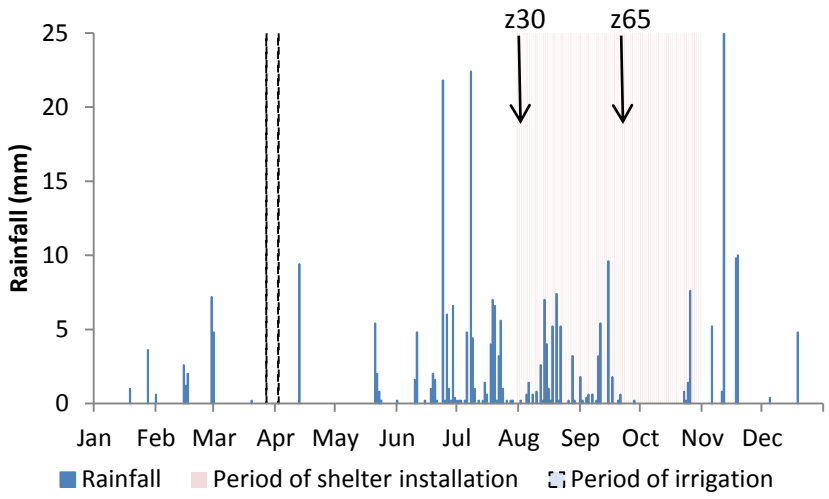


Figure 5.2: Periods of irrigation, rainout shelter installation (when OSD plots were covered on rainy days), days and amount of rain, and key development dates at Merredin 2009

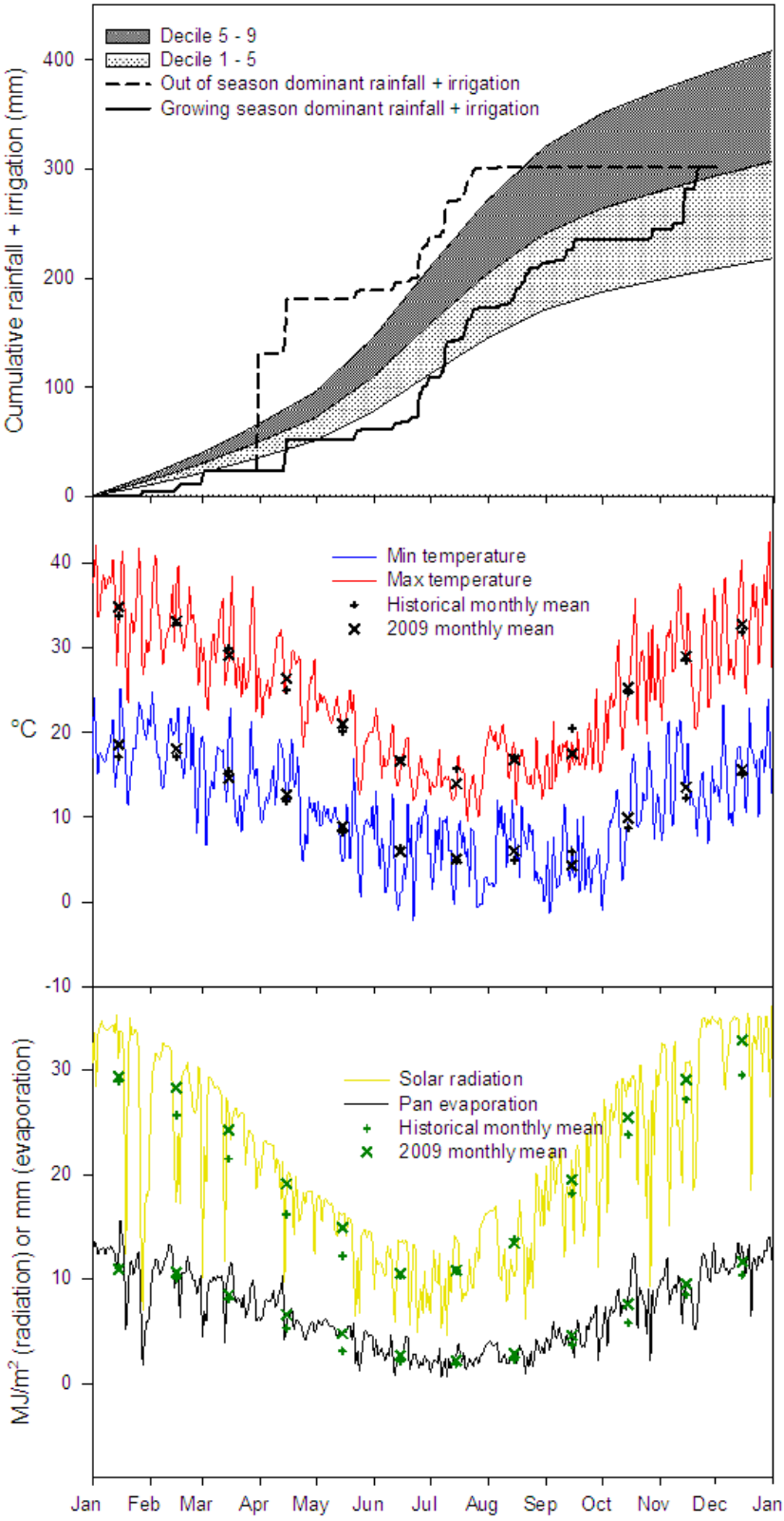


Figure 5.3: Cumulative rainfall, daily minimum and maximum temperatures, solar radiation and pan evaporation for the Merredin 2009 experimental site

5.3.2 Crop establishment

Dry conditions at and after sowing reduced crop establishment, particularly in the OSD treatment, which averaged 80 plants/m^2 compared to 102 in GSD. In the narrow row spacing, soil thrown from adjacent rows by the seeder tended to increase the depth of burial, which in turn resulted in reduced plant density. RS_{23} had 91 and 70 plants/m^2 in GSD and OSD rainfall treatments respectively while RS_{60} had 113 and 90.

5.3.3 Phenology

Phenology measurements taken around stem elongation showed that Silverstar had developed slightly faster than Wyalkatchem, with Silverstar showing an average Zadoks growth stage of 30.5 compared to 29.9 for Wyalkatchem ($P < 0.001$). At the anthesis sampling Silverstar again was slightly ahead in development, showing an average Zadoks growth stage of 70.8 compared to 70.2 in Wyalkatchem ($P < 0.001$).

5.3.4 Canopy development

There were no significant differences in biomass between any factors or interactions at the first sampling time, i.e. stem elongation (Table 5.6). RS_{23} (345 culms/m^2) had more culms per metre square than RS_{60} (305 culms/m^2) ($P < 0.05$) and genotype also had a significant impact on culm density with Wyalkatchem producing 399 culms/m^2 compared to only 250 culms/m^2 for Silverstar ($P < 0.001$). These differences didn't translate into greater biomass but they did result in increased leaf area index for Wyalkatchem ($P < 0.01$ for both row spacing and genotype) (Table 5.6). The timing of N didn't significantly increase culm density but N applied at tillering did result in a slightly greater LAI ($P < 0.1$) at stem elongation, when the other N treatment hadn't received its application yet. There was also an interaction between rainfall treatment and row spacing ($P < 0.1$) with the difference in LAI of the two row spacings being greater in the OSD treatment (RS_{23} 1.23, RS_{60} 0.93) compared to the GSD treatment (RS_{23} 0.73, RS_{60} 0.69).

Table 5.6: Effect of rainfall distribution, genotype, row spacing and timing of N on crop growth parameters. Merredin 2009

Treatment		Stem Elongation (Z30)			Anthesis (~Z70)				Maturity
		Culms per m2	LAI	Biomass (kg/ha)	% senesced	Infertile tillers per m2	LAI*	Biomass (kg/ha)	Biomass (kg/ha)
Rainfall Distribution	GSD	306	0.71	280	4.2%	99	-	2837	3202
	OSD	343	1.08	446	5.4%	110	1.46	2939	3569
	Ind. Lsd (0.05)	*90*	*0.38*	*176*	*0.7%*	*21*	-	*220*	*281*
	Sig.	**n.s.**	**n.s.**	**n.s.**	***	**n.s.**	-	**n.s.**	**
Genotype	Silverstar	250	0.76	345	3.1%	59	1.35	2891	3335
	Wyalkatchem	399	1.04	381	6.4%	151	1.58	2885	3436
	Ind. Lsd (0.05)	*34*	*0.14*	*60*	*0.8%*	*18*	*0.36*	*251*	*281*
	Sig.	***	***	**n.s.**	***	***	**n.s.**	**n.s.**	**n.s.**
Row	23 cm	345	0.98	387	5.4%	124	1.62	3275	3829
	60 cm	305	0.81	339	4.2%	86	1.31	2501	2942
	Ind. Lsd (0.05)	*35*	*0.15*	*57*	*0.8%*	*21*	*0.35*	*216*	*281*
	Sig.	**	**	**n.s.**	***	***	**n.s.**	***	***
Timing of	Stem elongation	308	0.84	341	4.6%	95	1.35	2750	3244
	Tillering	342	0.96	385	4.9%	114	1.57	3027	3527
	Ind. Lsd (0.05)	*34*	*0.14*	*59*	*0.4%*	*19*	*0.35*	*243*	*281*
	Sig.	**n.s.**	*	**n.s.**	**n.s.**	**	**n.s.**	**	**

n.s. not significant
* P < 0.1
** P < 0.05
*** P < 0.01

* LAI Leaf Area Index at Anthesis only conducted on Out of season dominant plots

By anthesis some differentials in biomass had opened up between row spacing ($P < 0.001$) and nitrogen timing treatments ($P < 0.05$). RS_{60} recorded an average biomass of 2501 kg/ha, which was lower than for plants growing in the narrow row spacing treatment RS_{23} at 3275 kg/ha. When N was applied earlier in the season at tillering, compared to N application at stem elongation, dry matter was greater at anthesis (3027 kg/ha compared to 2750 kg/ha, Table 5.6).

At maturity the same trends could be seen with row spacing ($P < 0.001$), nitrogen timing ($P < 0.05$) and rainfall distribution ($P < 0.05$) all having a significant effect on dry matter production (Table 5.6).Once again the narrow row spacing RS_{23} had greater biomass than RS_{60} (3829 kg/ha compared to 2942 kg/ha). N applied at Zadoks growth stage 15 also produced more biomass than when the same amount of N was applied at Zadoks growth stage 31. Dry matter accumulation in the row spacing and Nitrogen timing treatments are illustrated in Figure 5.4 and Figure 5.5 respectively.

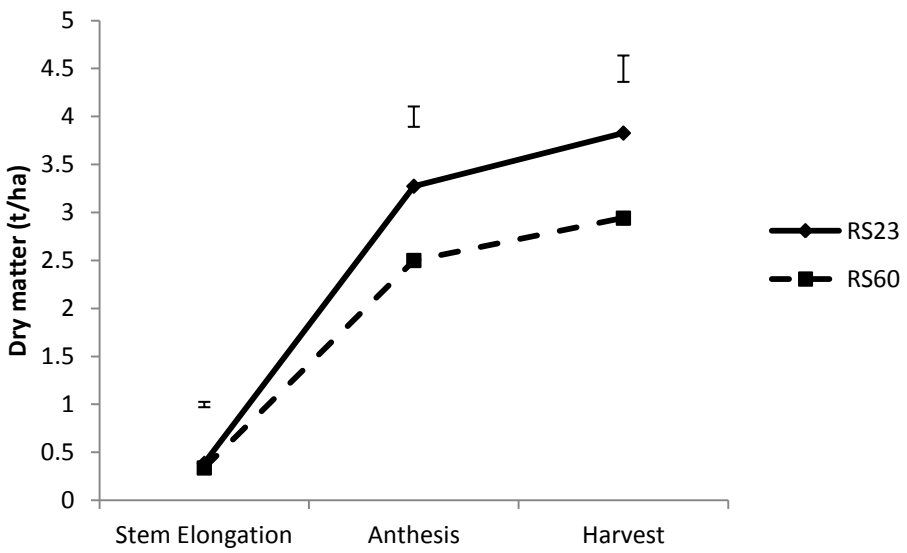


Figure 5.4: Dry matter accumulation as affected by row spacing (averaged across all other treatments). Error bars indicate least significant difference at P < 0.05. Merredin 2009.

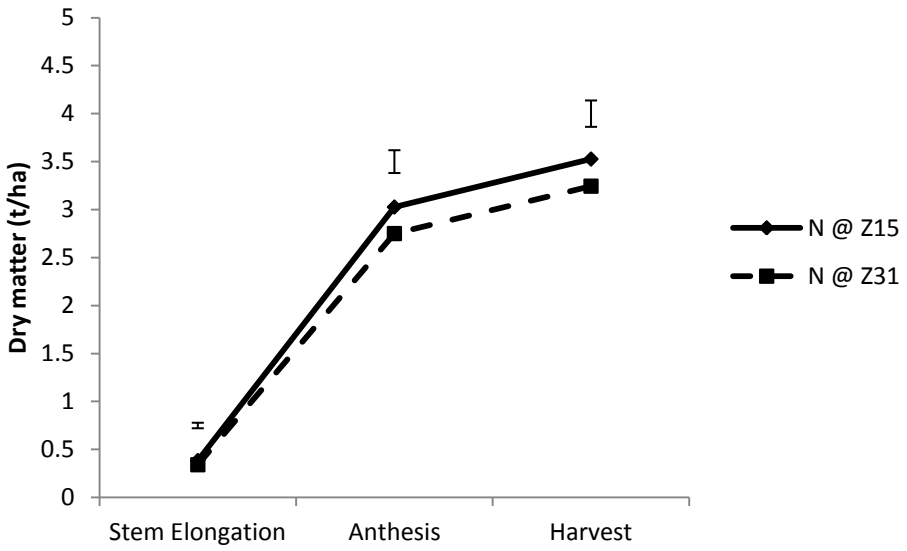


Figure 5.5: Dry matter accumulation as affected by timing of nitrogen application (averaged across all other treatments). Error bars indicate least significant difference at P < 0.05. Merredin 2009.

Due to yellow spot (*Pyrenophoua tuitici-repentis*) infestation at around anthesis, LAI measurements were not taken in the GSD rainfall treatment at this time. An altered restricted maximum likelihood (REML) procedure was applied to the LAI data with only the OSD data analysed at both stem elongation and anthesis. This meant that fewer replicates were included in the analysis of the main effects of row spacing, genotype and nitrogen timing. While earlier applied N and narrower spaced rows showed trends of having greater LAI, the effects were not significant (Table 5.6).

At anthesis there were a number of factors that had a significant effect on infertile tillers, namely row spacing ($P < 0.001$), nitrogen timing ($P < 0.05$) and genotype ($P < 0.001$) (Table 5.6). Generally, the treatments that had produced greater amounts of biomass at anthesis also produced more infertile tillers. RS_{23} had an average of 124 infertile tillers/m^2 compared to 84 in RS_{60}, Nitrogen applied at tillering had 114 infertile tillers/m^2 compared to 95 when N was applied at stem elongation, and Wyalkatchem had 151 infertile tillers/m^2 compared to only 59 in Silverstar. In the case of row spacing and genotype the number of infertile tillers translated into a greater percentage of senesced material ($P < 0.01$ and $P < 0.001$ respectively) (Table 5.6). The percentage of dead material to total dry matter was not significant in the nitrogen timing treatment. The opposite effect was true for rainfall distribution where there was no difference in infertile tiller number but the OSD treatment (5.4 percent) had more senesced material than the GSD treatment (4.2 percent) ($P < 0.001$.

5.3.5 Water use

Rainfall distribution

The OSD treatment had significantly more stored water at the start of the season but received less rain than the GSD treatment in the growing season (May to October), which resulted in less total evapotranspiration (Table 5.7). Using the method of estimating transpiration and evaporation mentioned in Chapter 3, Table 5.8 indicates a higher proportion of ET was used for transpiration in the OSD treatment (43 versus 32 percent).

Table 5.7: Effect of rainfall distribution and row spacing on seasonal evapotranspiration (mm), grain yield and water use efficiency (kg/ha.mm). Merredin 2009.

Rain treatment	Row Spacing (cm)	Starting SW a	Finishing SW b	Rain c	Evapo - transpiration d = (a-b) + c	Grain yield t/ha e	WUE e*100/d
GSD	23	136	138	192	190	1.48	8.0
	60	151	145	192	198	1.24	6.3
Mean		**143**	**142**	**192**	**194**	**1.36**	**7.1**
OSD	23	184	135	121	171	1.95	11.9
	60	197	158	121	160	1.47	9.3
Mean		**190**	**146**	**121**	**166**	**1.71**	**10.6**
	23 Mean	**160**	**136**	**157**	**180**	**1.72**	**9.9**
	60 Mean	**174**	**151**	**157**	**179**	**1.35**	**7.8**
	Rainfall treatment	**	n.s.	n/a	n.s.	*	n.s.
	Row spacing	*	**	n/a	n.s.	***	***
	Rainfall treatment* row spacing	n.s.	n.s.	n/a	n.s.	n.s.	n.s.

n.s.	not significant
*	P < 0.1
**	P < 0.05
***	P < 0.01

Table 5.8: Effect of rainfall distribution and row spacing on seasonal evapotranspiration (mm) and estimated transpiration and evaporation. Merredin 2009.

Rain treatment	Row Spacing	Evapotranspiration (mm) a	DM Yield t/ha b	Est. Transpiration (mm) c=b*1000/50	Est. Evaporation (mm) d=a-c	% Trans. c/a
GSD	23	190	3.37	67	123	35%
	60	198	2.73	55	143	28%
Mean		**194**	**3.05**	**61**	**133**	**32%**
OSD	23	171	3.99	80	91	47%
	60	160	3.15	63	97	39%
Mean		**166**	**3.57**	**71**	**94**	**43%**
	23 Mean	**181**	**3.68**	**74**	**107**	**41%**
	60 Mean	**179**	**2.94**	**59**	**120**	**33%**

The irrigation applied to the OSD treatment before sowing resulted in increased soil water at every soil layer relative to the GSD treatments, with the largest differences occurring in the 30, 50 and 70 cm soil layers (Figure 5.6). On July 24, soil water was the same between rainfall distribution treatments in the top three layers but differences still occurred at depth (70 and 90 cm). By September 14 soil water at depth was also equal. On the most part, extraction patterns were similar between rainfall distribution treatments (averaged over all sub-treatments), particularly in the second half of the growing season (Figure 5.7).

Row spacing

As mentioned in the materials and methods section of this chapter (section 5.2), RS_{60} plots included two access tubes for neutron moisture meter measurement, with one close to or in the crop row and the other in the inter-row with a view to investigate two-dimensional patterns (vertical and lateral) in water-use. There was little difference in water extraction between the two tube locations (Figure 5.8) so data from the two tubes was pooled in further analysis.

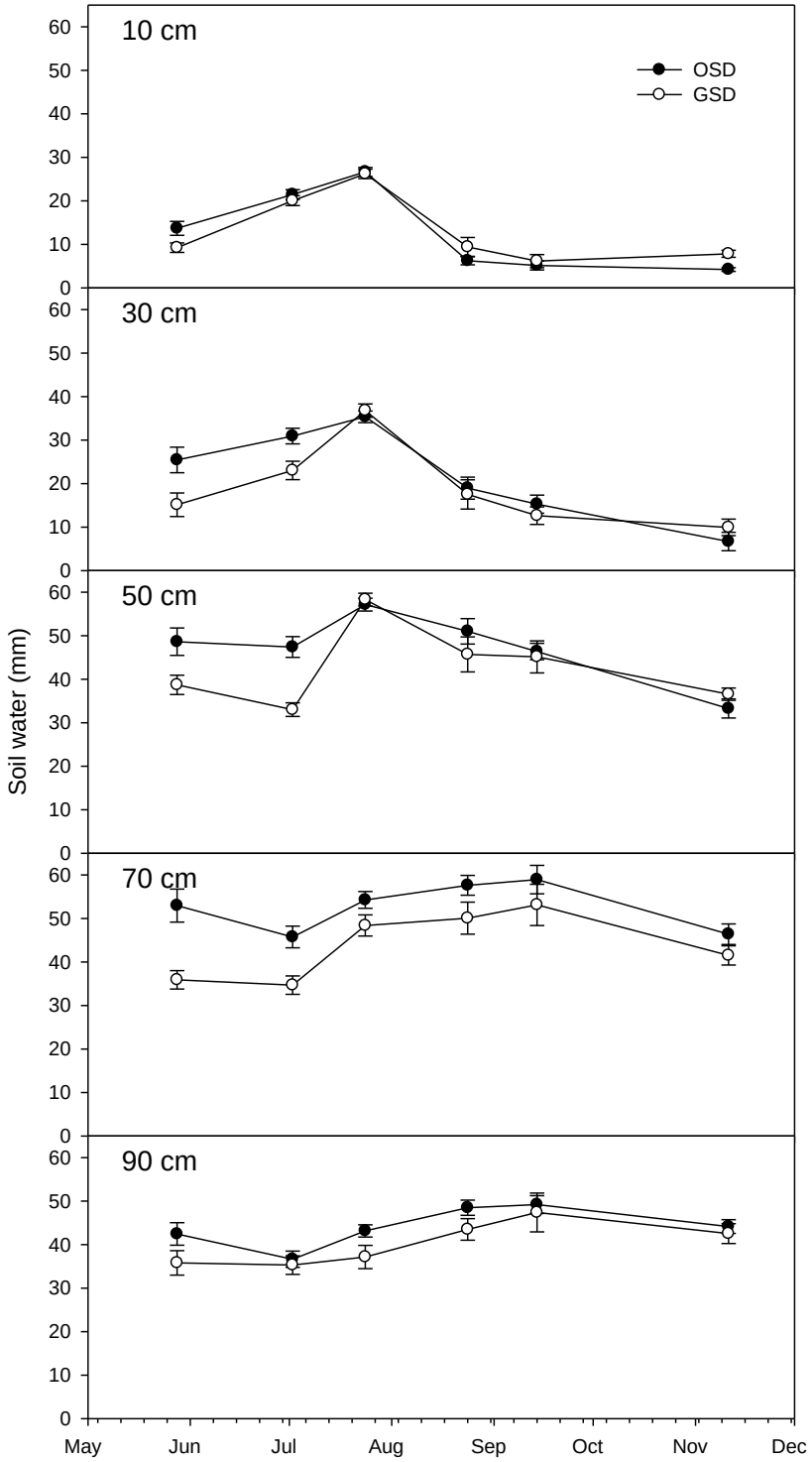


Figure 5.6: Soil water content throughout the soil profile as affected by rainfall distribution (row spacing 23 cm). Merredin 2009. Error bars indicate standard error of the mean.

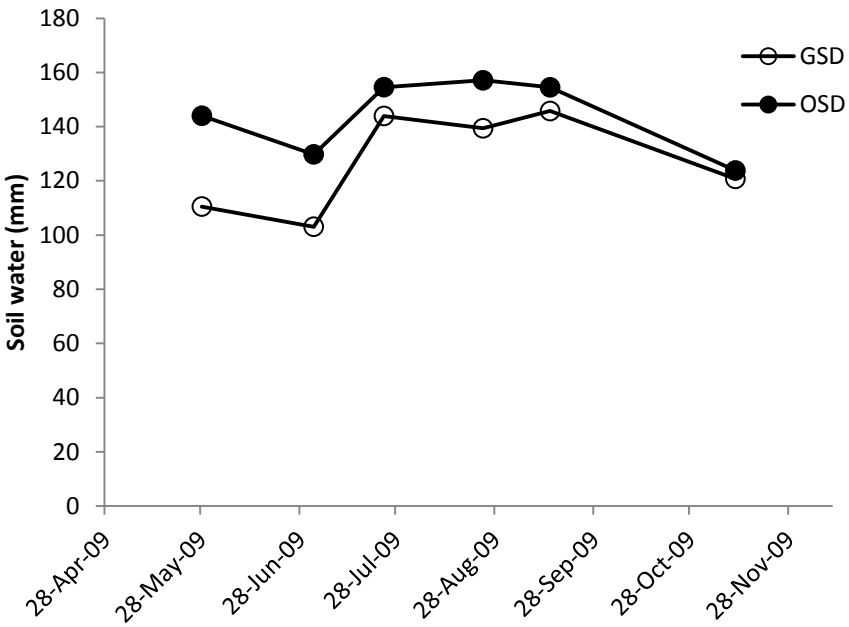


Figure 5.7: Total soil water content as affected by rainfall distribution (row spacing 23 cm) at Merredin 2009.

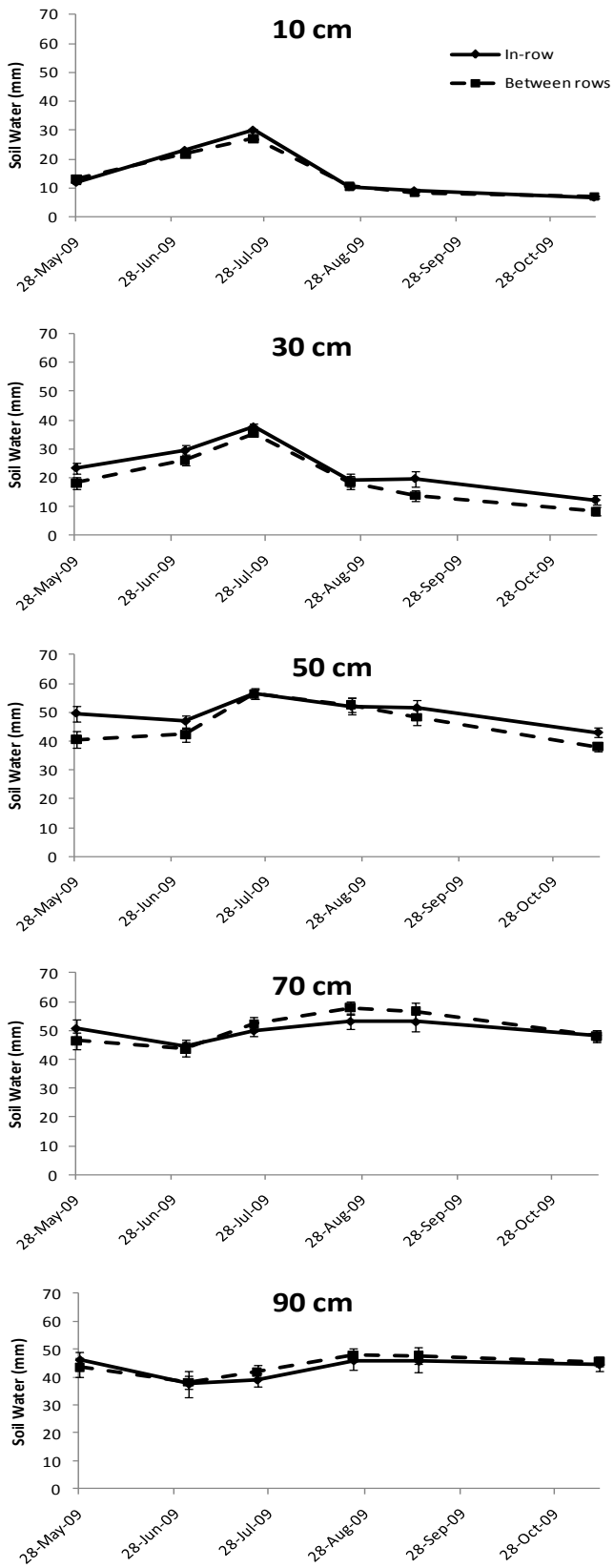


Figure 5.8: Comparison of soil water measurements derived from neutron moisture meter measurements in or near the crop row and in the inter-row of RS_{60} averaged across all other treatments. Merredin 2009.

The effect of row spacing on soil water for each rainfall distribution (averaged across genotype and nitrogen treatments) is illustrated in Figure 5.9. Due to soil water moving into the soil profile through rainfall, it is difficult to monitor extraction patterns in the GSD treatment. In the OSD treatment the most obvious effect is seen at 50 cm. From August 24 onwards RS_{60} had more soil water at 50 cm than RS_{23} and the difference increased as the season progressed (Figure 5.9). This lack of extraction of RS_{60} at depth is highlighted even more when the 50 cm soil zone is combined with 70 and 90 cm (Figure 5.10). After the crop had matured (measurements taken on November 11) there were also subtle differences in water content at depth between row spacing (5.1 mm at 70 cm and 4.6 mm at 90 cm) and 9.9 mm in the 50 cm layer. When averaged across both rainfall treatments soil water was greater in RS_{60} by 15 mm when totalled across all soil layers ($P < 0.05$, Table 5.7 and Figure 5.9). Total evapotranspiration for the year was equal between row spacing treatment as the wider row spacing finished with more residual water, that treatment had more soil water at sowing as a result of residual water from the season before (174 versus 160, Table 5.7). The percentage of ET estimated to be used as transpiration was higher in RS_{23} (41 to 33 percent, Table 5.8)

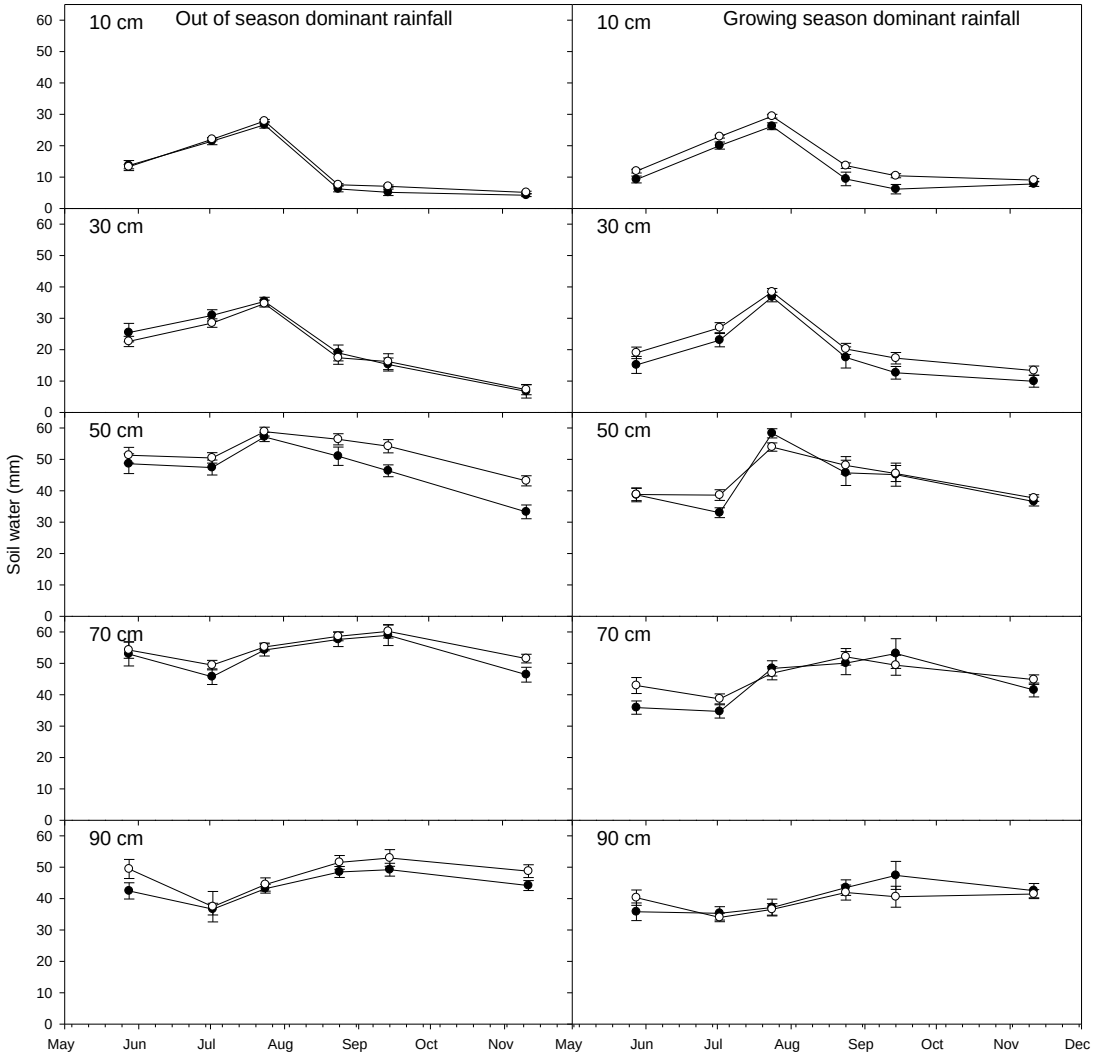


Figure 5.9: Soil water content throughout the soil profile as affected by rainfall distribution and crop row spacing. Solid symbols indicate RS_{23} and unfilled symbols RS_{60} . Merredin 2009.

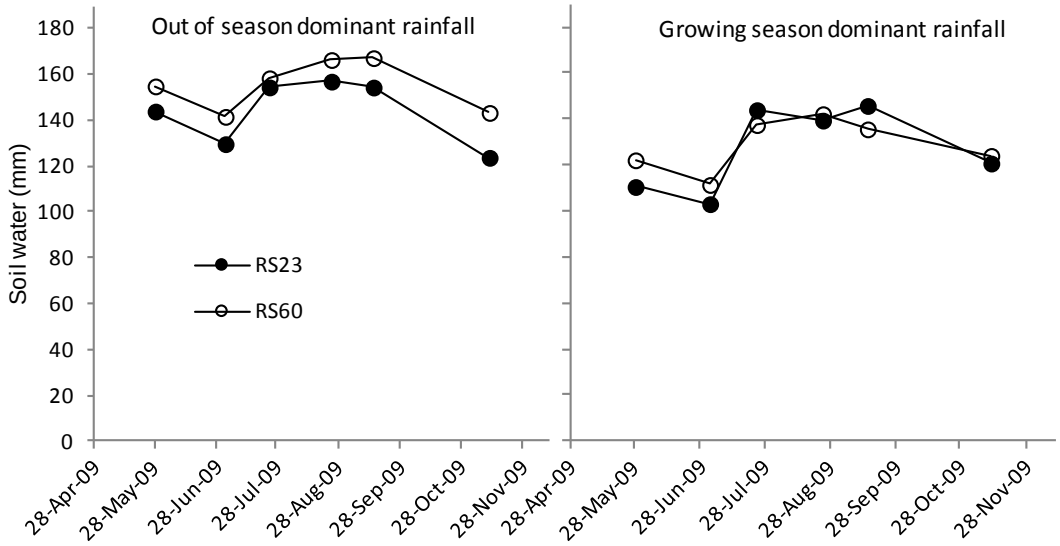


Figure 5.10: Soil water at depth (50 to 90 cm) as affected by rainfall distribution and crop row spacing. Merredin 2009.

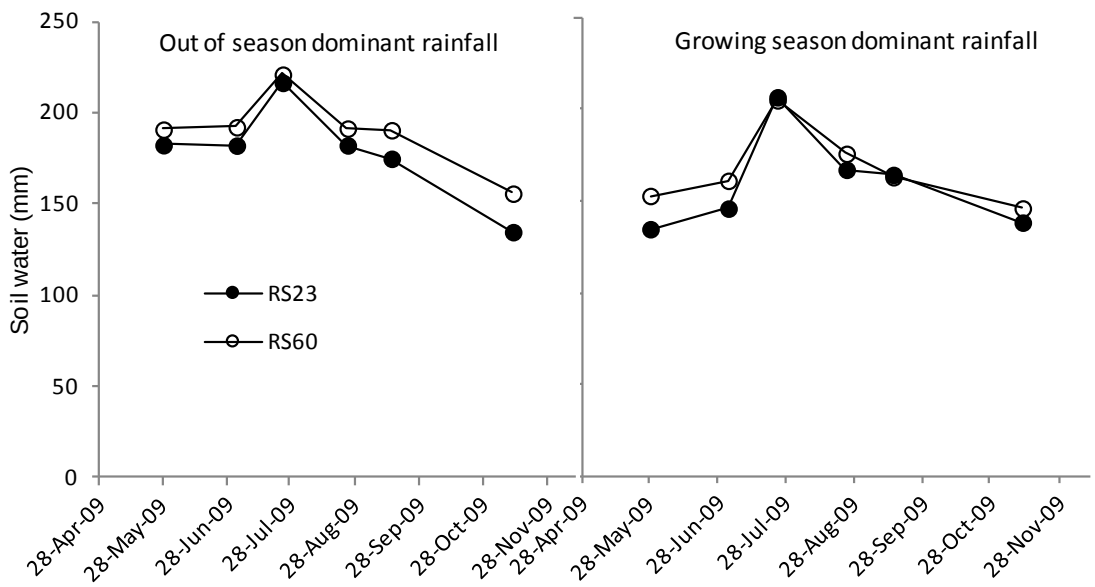


Figure 5.11: Total soil water as affected by rainfall distribution and crop row spacing. Merredin 2009.

Genotype and nitrogen timing

Rainfall distribution and row spacing created most of the variation in soil water, and as neutron moisture meter data was variable there was little meaningful genotype or timing of nitrogen effects observed with soil water.

Only one difference was observed between genotypes and that was in the RS_{60} treatment and at the 50 cm soil layer (which is where most differences in soil data occur because it is deep enough to escape evaporation and shallow enough that the roots penetrate the whole layer). Silverstar started extracting from the soil layer earlier than Wyalkatchem and was using more water from the layer from soon after stem elongation to about anthesis (Figure 5.12). There was no other noticeable difference in soil water at other depths throughout the season or in total evapotranspiration for the season (data not shown).

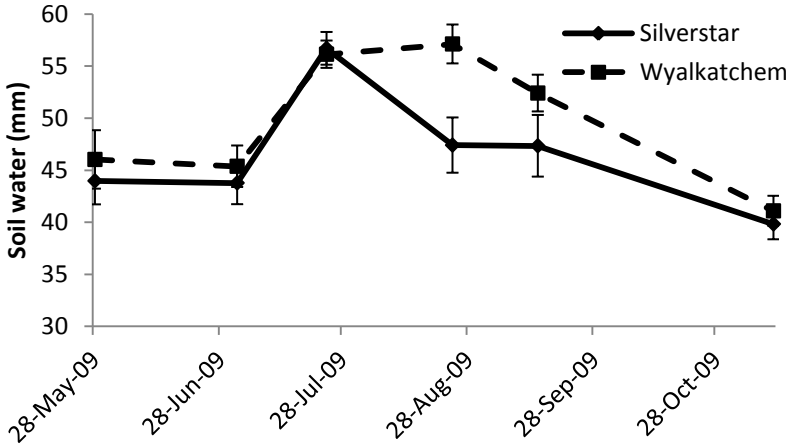


Figure 5.12: Effect of Genotype on soil water at 60 cm row spacing in the 50 cm soil layer. Merredin 2009.

5.3.6 Grain yield, harvest index and yield components

Main Effects

A summary of the main effects on yield and yield components can be viewed in Table 5.9. All data are presented in Table 5.10.

The OSD treatment had a higher grain yield (1.72 t/ha) when compared to the GSD treatment (1.36 t/ha). However, plants in the GSD treatments were affected by yellow spot (*Pyrenophora tritici-repentis*) after anthesis, which probably contributed to reductions in grain yield through lower individual grain weight (27.9 mg versus 33.8 mg for OSD) and a lower HI (0.38 versus 0.43) This will be discussed in greater depth in section 5.4 at the end of this chapter. It was also likely that the comparative drop in individual grain weight of GSD compared to OSD was partly due to water stress as soil water in latter parts of the growing season was lower in that treatment (by about 10.5 mm at anthesis). Head density was the

same between rainfall treatments but GSD had more grains in each head (36.2 to 33.3, $P < 0.1$).

When averaged across all other factorial treatments grain yield declined when row spacing increased (1.72 t/ha for RS_{23} and 1.37 t/ha for RS_{60}). Plants grown at the wider row spacing had fewer heads per m^2 (168 to 196) and grains in each head (32.9 versus 36.5) as a result of fewer spikelets (16.4 to 17.8). The result was a substantially reduced number of grains per m^2 in the wide row treatment with RS_{60} having only 5476 while RS_{23} had 7144. Harvest Index increased in the wider row spacing (0.42) compared to the narrower row spacing (0.40) ($P < 0.1$).

There was no difference in yield between the two genotypes used in the experiment, however, they constructed yield differently. Head densities were similar but Silverstar had more grains per head (37.7 versus 31.7) and grains per m^2 (6730 to 5889). Wyalkatchem made up for lower number of grains with heavier grains (34.2 mg to 27.4 mg).

Timing of nitrogen fertiliser also affected grain yield when averaged across all other treatments. When N was applied at tillering grain yield was 1.63 t/ha, whilst when application was delayed until stem elongation it dropped to 1.46 t/ha. The increase in yield when N was applied earlier was associated with increased head density. Nitrogen applied at tillering produced 189 heads/m^2 while N applied at stem elongation generated 175 heads/m^2, which resulted in more grains per m^2 (6586 from tillering application of N to 6033 after application at stem elongation).

Table 5.9: Rainfall distribution, genotype, row spacing and timing of N main effects on yield components at Merredin, 2009.

Treatment		Grain yield t/ha	Heads /m2	Grains /head	Spikelets/head	Grains /spikelet	Grains/m2	Individual grain wt (mg)	Harvest Index
Rainfall distribution	Growing season dominant	1.36	184	36.2	16.8	2.16	6648	27.89	0.38
	Out of season dominant	1.72	179	33.3	17.4	1.92	5971	33.81	0.43
		*	n.s.	*	n.s.	*	n.s.	*	*
Genotype	Silverstar	1.56	179	37.7	16.6	2.27	6730	27.45	0.42
	Wyalkatchem	1.52	185	31.7	17.6	1.81	5889	34.25	0.39
		n.s.	*n.s.*	***	***	***	***	***	***
Row spacing	23 cm	1.72	196	36.5	17.8	2.07	7144	29.82	0.40
	60 cm	1.37	168	32.9	16.4	2.01	5476	31.87	0.42
		***	***	***	***	*n.s.*	***	***	*
Timing of N	Stem elongation	1.46	175	34.8	16.9	2.06	6033	30.62	0.41
	Tillering	1.63	189	34.7	17.2	2.02	6586	31.08	0.41
		**	**	*n.s*	*n.s.*	*n.s.*	**	*n.s.*	*n.s.*

n.s.	not significant
*	P < 0.1
**	P < 0.05
***	P < 0.01

Interactions

There is a trend in the data that suggests the yield differential between row spacing treatments is less in Wyalkatchem (in terms of grain yield), although it isn't statistically significant. The trend is driven by a smaller decline in head density and greater increase in grain weight in Wyalkatchem (Figure 5.13). Yield, yield components and harvest indices for treatment combinations can be viewed in Table 5.10.

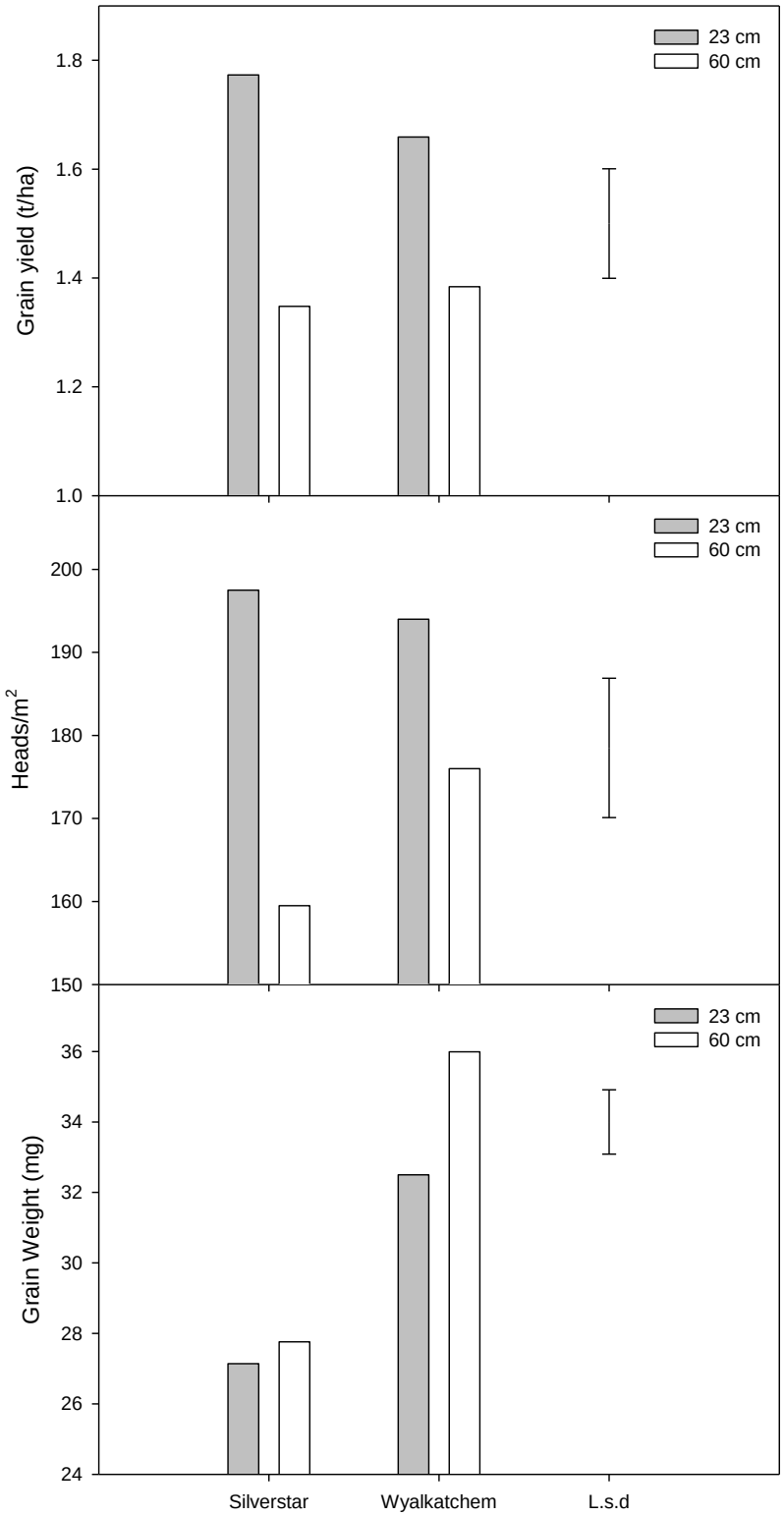


Figure 5.13: Genotype by row spacing interaction effects on grain yield (top), head density (middle), and grain weight (bottom). Merredin 2009.

There was a rainfall distribution by row spacing interaction affecting grain weight. In the GSD treatment grain weight increased when row spacing was increased, while this was not the case in the OSD treatment. This equated to a difference in harvest index (Figure 5.14).

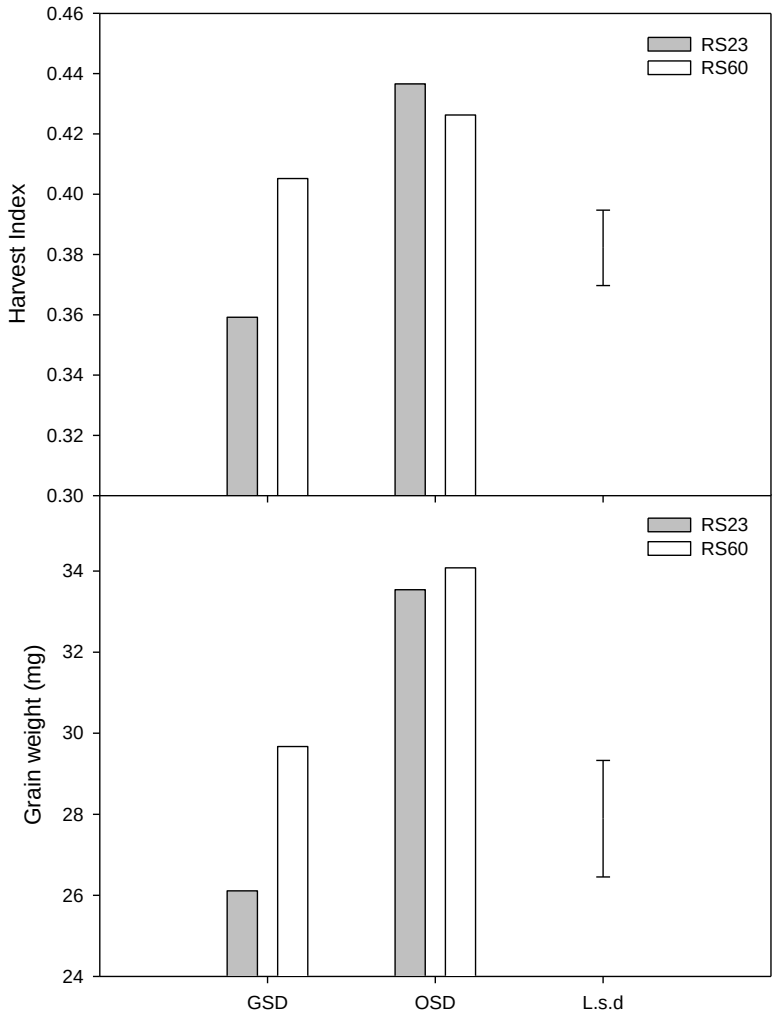


Figure 5.14: Effect of rainfall distribution and row spacing on grain weight (top) and harvest index (bottom). Merredin 2009.

There was a rainfall distribution by timing of N by row Spacing interaction ($P < 0.1$) in grain yield indicating that wide rows in the OSD treatment benefitted from early N fertilisation. A timing of N by row spacing interaction didn't occur in the GSD treatment or when averaged across both rainfall distributions. The differences in grain yield tended to be driven by an increase in grains per square metre, and in the case of Silverstar, grain size (Table 5.10).

Table 5.10: Effects of rainfall distribution, genotype, row spacing and timing of N interactions on grain yield and yield components at Merredin, 2009.

Genotype	RS	Timing of N	Grain yield t/ha			Heads/m2			Grains/head			Spikelets/head			Grains/spikelet			Grains/m2			Individual grain wgt (mg)			Harvest Index		
			GSD	OSD	Avg	GSD	OSD	Avg	GSD	OSD	Avg	GSD	OSD	Avg	GSD	OSD	Avg	GSD	OSD	Avg	GSD	OSD	Avg	GSD	OSD	Avg
Silverstar	23 cm	Stem Elongation	*1.29*	*2.11*	1.70	*179*	*188*	184	*42.57*	*37.09*	39.83	*16.83*	*17.41*	17.12	*2.53*	*2.13*	2.33	*7650*	*6927*	7289	*22.16*	*33.18*	27.67	*0.363*	*0.454*	0.409
		Tillering	*1.67*	*2.03*	1.85	*222*	*201*	212	*41.21*	*38.26*	39.74	*16.77*	*18.22*	17.50	*2.46*	*2.10*	2.28	*9124*	*7685*	8405	*23.40*	*29.84*	26.62	*0.370*	*0.445*	0.407
		Avg	1.48	2.07	**1.77**	200	195	**198**	41.89	37.68	**39.78**	16.80	17.82	**17.31**	2.49	2.12	**2.30**	8387	7306	**7847**	22.78	31.51	**27.15**	0.366	0.450	**0.408**
	60 cm	Stem Elongation	*1.14*	*1.29*	1.21	*145*	*153*	149	*37.56*	*34.82*	36.19	*15.96*	*15.76*	15.86	*2.35*	*2.21*	2.28	*5241*	*5391*	5316	*25.18*	*27.87*	26.53	*0.408*	*0.430*	0.419
		Tillering	*1.23*	*1.74*	1.48	*170*	*170*	170	*36.66*	*33.52*	35.09	*15.61*	*16.33*	15.97	*2.35*	*2.05*	2.20	*6158*	*5662*	5910	*26.83*	*31.15*	28.99	*0.421*	*0.465*	0.443
		Avg	1.19	1.51	**1.35**	157	162	**159**	37.11	34.17	**35.64**	15.79	16.05	**15.92**	2.35	2.13	**2.24**	5700	5527	**5613**	26.01	29.51	**27.76**	0.415	0.447	**0.431**
Wyalkatchem	23 cm	Stem Elongation	*1.34*	*1.80*	1.57	*201*	*207*	204	*33.24*	*31.03*	32.14	*17.73*	*18.62*	18.18	*1.87*	*1.67*	1.77	*6582*	*6449*	6516	*28.47*	*34.97*	31.72	*0.333*	*0.413*	0.373
		Tillering	*1.63*	*1.88*	1.75	*189*	*180*	184	*35.14*	*33.81*	34.48	*18.09*	*18.47*	18.28	*1.94*	*1.83*	1.89	*6659*	*6072*	6366	*30.40*	*36.17*	33.29	*0.371*	*0.435*	0.403
		Avg	1.48	1.84	**1.66**	195	193	**194**	34.19	32.42	**33.31**	17.91	18.55	**18.23**	1.91	1.75	**1.83**	6621	6261	**6441**	29.44	35.57	**32.50**	0.352	0.424	**0.388**
	60 cm	Stem Elongation	*1.27*	*1.42*	1.35	*165*	*163*	164	*33.37*	*28.43*	30.90	*16.40*	*16.87*	16.64	*2.03*	*1.69*	1.86	*5472*	*4552*	5012	*34.01*	*39.11*	36.56	*0.406*	*0.395*	0.400
		Tillering	*1.30*	*1.55*	1.42	*204*	*172*	188	*29.51*	*29.25*	29.38	*17.21*	*17.26*	17.24	*1.71*	*1.69*	1.70	*6297*	*5032*	5665	*32.65*	*38.19*	35.42	*0.386*	*0.415*	0.400
		Avg	1.29	1.48	**1.38**	184	168	**176**	31.44	28.84	**30.14**	16.81	17.07	**16.94**	1.87	1.69	**1.78**	5885	4792	**5338**	33.33	38.65	**35.99**	0.396	0.405	**0.400**
Lsd for same…		*Rainfall distribution*	*0.40*			*33*			*5.92*			*1.15*			*0.35*			*1347*			*3.76*			*0.041*		
		Row Spacing	*0.41*			*35*			*5.81*			*1.16*			*0.35*			*1404*			*4.28*			*0.043*		
		Genotype	*0.41*			*35*			*5.84*			*1.16*			*0.35*			*1414*			*4.32*			*0.043*		
		Timing of N	*0.41*			*35*			*5.83*			*1.16*			*0.35*			*1412*			*4.32*			*0.043*		
Row Spacing		**23 cm**	1.48	1.95		198	194		38.04	35.05		17.36	18.18		2.20	1.93		7504	6783		26.11	33.54		0.359	0.437	
		60 cm	1.24	1.50		171	165		34.28	31.51		16.30	16.56		2.11	1.91		5792	5159		29.67	34.08		0.405	0.426	
Lsd for same…		*Rainfall distribution*	*0.20*			*17*			*2.96*			*0.58*			*0.17*			*669*			*1.87*			*0.020*		
		Row Spacing	*0.21*			*19*			*2.54*			*0.61*			*0.17*			*853*			*3.32*			*0.027*		
Genotype		**Silverstar**	1.33	1.79		179	178		39.50	35.92		16.29	16.93		2.42	2.12		7043	6416		24.39	30.51		0.391	0.449	
		Wyalkatchem	1.38	1.66		190	180		32.82	30.63		17.36	17.81		1.89	1.72		6253	5526		31.38	37.11		0.374	0.414	
Lsd for same…		*Rainfall distribution*	*0.20*			*17*			*3.01*			*0.57*			*0.18*			*687*			*1.96*			*0.021*		
		Genotype	*0.21*			*20*			*2.73*			*0.59*			*0.18*			*897*			*3.48*			*0.028*		
Timing of N		**Stem Elongation**	1.26	1.65		173	178		36.69	32.84		16.73	17.17		2.20	1.92		6236	5830		27.46	33.78		0.377	0.423	
		Tillering	1.46	1.80		196	181		35.63	33.71		16.92	17.57		2.12	1.92		7060	6113		28.32	33.84		0.387	0.440	
Lsd for same…		*Rainfall distribution*	*0.20*			*17*			*2.96*			*0.58*			*0.17*			*665*			*1.84*			*0.020*		
		Timing of N	*0.21*			*19*			*2.63*			*0.60*			*0.18*			*872*			*3.38*			*0.028*		

5.3.7 Fallow

On the fallowed area the grain yields between row spacing treatments were closer than in the main treatments GSD and OSD. The wider rows in this instance had a greater harvest index brought about through heavier individual grain weights (Figure 5.15). Wyalkatchem once again performed better than Silverstar in wide rows and had numerically higher grain yield (Figure 5.16), individual grain weight and harvest index in the RS_{60} treatment (Figure 5.15). Figure 5.17 shows that the number of grains per metre square is more constant across row spacings in Wyalkatchem than Silverstar.

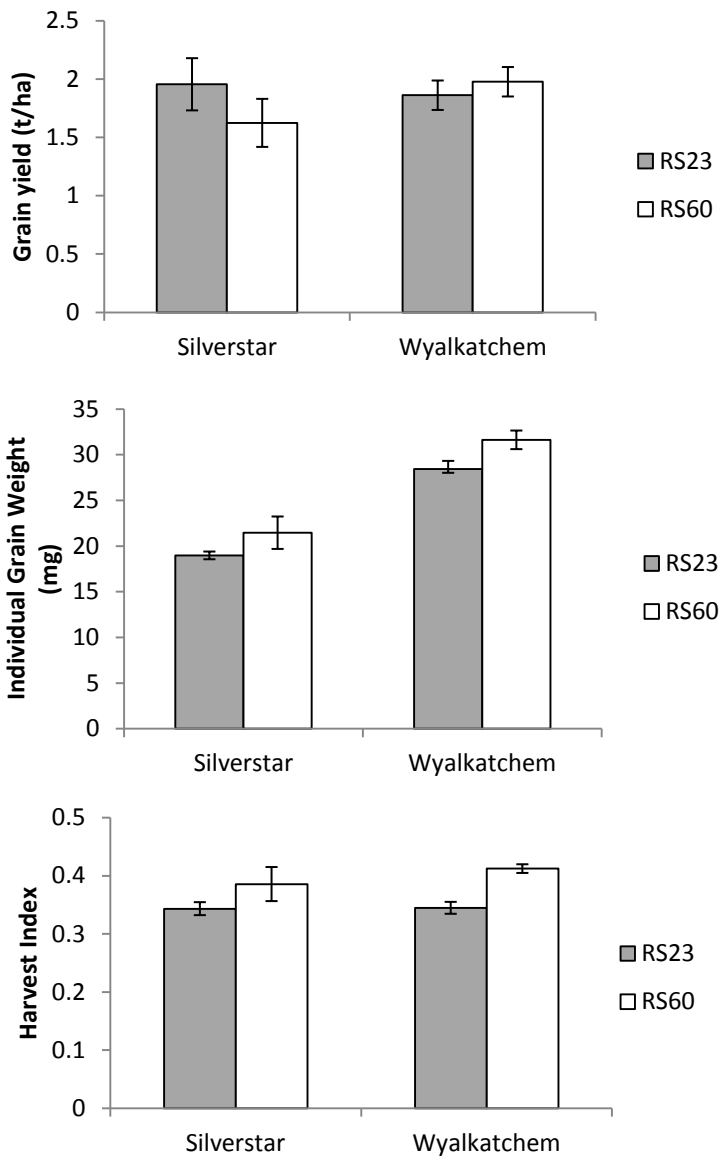


Figure 5.15: Effect of row spacing by genotype interaction on grain yield (top), individual grain weight (centre) and harvest index (bottom) in wheat grown on Fallow. Error bars indicate standard error of the mean. Merredin 2009.

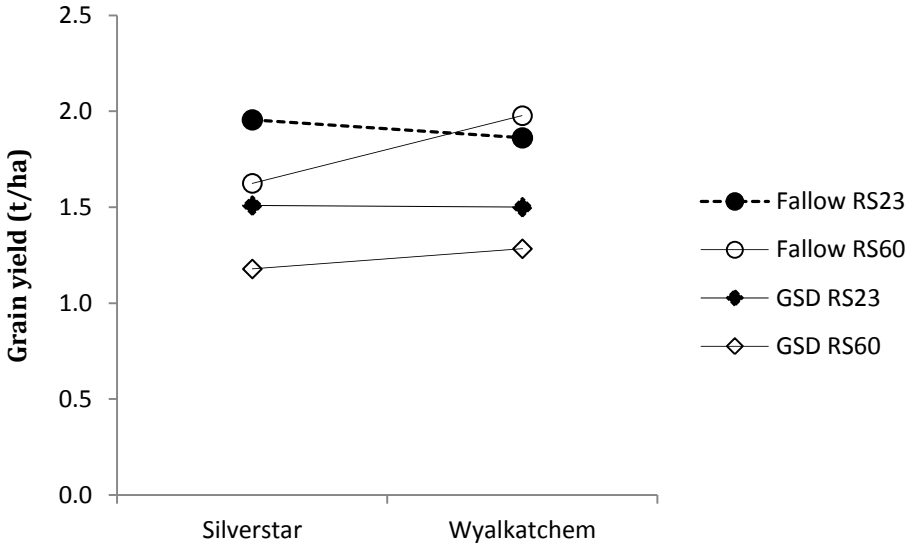


Figure 5.16: Effect of row spacing by genotype interaction on grain yield in growing season dominant rainfall treatment following a wheat crop versus following chemical fallow. Merredin 2009.

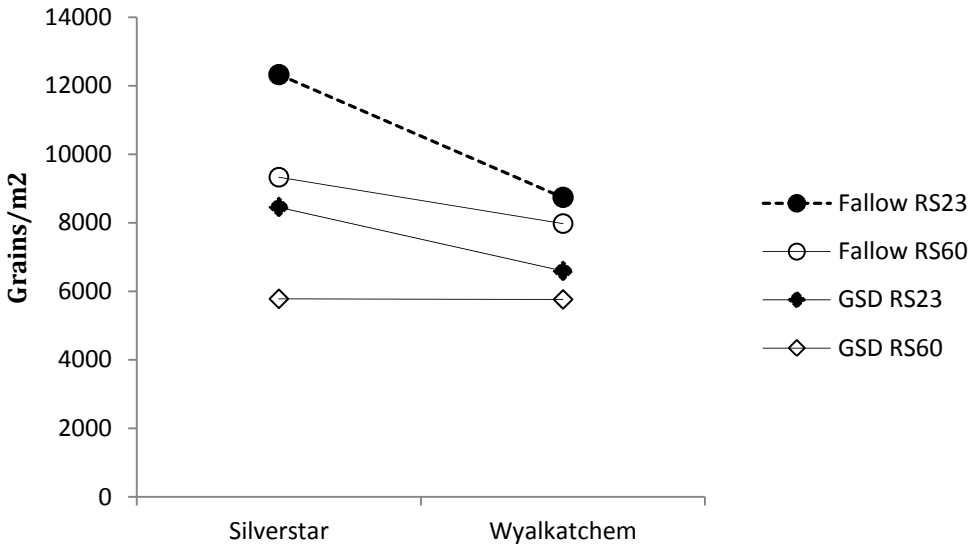


Figure 5.17: Effect of row spacing by genotype interaction on grain per metre square in growing season dominant rainfall treatment following a wheat crop versus following chemical fallow. Merredin 2009.

5.3.8 Grain protein

There was no statistical difference in grain protein between timing of N or row spacing treatments, however, rainfall distribution and genotype did have an impact ($P < 0.05$ and $P < 0.001$ respectively). The OSD treatment ended the season with greater grain nitrogen (12.9 to 11.3 percent). Wyalkatchem (12.8 percent) had significantly greater levels of grain protein than Silverstar (11.5 percent) (Table 5.11).

Table 5.11: Effect of rainfall distribution, row spacing, riming of N and genotype on grain protein. Merredin 2009.

Treatment		Protein	Significance
Rainfall Distribution	GSD	11.3	P < 0.05
	OSD	12.9	
Row Spacing	RS23	12.2	n.s.
	RS60	12.1	
Timing of N	N @ Z15	12.0	n.s.
	N @ Z31	12.2	
Genotype	Silverstar	11.5	P < 0.001
	Wyalkatchem	12.8	

5.3.9 Water use efficiency

Water use efficiency (grain yield / evapotranspiration, see Table 5.7) was not significantly affected by rainfall distribution (P = 0.106) but tended to be higher in the OSD treatment (10.6 kg/ha.mm) compared to GSD (7.1 kg/ha.mm). Row spacing had a significant effect on WUE (P < 0.001) with RS_{23} producing more grain yield per unit of evapotranspiration than RS_{60} (9.9 kg/ha.mm and 7.8 kg/ha.mm respectively). The timing of N application also had a significant impact (P < 0.05) on WUE. When N was applied earlier in the season at Zadoks growth stage Z15 (tillering) WUE was 9.4 kg/ha.mm while when it was applied at growth stage Z30 WUE was 8.4 kg/ha.mm.

5.4 Discussion

5.4.1 Effect of rainfall distribution

This experiment showed that good water storage before seeding can result in grain yields comparable to those when soil water becomes available during the growing season. Close to 150 mm of water was applied to the OSD treatment before seeding, which resulted in about 50 mm of stored plant available water (30 percent efficiency). This of course was an artificial situation with regulated irrigation and not natural rainfall which falls in irregular amounts and at irregular intensity. A study on the efficiency of soil water storage after the summer-autumn fallow period in southwest Australia suggested an average fallow efficiency of 25 percent and a range of 7 to 40 percent (Dolling et al. 2006). Evaporation was the largest component of soil water loss, but transpiration by weed plants contributed up to 44 percent of soil water loss when weeds weren’t controlled, emphasising the importance of summer weed control to maximize fallow efficiency. A study in the similar climate of north-western Victoria showed summer weed control to be the most important factor to fallow efficiency (Browne et al. 2010).

This experiment showed that with the relatively small canopy and low plant density, the water stored in the soil in autumn was sufficient to sustain the crop with no rain after July (121 mm from May to July) and produce grain yields of up to 2 t/ha (23 cm row spacing). When rainfall was growing season dominant, water-use-efficiency tended to be lower, probably because of a larger soil evaporation component. Evaporation was estimated to account for 68 percent of ET in the GSD treatment compared to 57 percent in the OSD treatment. Evaporation tends to be greater in sparse crops when the soil surface is wet (Ritchie 1983) and forms a large proportion of evapotranspiration (ET) in southwest Australia. Other experiments conducted close to the site of this experiment showed that evaporation accounted for about 40 percent (Siddique et al. 1990) to 60 percent (Yunusa et al. 1993) of total ET. The extra water available in the subsoil of the OSD rainfall treatment would have also contributed to higher individual grain weight and grain yield, as Kirkegaard et al. (2007) showed that subsoil water can contribute to high water use efficiency of soil water after anthesis (up to 59 kg/ha.mm).

Grain yields were reduced in the GSD rainfall distribution treatment due to yellow spot disease. APSIM modelling (assuming no disease) suggested that in the absence of the disease, dry matter would have been significantly greater in the treatment, but grain yield about the same, as water extraction by the larger (uninfected) canopy would have left less soil water available for grain production (Figure 5.18).

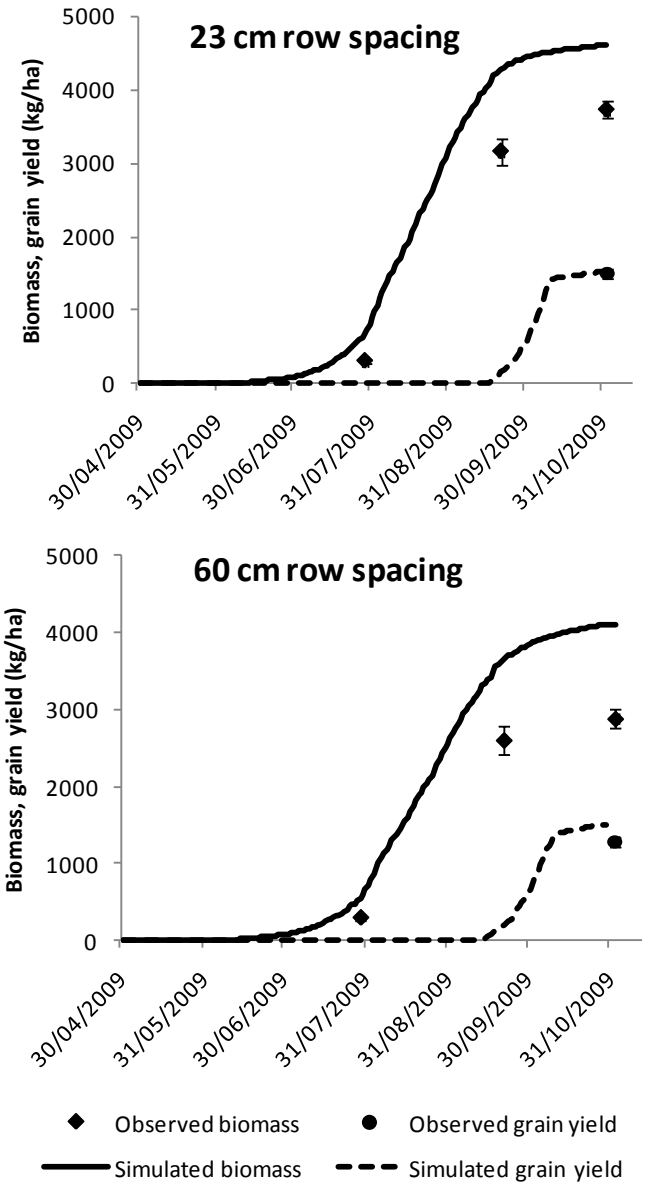


Figure 5.18: Estimating the impact of disease on biomass accumulation over time in the GSD treatment. Merredin 2009.

5.4.2 Effect of row spacing

Increasing row spacing reduced grain yield and a number of yield components. Increased competition for light, water, and nutrients in the crop row early in the season is expected as more plants are placed into a single row. The results show that this early competition reduced the number of tillers on plants in the wider rows, which in turn reduced head density (heads per unit area) at harvest, even though plant establishment in the wider row spacing was better (due to less soil throw and shallower sowing). Reduced head density in response to widening row spacing has been commonly recorded in the literature (Chen et al. 2008; Doyle 1980; Johnson, Witters, and Ciha 1981; Kleemann and Gill 2010).

More surprising was the reduced numbers of grains in each head in wide rows. The soil water between tillering and anthesis was similar for the two row spacing treatments in both rainfall distributions and so it is unlikely to be due to water stress. Kleemann and Gill (2010) found that grains/head decreased when row spacing increased from 36 cm to 54 cm in two out of their three experiments. However, the 54 cm row spacing had more grains/head than the 18 cm row spacing in one experiment, while the opposite effect occurred in another. Other studies recorded the opposite effect to what occurred in my experiment; more grains per head as row spacing was increased (Johnson, Witters, and Ciha 1981; Tompkins, Fowler, and Wright 1991). The 2008 experiment (Chapter 4) showed no significant difference between row spacings, but there was a trend for more grains per head in the narrow row spacing. The reduction may have been due to competition for light within the row (Fischer and Stockman 1980) but this was not measured.

It wasn't until late in the season that the plants sown on wide rows were able to take advantage of extra soil water, which increased individual grain weight and harvest index in wide rows in the GSD treatment, but not in the OSD treatment, as the OSD treatment had more soil water during grain filling. The 2008 experiment showed no significant response in individual grain weight to row spacing. The literature also produces variable results in this regard, with some studies suggesting decreases in grain weight in response to widening row spacing (Kleemann and Gill 2010), others showing no significant difference (Chen et al. 2008; Chen et al. 2010; Tompkins, Fowler, and Wright 1991), and still others showing increased grain weight in response to widening row spacing (Blackwell, Pottier, and Bowden 2006; Johnson, Witters, and Ciha 1981). The discrepancies are likely due to water availability during grain filling (Sharma and Anderson 2004). When there is late rainfall narrow rows could possibly benefit more through increased grain weight as less of the water is lost to evaporation due to a larger canopy (Passioura 2004), while wide rows might have greater grain weight when there is water stress in the post anthesis period, due to slower water use during the season and therefore more available water after anthesis (Tompkins, Fowler, and Wright 1991).

As was the case in the 2008 experiment, the RS_{60} treatment had more residual water (15 mm) left over at the end of the season than the RS_{23} treatment. Given that late season water use is very efficient at being converted into grain (Kirkegaard et al. 2007), an extra 15 mm could potentially have been converted into 885 kg/ha extra grain (59 kg/ha.mm).

For the soil water that was used by the crop (ET), the narrow row spacing treatment was more efficient in converting it into grain (increased WUE). This was also the case in the 2008 experiment and is likely due to a greater amount of transpiration as a proportion of total ET

(Eberbach and Pala 2005; Johnson, Witters, and Ciha 1981; Tompkins, Fowler, and Wright 1991).

5.4.3 Interaction of row spacing with rainfall distribution

There was no row spacing by rainfall distribution interaction for grain yield that would suggest wide rows perform comparatively better when rainfall is out of season dominant. In fact, as a percentage, the yield penalty for wide rows was less in the growing season dominant treatment (17 percent versus 24 percent in OSD), due to increased individual grain weight in wide rows in GSD. This is understandable when you consider that the OSD treatment had greater soil water at depth during grain filling (Figure 5.6). Figure 5.18 suggests that in the absence of yellow spot disease, which affected biomass accumulation and water use in the GSD treatment, the yield penalty would have been even less in wide rows in the GSD treatment.

In the 2008 experiment, there was a surprisingly large amount of residual soil water in the wide row treatment in the heavily droughted OSD treatment. The individual grain weights indicated extreme water deficit during grain filling, even though there was water available in the soil profile. It was suggested in Chapter 4 that the reason for this may have been an underdeveloped root system as a result of glyphosate spray drift, early in the crops life cycle. The residual soil water levels in wide rows in this experiment were less substantial than in that treatment in 2008 (15 mm averaged across both rainfall distribution treatments versus 34 mm) in 2008, which would suggest the glyphosate did affect the crops ability to access soil water.

Therefore, the hypothesis that crops grown in wide rows will perform comparatively better when rainfall is out of season dominant cannot yet be answered, based on the findings of these two experiments. In the first year of OSD rainfall, the data was likely affected by spray drift and in the second, there was no terminal drought as a result of the OSD treatment and in fact, the GSD treatment had less soil water during grain filling. The treatment that showed the most obvious signs of water deficit after anthesis as a result of vigorous early growth, which resulted in wide rows being comparable to narrow rows in grain yield but with larger grains, was the fallow treatment. As this was not a part of the main experiment and was not fully measured and replicated, no firm conclusions can be drawn from it. Variable seasons are common in low rainfall parts of southwest Australia, which is why simulation modelling ran over a number of years, can provide a better understanding of the impact of changes in management. Long-term simulation modelling involving row spacing is conducted in Chapter 6.

5.4.4 Interaction of row spacing with genotype

The genotype Wyalkatchem, which generally has a greater individual grain weight than Silverstar, increased in individual grain weight more than Silverstar when sown on the wider rows. Wyalkatchem was also better able to maintain head density when row spacing was increased and accordingly showed less yield penalty in wide rows when compared to Silverstar. Results in Chapter 4 suggested a similar trend with wide rows decreasing grain yield in Silverstar by 46 percent compare to 30 percent in Wyalkatchem. The reason for this is not known. It could be different root architecture allowed Wyalkatchem to explore more of the inter-row space in wide rows. A study by Manschadi et al. (2008) looking at root architecture of seedlings from a range of wheat genotypes found that Wyalkatchem tended to have greater seminal root angle while Silverstar tended to have a greater number of seminal roots.

Another possibility is that the morphology shown in Wyalkatchem (short erect leaves) increased light quality (red:far red) to the tiller buds, which results in less reduction in the number of tillers when plants are concentrated within the row at wider row spacing (when sown at the same seed rate), as has been found to occur in grasses sown at high density (Simon and Lemaire 1987). Increased number of tillers per plant is likely to result in an increased number of heads and also nodal roots, which may explore a greater portion of the inter-row space, which in turn could increase grain weight late in the season.

A larger increase in grain weight in Wyalkatchem could also be a result of slightly longer phenology, giving access to late season soil moisture found in the inter-row of the wide rows. In the previous years' experiment the longest season genotype, Halberd, had grain yields in wide rows and narrow rows that were closer than for the shorter-season genotypes. Amjad and Anderson (2006) also suggested that the reason the longer-seasoned genotype Camm did comparatively well in wider rows against shorter-seasoned genotypes is a longer growing period and greater biomass. The 2008 experiment also found that the two genotypes that had larger canopies early in the season performed comparatively better in the wide rows, suggesting that early vigour could be important in such a planting arrangement. The possible reasons may be more shading of the interrow that results in more competition with weeds through greater leaf area index (Olsen and Weiner 2007) and reduced evaporation from greater ground cover (Passioura 2004). Adding support to this argument, an early application of N fertiliser was found to be advantageous in wide rows when water was not limiting, due to greater LAI at stem elongation and biomass at anthesis.

The above discusses traits useful for increased grain yield in wide rows which farmers, researchers and wheat breeders may wish to consider. Crop row spacings seemingly continue to widen in southwest Australia associated with practical benefits of increased sowing speeds

and timeliness of sowing, reduced horsepower requirement (fewer tines per sowing implement), possibilities of inter-row spraying, reduced cost of seeding equipment (Jones and O'Halloran 2006). However, the commonly perceived advantage of drought proofing the cropping system has proved unfounded at row spacings as wide as were used in this research, and in other literature discussed earlier.

5.4.5 Interaction of rainfall distribution with genotype

There was very little evidence in this study to suggest that the two genotypes tested here performed differently under contrasting rainfall distributions, even though they contrasted greatly in the way they constructed yield.

5.4.6 Interaction of nitrogen timing with row spacing

In an experiment that had low plant density, applying the second N application earlier in the season (at tillering) resulted in greater head density, which in turn resulted in increased grain yields. Water use efficiency was also greater when N was applied earlier, possibly due to greater surface shading and a reduce evaporation component of ET (Passioura 2004).

The timing of nitrogen treatment was included in the experiment partly because it was hypothesised that it would interact with row spacing. Because head density was an important limitation to grain yield in wide rows in the 2008 experiment, it was thought that an application of N at tillering would increase head density and therefore grain yield in wide rows. While the earlier applied N treatment did tend to increase head density in wide rows, there was no significant effect with row spacing.

5.5 Conclusions

This experiment showed that good storage of soil water at sowing (~50 mm) can result in good wheat yields (~2 t/ha, for low-rainfall southwest Australia) even when the following in-season rainfall is historically low relative to the long term average (less than 125 mm) and there is no rainfall after stem elongation. When this result is contrasted with the out of season dominant rainfall treatment in the 2008 experiment, the importance of water storage efficiency is highlighted.

It has been generally thought that the yield penalty suffered by widening row spacing becomes greater as yield potential increases. The results from this experiment suggest that there are environmental conditions that make wide row grain yields comparable with those of narrow rows. These are the environmental conditions that promote large amounts of biomass to be produced before anthesis, such as early establishment, high plant density and high amounts of soil water and nitrogen. These conditions create a high water demand after anthesis. When soil water is limited late in the season and plant demand of soil water far

exceeds available supply then individual grain weight and even grain yield can suffer. When these conditions don't occur, a lack of head density can (and usually does) result in reduced grain yield in wide rows. Two years of experiments showed that widening row spacing slowed evapotranspiration rates so that more soil water was available to the crop during grainfill. However, the crop grown on wide rows was unable to fully utilise the extra available soil water and left more water in the soil at maturity than the narrow row spacing. Estimated soil evaporation was also higher in wide rows than narrow rows, meaning wide row crops transpired less water than narrow row crops. This thesis has described two field experiments testing the effects of widening row spacing over four site years, representing traditional and trending rainfall patterns. These results can be extrapolated over many more historic and expected future seasons with the use of simulation modelling.

This experiment added to the finding from the previous year's experiment of genotypic interaction with row spacing in wheat, a finding not yet described in the literature. The yield differential between wide and narrow rows varied with genotype and tended to be associated with head density, early vigour and longer phenology. This may have implications for breeders if producers continue to widen row spacing to lower costs and increase the speed of and therefore timeliness of sowing.

Further research is required to determine the comparable performance of wide rows to narrow over a range of seasons and in the light of rainfall trends and projections due to climate change. This is addressed in the following chapter of this thesis.

Chapter six

Effect of simulated agronomic management factors on wheat yield under historical and predicted changes in rainfall

"When everything seems to be going against you, remember that the airplane takes off against the wind, not with it"

- Henry Ford

6. Effect of simulated agronomic management factors on wheat yield under historical and predicted changes in rainfall

6.1 Introduction

Chapters 4 and 5 discussed results from two field experiments that investigated the effects and interactions of rainfall distribution, row spacing, genotype (Chapters 4 and 5) and timing of nitrogen application (Chapter 5 only). Two rainfall distribution treatments were imposed in both experiments, one with a typical mediterranean-type rainfall pattern of dry summer and autumn and wet winter and the other with increased out of season rainfall and decreased winter rainfall (as has been the trend in parts of the southwest Australian wheatbelt). The experimental results suggested that with good water storage (47 mm) before sowing, grain yields of 2 t/ha can be achieved, even when growing season rainfall is less than 125 mm and there is no rainfall after stem elongation. Estimated in-season evaporation calculations suggested that the proportion of E in ET was less when the crop was grown partly on stored water.

Increasing row spacing from 60 cm to 23 cm decreased grain yields in all rainfall distribution treatments mostly due to reduced head density and grains per square metre. Widening row spacing slowed evapotranspiration rates (ET) so that more soil water was available for use during grainfill, but the crop grown on wider rows failed to make use of the additional soil water after anthesis and left more water in the soil at maturity than the narrow row spacing. The two field experiments tested the effects over four site years, managed to represent traditional and trending rainfall patterns. Simulating modelling has been recognised as a valid method of testing agronomic options over a number of years (Fischer 2011) provided the model is sensitive to the major mechanisms operating and has been validated as doing so. When validated, the model can be used to test agronomic options in different time periods to test for interactions.

Bates et al. (2008) investigated climatic changes in the southwest of Australia and observed a substantial decline in rainfall, particularly for early winter months (May – July), after 1975. Ludwig, Milroy and Asseng (2009) used the post-1975 ‘drop off’ in rainfall to investigate how recent climate change has affected wheat yields at various locations in the southwest Australian wheatbelt. In their analysis, locations were generally in the medium rainfall zone (~ 325 to 450 mm annual rainfall) and with the use of the APSIM crop model they determined there to be no significant change in grain yields before and after 1975 even though at most locations there was a decline in winter rainfall. It was determined that most of the decline in

rainfall occurred at times of the year when soil water was in excess and often lost to deep drainage. The study also included nitrogen strategies as part of the analysis, which generally found wheat to be more responsive to nitrogen before 1975.

The focus of the current investigation was on the more marginal parts of Australia's southwest wheatbelt (≤ 325 mm annual rainfall) to determine the effect of recent climate change on wheat grain yield and individual grain weight. An analysis of changes in rainfall in this thesis (section 2.4.1) at eight locations in low rainfall parts of southwest Australia showed slightly different trends in different parts but generally showed reductions in winter rainfall and increases in out of season rainfall after 1975 (Figure 6.3).

Also tested in this investigation were row spacing, nitrogen and phenology interactions with historical and plausible future climates. It has been proven that nitrogen rates (Norton and Wachsmann 2006; van Herwaarden et al. 1998) and row spacing (Johnson, Witters, and Ciha 1981; Tompkins, Fowler, and Wright 1991) can affect the rate of water use by the crop. It was hypothesised that as southwest Australia dries and out of season rainfall (Nov-Apr) increases in some parts, it will be advantageous to grain yield and individual grain weight to widen row spacing (Chapter 1). In two experiments consisting of four rainfall distributions (Chapters 4 and 5), this failed to be the case. Simulation modelling over a greater range of seasons would allow a better understanding of the full impact of altering row spacing on grain yield in low rainfall southwest Australia.

Soil water, crop growth and development, grain yield and individual grain weight data were taken from a field experiment conducted at Merredin Research Station in 2009 (see Chapter 5) and used to calibrate the Agricultural Production Systems Simulator (APSIM) (Keating et al. 2003) version 7.1. The methods used to collect and analyse data in that experiment can be viewed in the previous chapter. The calibrations derived from this data were used in long term simulations to investigate wheat grain yield and individual grain weight using historical and projected future climate data.

6.2 Materials and methods

6.2.1 The APSIM Model

The APSIM crop model allows the linkage of modules to simulate crop production for a given set of management and genetic factors and a given climate and soil type. The model was developed by the Agricultural Production Systems Research Unit in Toowoomba, Queensland and has been extensively tested against field measurement in the mediterranean-type climate of southwest Australia (Asseng et al. 1998). The two modules that were parameterised in the calibration for this study were the wheat and soil water modules.

The APSIM wheat module simulates development and growth of a wheat crop on an area basis in a daily time-step. Growth and development is driven by weather (temperature and radiation), soil water and soil nitrogen. The growth module communicates information back to the soil water and nitrogen modules so that they can reset on a daily basis. Potential daily biomass production is calculated using light interception and radiation use efficiency. Reductions are made to potential biomass increments under sub-optimal temperatures, soil water and N-deficit constraints. The module simulates leaf area growth, biomass and N concentration of leaves, stems, roots and grains on a daily basis, and grain size and number.

Radiation interception is calculated from leaf area index (LAI) and a canopy extinction coefficient (*k*). Extinction coefficient is the relationship between LAI and the proportion of solar radiation intercepted by the crop and varies according to row spacing in some crop modules but not the wheat module as it stands in version 7.1.

Crop phenology in the wheat module is governed mostly by thermal time, which is determined by daily maximum and minimum temperatures and affected by vernalisation and photoperiod. Eleven crop stages exist in the model with the commencement of each stage (with the exception of sowing and germination) being determined by the accumulation of thermal time. APSIM has its own stage code but can also output Zadoks growth stage equivalents.

The wheat module is in daily communication with the soil water module to calculate the water uptake by the crop. Potential water supply is defined by simulated plant available soil water, root depth and the fraction of available water able to be extracted per day (*kl*) for each soil layer containing roots. The root exploration front has an optimal rate of elongation of 30mm d^{-1} but can be limited by high and low temperatures, dry soil and a parameter labelled *xf* that can be set for each layer. *Xf* along with *kl* can vary with crop species and soil type.

Transpiration demand is calculated by dividing the current day's crop growth rate (intercepted radiation*RUE) by the transpiration efficiency, which is related to the daylight averaged vapour pressure deficit. Crop water demand is capped to below a given multiple of potential ET. The actual rate of water uptake is the lesser of water demand and supply.

The Soil Water module in APSIM is based on previous water balance models in CERES (Jones and Kiniry 1986) and PERFECT (Littleboy et al. 1992). It is a cascading water balance in which water movement into any soil layer that exceeds the saturation capacity of that layer automatically cascades into the next.

The amount of water the soil can hold is determined by the 'bucket size'. The bottom of the bucket is the lower limit at -15 Bar or the crop lower limit that is specific to different crop types. The drained upper limit (DUL) is the content of water retained after gravitational flow,

also known as 'field capacity'. The top of the bucket is the soil at the DUL. These parameters are defined for each soil layer.

When the water content is above the DUL of that layer a fraction of the water drains to the next layer. There is also water movement between layers when the soil is below DUL. This depends on the water content gradient between neighbouring layers and the diffusivity of the soil. Unlike CERES and PERFECT the diffusivity coefficients and the proportion of soil water above DUL that drains in one day can be altered in APSIM to suit different soil types but not different soil layers.

6.2.2 Calibration

The calibration process started with choosing a cultivar within the model (Silverstar) and checking that phenology observed in the field matched that produced by the model (Figure 6.1). It was found the Silverstar phenology in the model matched the observed phenology of Wyalkatchem better than Wyalkatchem in the model. Adjustments were made to soil parameters (root front velocity and soil water extraction rate) as well as the crop extinction coefficient.

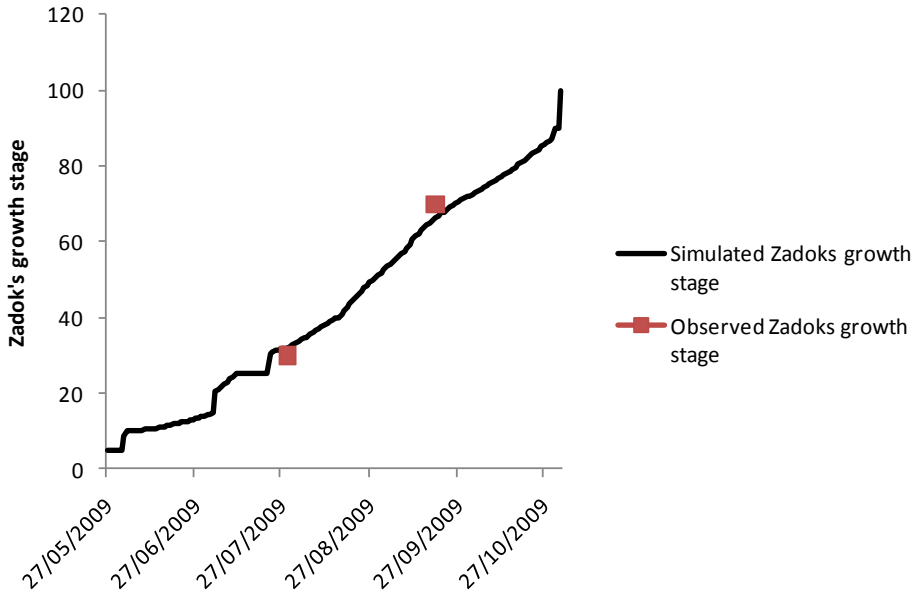


Figure 6.1: Observed versus simulated Zadoks growth stage for Wyalkatchem.

A shallow loamy duplex soil was selected from the Western Australian soils in the APSIM program and altered to match field measurements. Initial water and initial soil nitrogen levels were matched to those recorded at the start of the 2009 season in the field. N levels were considered for typical eastern wheatbelt soils. The upper and lower limit of each soil layer in the model was set based on the maximum and minimum soil water values measured by a

neutron moisture meter in the field. Viewing the soil water data for each soil layer as a time series made it possible to identify the time at which the crop roots reached that layer and the rate of soil water extraction once the roots had entered that layer. By altering these parameters in the model it was possible to match the water extraction patterns generated by the model to what was measured in the field.

This was done in conjunction with comparisons of biomass accumulation, harvested grain yield and individual grain weight. Radiation extinction coefficient in the model was lowered from the default setting (0.5) to 0.44 to better match observed to modelled biomass accumulation.

Once the model was well matched to the control treatment (RS_{23}) in the 2009 experiment (Chapter 5) another calibration was conducted for the wide row spacing treatment (RS_{60}). The previous chapter showed that RS_{60} produced less biomass, used soil water more slowly and had a higher harvest index due to heavier grains.

Three approaches were tested to achieve this calibration as there is little literature on the modelled performance of wheat crops in relation to row spacing:

a) Approach A involved mostly making alterations to the canopy light extinction coefficient (*k*). Lowering *k* reduced the amount of light intercepted by the canopy for a given leaf area index (LAI). This, in general, reduced the growth rate of the crop, which in turn lowered the water demand.

b) Approach B used mainly the root exploration factor (*xf*) to slow down the rate at which the roots explore the soil thereby reduced water supply. This in turn reduced biomass accumulation rate and soil water demand by the crop.

c) Approach C slowed down water supply by changing the rate at which the crop can extract water from a given soil layer (governed by *kl*). Slower water extraction from the 40-60cm layer in RS_{60} versus RS_{23}, in particular, was observed in the field.

The simulated data for harvest biomass, grain yield and individual grain weight from the three approaches were compared to experimental data using linear regressions to determine the best fit. Root Mean Square Deviation (RMSD) was also calculated to test which approach best matched observed data (Figure 6.2). Close attention was also paid to matching soil water in the model at each layer to that observed in the field (Appendix 3 to Appendix 6).

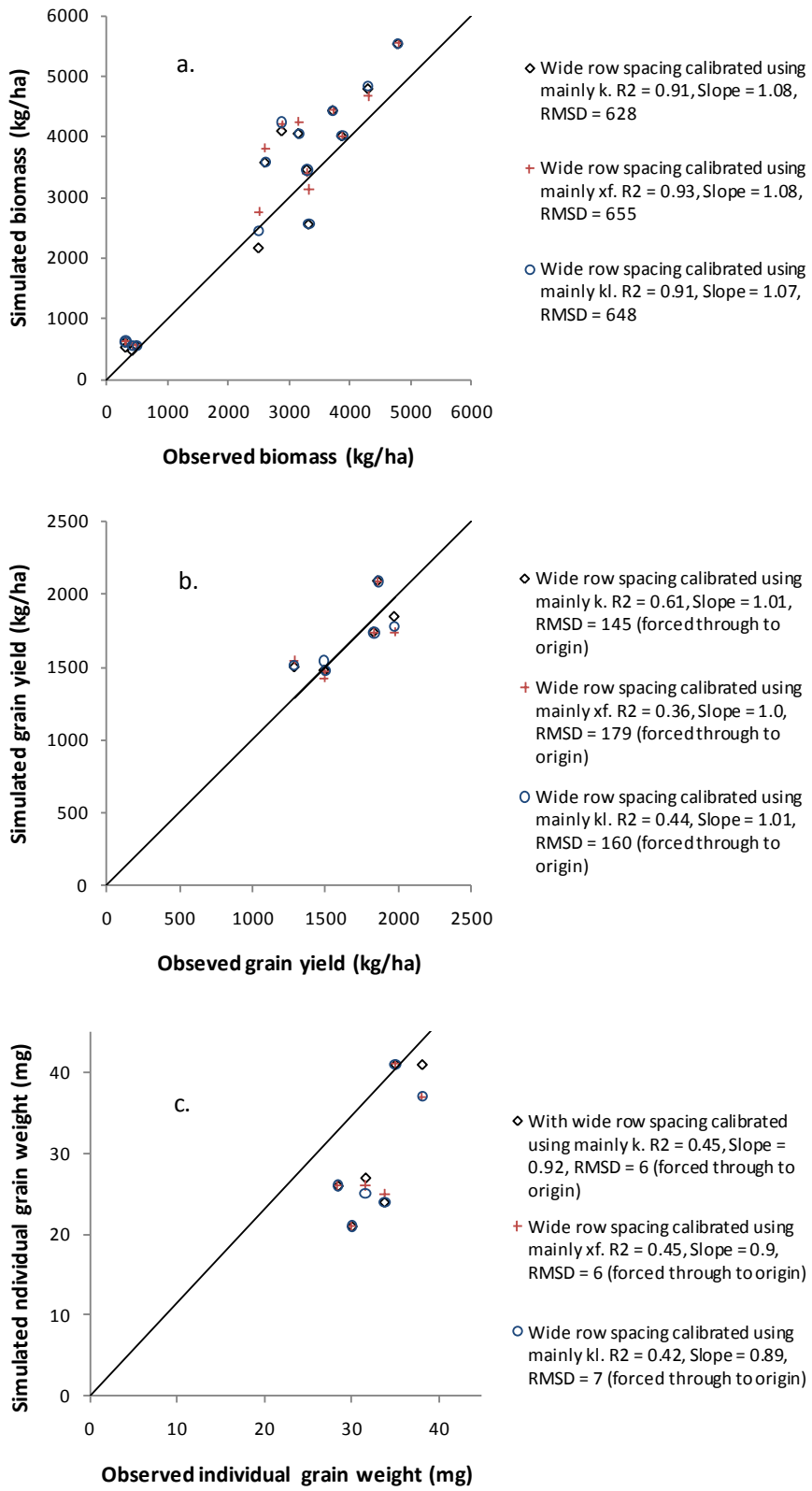


Figure 6.2: Simulated versus observed (Merredin 2009) value comparisons (RS23 and RS60 for OSD, GSD and Fallow treatments) for each approach; canopy light extinction coefficient (k), root exploration factor (xf) and water extraction rate (kl) (see text for details); for biomass (a), grain yield (b) and individual grain weight (c). Solid line indicates 1:1. See legend for R^2, Slope and RMSD values.

From this analysis it was decided that the Approach A, i.e. varying the canopy light extinction coefficient, delivered the results that best matched those observed in the field (Figure 6.2). This method is already used in the Sorghum module of APSIM version 7.1 and reduced k in widening row spacings has been found in numerous crops (Flenet et al. 1996). This approach produced the best fitting regressions, lowest RMSD's and slopes close to 1. This approach also produced well matched soil water data that can be viewed in (Appendix 3 to Appendix 6). The soil parameters used in the model can be viewed in Table 6.1.

Table 6.1: Soil parameters used for APSIM modelling

Depth	Bulk Density	Saturation	Drained Upper Limit	Lower Limit	Plant Available Water	Water extraction Coefficient Row Spacing (KL)		Root Exploration Factor (XF)
	(cm)	(mm/mm)	(mm/mm)	(mm/mm)	(mm)	23 cm	60 cm	
0-10 cm	1.6	0.35	0.1	0.02	8	0.11	0.11	1
10-20 cm	1.6	0.35	0.1	0.02	8	0.11	0.11	1
20-40 cm	1.7	0.32	0.16	0.04	24	0.11	0.1	0.5
40-60 cm	1.7	0.3	0.28	0.165	23	0.04	0.02	0.35
60-80 cm	1.7	0.3	0.28	0.18	20	0.02	0.015	0.35
80-100 cm	1.7	0.3	0.25	0.18	14	0.02	0.015	0.35

6.2.3 Recent climate change simulations

APSIM was set up to run simulations from 1940 to 2009 using observed and interpolated weather data from the eight locations indicated in Table 6.2 (see also section 2.4.1). The locations were chosen for geographical spread along the low rainfall zone of the southwest Australia wheatbelt (Figure 6.3).

Sowing rules were put in place to govern the simulation of sowing date. The sowing window was between May 1 and June 15, and sowing was triggered when a total of 10 mm of rain was recorded in the preceding three days, with no stored soil water requirement. If the sowing rule was not satisfied before June 15 the crop was sown on that day. The crop was sown at 150 plants per metre square.

In addition to the 'Location' treatment, two row spacing, three nitrogen and two phenology treatments were included in the simulation set. Data were analysed in two separate time periods to judge the effect of climate change post 1975 (Table 6.2). All treatments were combined factorially.

Table 6.2: Treatments included in long-term simulations.

Treatment	Labels	Description	GRDC Agroecological zone
Location	Mullewa Perenjori	Northern* (Agzone 4)**	WA Northern
	Bonnie Rock Southern Cross	Eastern (Agzone 4)	WA Eastern
	Dalwallinu[1] Merredin[2]	Central (Agzone 4)	WA Central WA Eastern
	Hyden Salmon Gums	Southern (Agzone 5)	WA Central WA Mallee and Sandplain
Nitrogen	50N Upfront 20N Upfront	50 units of UreaN @ sowing 20 units of UreaN @ sowing	
	50N Split	20 units of UreaN @ sowing + Additional 30 @z30	
Row spacing	RS_{23}	23cm row spacing	
	RS_{60}	60cm row spacing	
Phenology	Short-seasoned	Very Early maturing APSIM genotype - Silverstar	
	Long-seasoned	Mid-late maturing APSIM genotype - Calingiri	
Time	Pre-1975	1940-1974 (35 years)	
	Post-1974	1975-2009 (35 years)	

* Selection criteria in this study based upon ~325 mm annual rainfall or less and geographical spread across the southwest wheatbelt.

**Agzones have been developed by the Department of Agriculture and Food, Western Australia through statistical approaches to group together environmental regions that give similar crop performance.

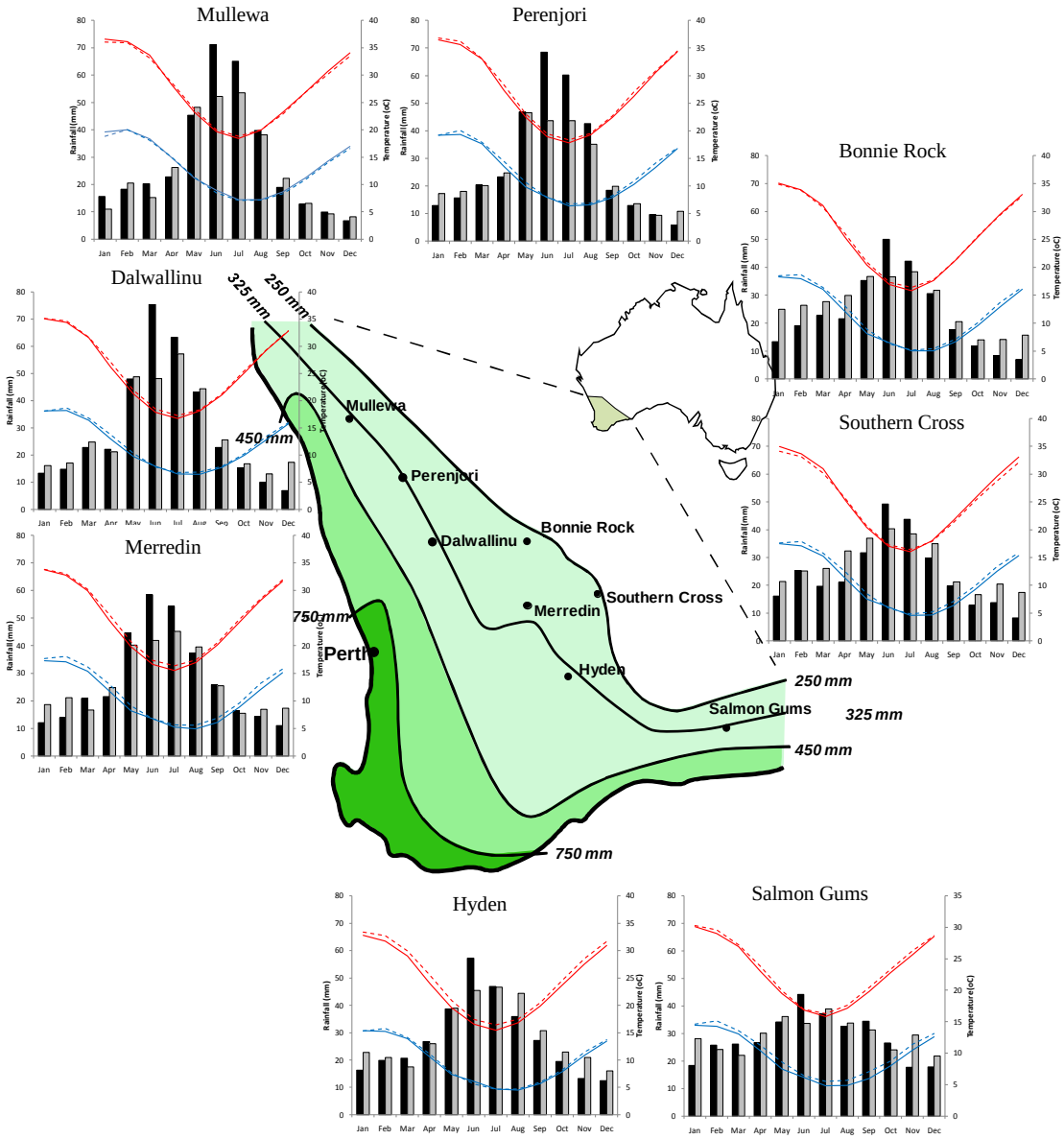


Figure 6.3: Rainfall (columns), average minimum temperatures (blue lines) and average maximum temperature (red lines) before and after 1975 for each location according to region. Dark columns and solid lines indicate before 1975.

Soil water and nitrogen were reset on January 1 each year. Soil water was set back to nil plant available soil water and the nitrogen profile was reset according to that measured in the experimental field site before the 2009 Merredin experiment.

Data analysis

GenStat software was used to conduct a general Analysis of Variance (ANOVA) and Tukey's post-hoc comparisons. Two analyses were conducted: the first including 'Location' as a treatment to investigate interactions between Location and other treatments and the second analysis compared treatments within each Location. The analysis involving all locations had 560 simulations (70 years and eight locations) creating the necessary variance for analysis while analysis within location included 70 simulations (70 years of climatic data).

The percentage of the Total Sum of Squares explained by each factor and interaction was used to determine those factors and interactions that were deemed more important by accounting for more variance.

6.2.4 Plausible future climate simulations

Two plausible climatic futures were created to represent the span of what could occur across southwest Australia by 2030. The CSIRO's Ozclim climate change generator (www.csiro.au/ozclim) was used to generate plausible changes in monthly temperatures and rainfall for a grid of longitude and latitudes across Australia. Figures were taken from the global position closest to the eight locations mentioned above and applied to daily observations for the 1975-2009 time period.

The first scenario represents a pessimistic (hotter and drier) plausible future generated using the CSIRO-Mk3 Global Circulation Model married with the SRES Marker A2 emissions scenario and the high rate of global warming. Emissions scenarios in OzClim are based on the Intergovernmental Panel on Climate Change (IPCC) fourth assessment report (IPCC 2007). Scenario A2 (SRES Marker A2) indicates moderately high CO_2 emissions, increasing throughout the 21st century. The rate of global warming comes from the same source. The effects on the emissions scenarios and rate of warming become greater as the 21st century progresses while difference between climate models are important in the early years of projection.

The second scenario represents a more optimistic plausible future and was generated using the Max Plank Institute model ECHAM5/MPI-OM from Germany. The emissions scenario used was SRES MarkerA1B which indicates medium CO_2 emissions, peaking around 2030, with a low rate of global warming.

Two GCM models were used at the suggestion of Bryson Bates (pers comm. 2010) as they can vary in their outputs. The ECHAM5/MPI-OM generally predicts less change in rainfall and temperature for Australia compared to CSIRO-Mk3. Both models have been found to reproduce key features of present-day Australian climate, including means and spatial variability patterns of temperature and rainfall and were tested and used by Bates et al. (2008) in a climatic study on southwest Australia. Monthly changes according to the model outputs were distributed to individual days. Average monthly rainfall, minimum temperature and maximum temperature in the future climates are compared to historical data in Figure 6.4. Maps of Australia showing the outputs from each scenario of rainfall and mean temperature can be viewed in Appendix 7 to Appendix 16.

The same set of treatments were included in the simulations as were used in the previous analysis (Table 6.2) with the addition of another Time factor level labelled 2013-2047 to represent the adjusted climate data generated for the year 2030 (either the pessimistic of optimistic future mentioned above).

Data analysis

The data from the simulation was analysed in GenStat using ANOVA. The ANOVA included Time as a factor with an extra factor level representing the plausible future climate. The two plausible futures were analysed against historical climate separately as Time factor level '2013-2047' and then compared to each other with an added factor 'Climate Model' with levels 'CSIRO-MK3' and 'ECHAM5/MPI-OM' with the Time factor removed to test for significant differences between the two plausible futures.

Re-running experiments with residual soil water carried over

Residual soil water simulated at the end of the growing season tended to vary from treatment to treatment. If a system (i.e. wide row spacings) resulted in increased residual water in some years, the residual water may have been used by the crop in the following season, thus helping to protect against the effects of severe drought and potentially resulting in a more robust system.

To assess the value of residual water, the simulations were re-run with the initial soil water being re-set at the start of each year to the average residual water in each soil layer for a given treatment. The data were then analysed with the added factor Residual Soil Water with levels Residual and No-residual. This method did not alter the magnitude or ranking of the data, so was not used in the detailed analysis.

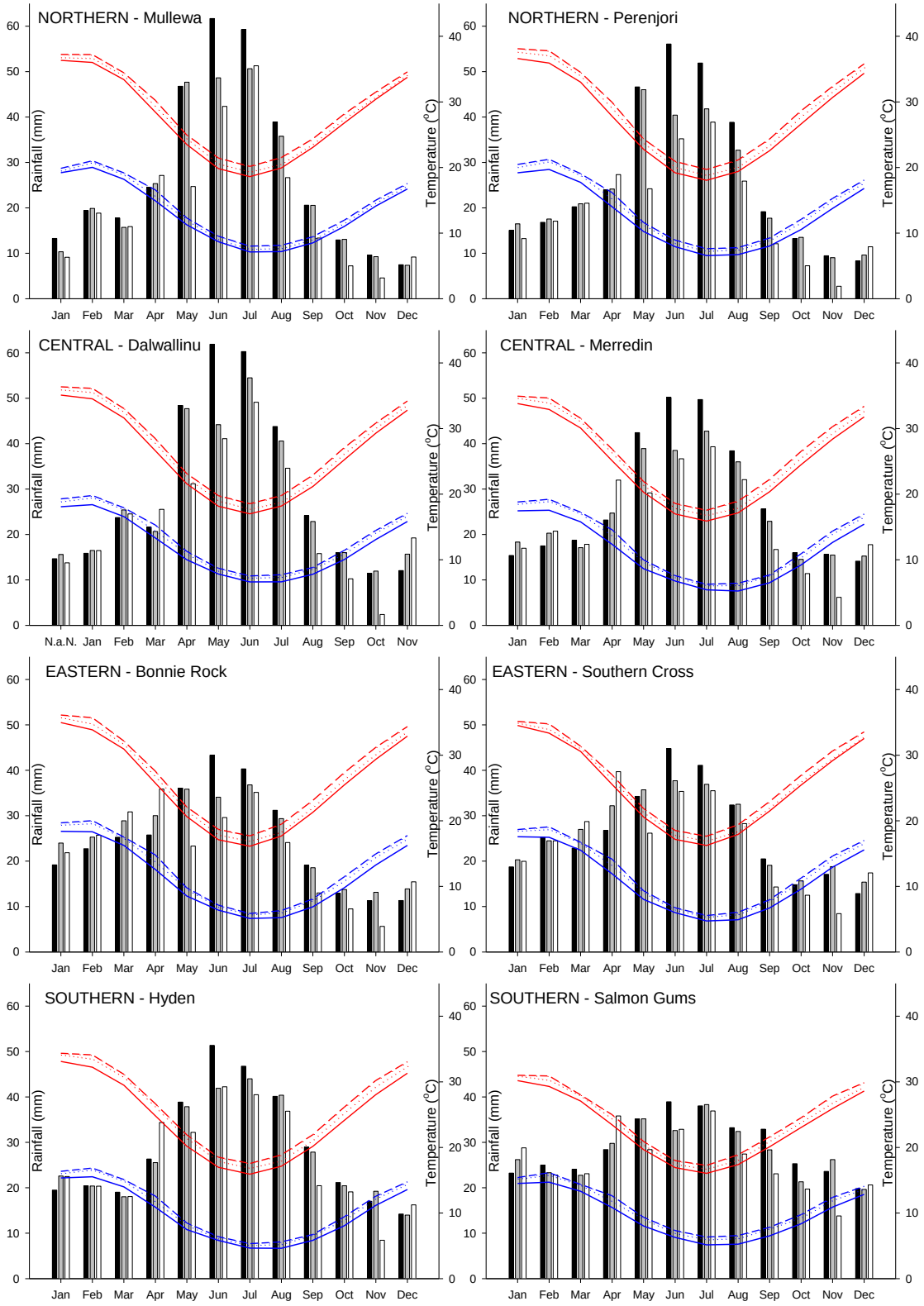


Figure 6.4: Average monthly rainfall (columns), minimum temperature (blue lines) and maximum temperature (red lines) for 1940-2009 (black columns and solid lines), optimistic future climate (grey columns and dotted lines) and pessimistic future climate (white columns and dashed lines) at eight locations in the low-rainfall area of the southwest Australian wheatbelt.

Gross margins

Gross margins were calculated based on grain and urea nitrogen prices on the 19th of January 2011 and using the following formula:

$$GM = (Grain\ price\ \times grain\ yield) - variable\ costs - (N\ price\ \times N\ rate)$$

Price was adjusted according to the quality segregation of the simulated grain based on screenings (percentage of small grain). The price given to each segregation was calculated as the average price from eight major grain buyers for that segregation. Farm gate prices were calculated as follows; $283 APW2 (Australian Premium White), $251 GP1 (General Purpose), $194 FED1 (Feed), and $190 pig feed. Screenings were derived from the simulated individual grain weight (following the correlation between individual grain weight and screenings developed by Sharma and Anderson (2004), as shown in Figure 6.5. Urea was priced at $1.20 per unit of N. Variable costs excluding N were set at $147/ha based on an actual farm budget from the target area.

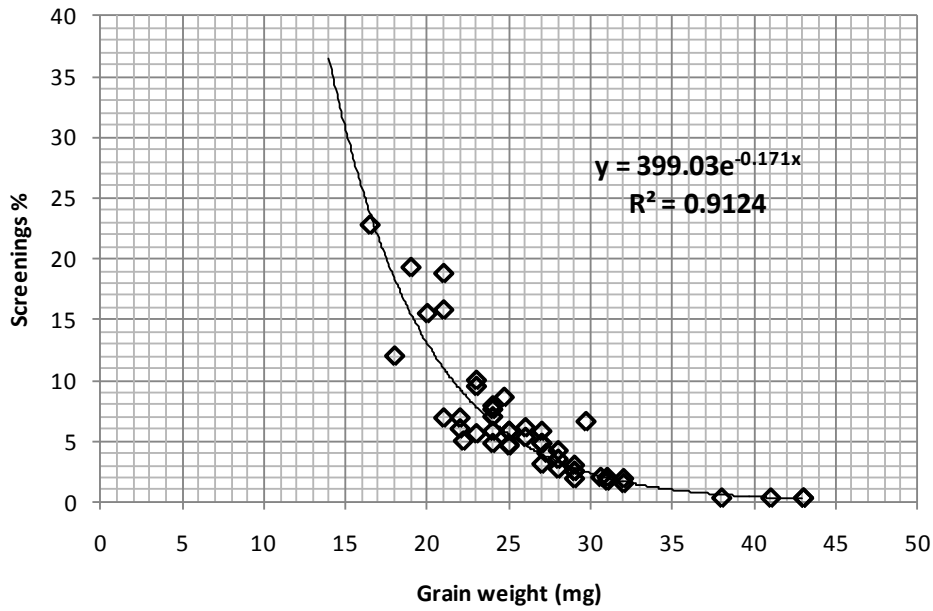


Figure 6.5: Regression used to calculate percent screenings from individual grain weight (Adapted from Sharma and Anderson 2004).

6.3 Results

6.3.1 Recent climate change simulations

Location as factor

Grain yield

All factors had a significant effect on grain yield at the highest level of significance (P < 0.001). Southern Cross, Bonnie Rock and Salmon Gums were the lowest yielding locations (averaged across both Time periods), and Dalwallinu was the highest yielding location Table 6.3). Location accounted for seven percent of the variation in yield, but residual error accounted for most of the variation within the analyses.

Table 6.3: Effect of time period (1940-74 versus 1975-2009) on simulated grain yield (kg/ha) at the eight locations in southwest Australia

Location	1940-1974 Grain yield	Coefficient of variation	1975-2009 Grain yield	Coefficient of variation	% change In yield	Average Grain yield	Tukey's comparison**
Bonnie Rock	1401	0.52	1509	0.54	8%	1455	a
Dalwallinu	2173	0.30	2024	0.42	-7%	2098	c
Hyden	1811	0.43	1938	0.41	7%	1874	b
Merredin	1919	0.42	1688	0.46	**-12%***	1803	b
Mullewa	1965	0.37	1736	0.54	**-12%***	1851	b
Perenjori	2037	0.33	1585	0.58	**-22%***	1811	b
Salmon Gums	1602	0.56	1492	0.55	-7%	1547	a
Southern Cross	1322	0.61	1564	0.50	**18%***	1443	a

* Asterix indicates significant difference in grain yield between Time periods
** Locations with same notation are statistically the same

Location interacted strongly with time (P < 0.001), accounting for 2 percent of the variation (Table 6.4). Southern Cross experienced an 18 percent increase in grain yield after 1974 relative to before 1975. Perenjori and Mullewa saw large increases in variability of yield (77 and 48 percent increase in coefficient of variation [cv] respectively) in addition to large declines in grain yield (22 and 12 percent respectively). Yields at Dalwallinu did not decline significantly but showed a 42 percent increase in variability. Merredin had a significant decline in grain yield and little change in variability.

Table 6.4: Significance and variance of all treatments and first level interactions.

Source of variation	Sig.	% of total variance	% of variance less residual
Location	<.001	7%	50%
Time	<.001	0%	2%
N	<.001	0%	3%
Row Spacing	<.001	1%	5%
Phenology	<.001	3%	20%
Location*Time	<.001	2%	12%
Location*N	1	0%	0%
Time*N	0.882	0%	0%
Location*Row Spacing	0.993	0%	0%
Time*Row Spacing	0.704	0%	0%
N*Row Spacing	0.71	0%	0%
Location*Phenology	<.001	1%	4%
Time*Phenology	0.04	0%	0%
N*Phenology	0.117	0%	0%
Row Spacing*Phenology	0.031	0%	0%
Residual		87%	

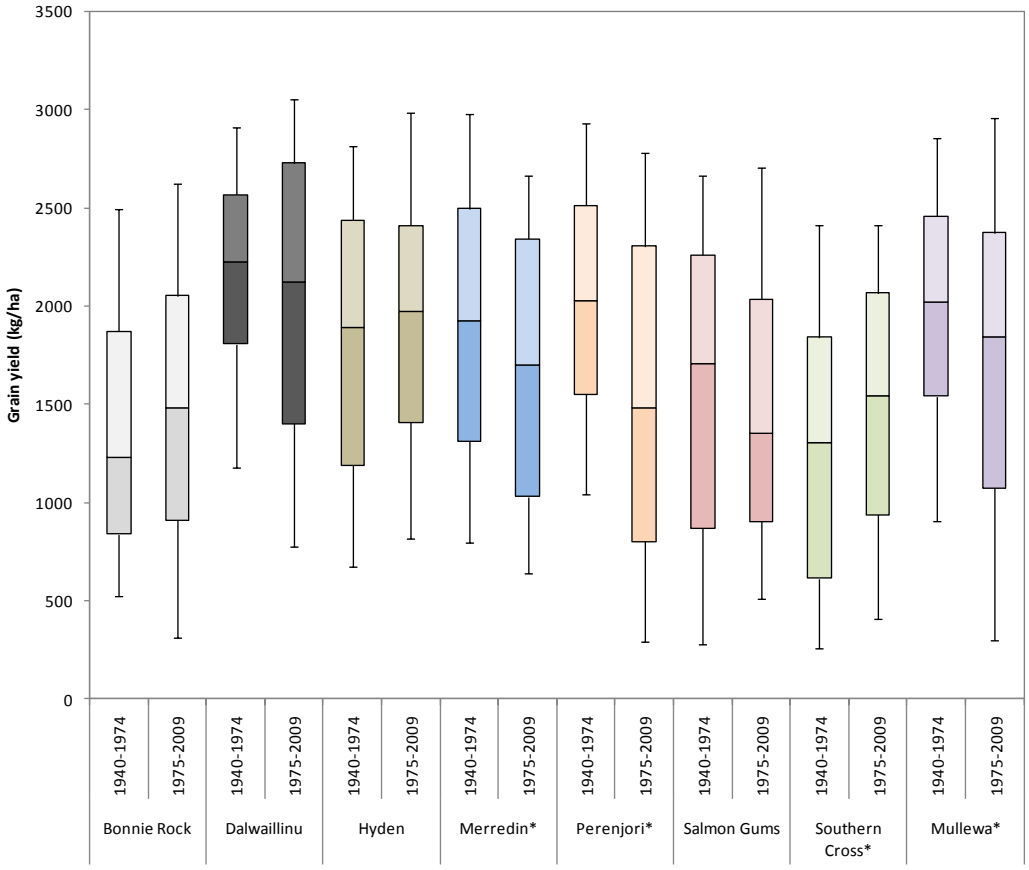


Figure 6.6: Boxplot showing the effects of location and time period (1940-1974 versus 1975-2009) on grain yield. Upper whisker = 90th percentile, upper edge of box = 75th percentile, centre line = median, lower edge of box = 25th percentile, and lower whisker = 10th percentile. * Indicates significant change in grain yield of that location between time periods.

Phenology was the second most important factor in the analysis accounting for three percent of the variation in grain yield (Table 6.4). In comparisons of phenology it is important to mention that APSIM does not simulate the effect of frost, which in reality is likely to interact with phenology in years when large frost events occur and in areas where frost damage occurs regularly. In the absence of any impact of frost, the short season genotype generally performed better with a grain yield of 1872 kg/ha when averaged across all other treatments compared to 1598 kg/ha for the long-season genotype. Phenology interacted with location ($P < 0.001$) with the two most southerly locations showing no significant difference in grain yield between the phenology treatments, while all other locations suffered yield decline when phenology was longer.

Across both time periods, row spacing accounted for just one percent of the variation in yield. While there were occasions when the wider row spacing out-yielded the narrow, generally RS_{23} was higher yielding (1804 kg/ha versus 1666 kg/ha) when averaged across all other treatments. There was an interaction between row spacing and phenology with the long season treatment tending not to suffer as big a yield penalty under the wider row spacing ($P < 0.05$). The long-seasoned variety had an average simulated yield of 1646 kg/ha in RS_{23} and 1550 in RS_{60} while the short-seasoned variety yielded 1962 kg/ha and 1783 kg/ha in RS_{23} and RS_{60} respectively.

Nitrogen impacted on yield with $20_{\text{N Upfront}}$ recording a significantly lower grain yield than the treatments involving 50 kg/ha of N. The impact of the timing of the 50 units application was not significant.

Individual grain weight

The effect of time on individual grain weight (IGW) was not as substantial as the effect on grain yield. Time as a main effect accounted for five percent of variation in IGW at $P < 0.05$. All other main effects also had a significant impact on IGW at $P < 0.001$, with the exception of row spacing, which had a significance of $P < 0.05$. There were no significant interactions with the time factor.

There was a strong interaction between Location and Time ($P < 0.001$) with a similar pattern to what occurred with the simulated grain yield. Individual grain weight at most locations tended to be lower after 1974, but Southern Cross and Bonnie Rock tended to increase although the only Locations to have significant changes in individual grain weight between the two time periods were Southern Cross (increase) and Perenjori (decrease) (Figure 6.7).

Phenology was the most important factor by far, accounting for 26 percent of the variation in IGW. When the short-seasoned genotype was averaged across all other treatments it had an IGW of 31.6 mg, compared to 22.5 mg for the long-seasoned genotype.

Phenology interacted with N and Location. At Salmon Gums, simulated IGW for the long-seasoned variety was numerically the highest of any location. However, for the short-seasoned variety it ranked sixth among locations (Table 6.5).

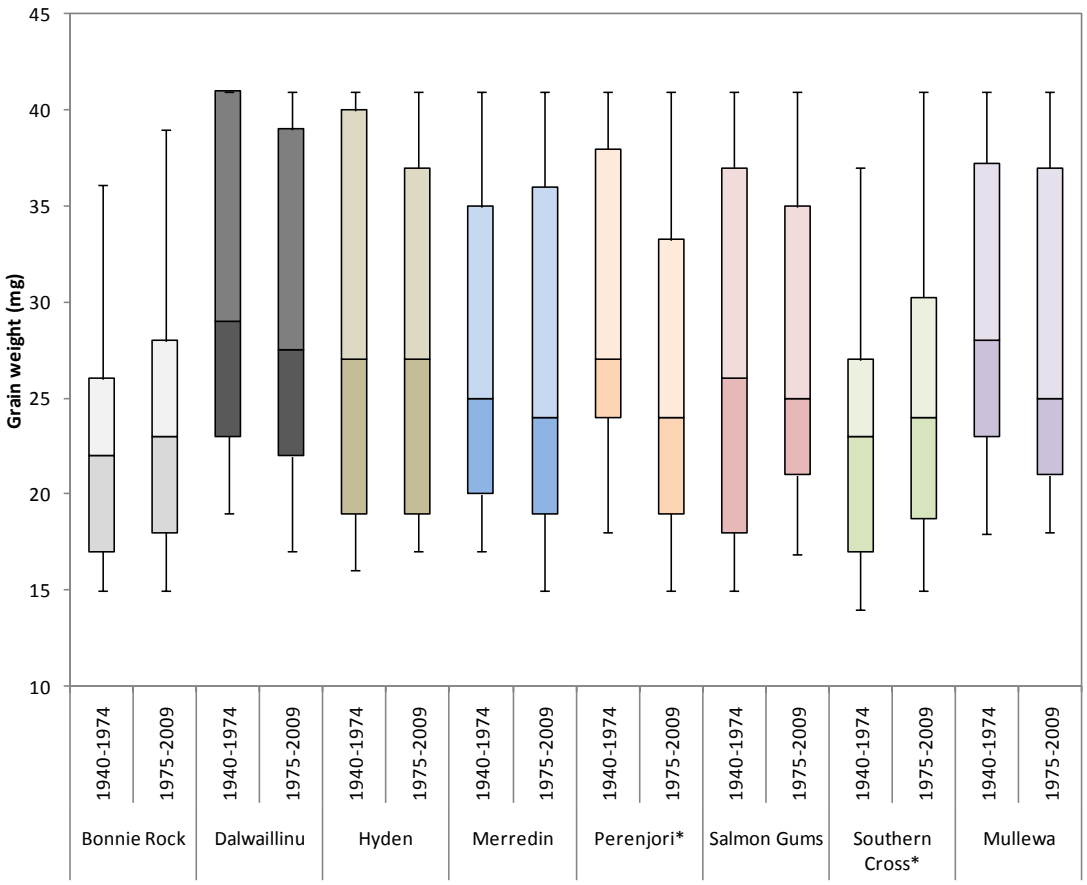


Figure 6.7: Boxplot showing the effects of location and time period (1940-1974 versus 1975-2009) on individual grain weight. Upper whisker = 90th percentile, upper edge of box = 75th percentile, centre line = median, lower edge of box = 75th percentile, and lower whisker = 10th percentile. * Indicates significant change in individual grain weight for that location between time periods.

Table 6.5: Effect of location and phenology on simulated individual grain weight.

Long-seasoned genotype			Short-seasoned genotype		
Location	mg	Tukey's comparison*	Location	mg	Tukey's comparison*
Bonnie Rock	20.4	a	Bonnie Rock	26.5	d
Southern Cross	21.0	ab	Southern Cross	28.0	d
Perenjori	22.2	bc	Salmon Gums	30.7	e
Merredin	22.5	bc	Merredin	31.8	ef
Hyden	23.0	c	Perenjori	33.1	f
Dalwallinu	23.4	c	Hyden	33.3	f
Mullewa	23.4	c	Mullewa	33.3	f
Salmon Gums	23.9	c	Dalwallinu	35.8	g
MEAN	22.5		MEAN	31.6	

* Locations with the same letter notation are not statistically different

There was a phenology by N interaction effecting IGW (P<0.01). When the short-seasoned genotype was used in the simulation there were no significant differences in individual grain weight between the N treatments. However, when the long-seasoned genotype was used, the split N application treatment produced a significantly greater individual grain weight than when 50 units of N were applied at sowing (Table 6.6), although all differences were small.

Table 6.6: Effect of nitrogen and phenology on individual grain weight

Long-seasoned genotype			Short-seasoned genotype		
Treatment	mg	Tukey's comparison	Treatment	mg	Tukey's comparison
$50_{\text{N Upfront}}$	21.8	a	$20_{\text{N Upfront}}$	31.1	c
$20_{\text{N Upfront}}$	22.5	ab	$50_{\text{N Upfront}}$	31.7	c
50N Split	23.1	b	50N Split	31.9	c
MEAN	22.5		MEAN	31.6	

Location was the second most important main effect in relation to individual grain weight, accounting for five percent of the variation. Grain grown at Bonnie Rock and Southern Cross had the lowest individual grain weight, while Dalwallinu had the greatest (Table 6.7).

Table 6.7: Effect of location on individual grain weight

Location	mg	Tukey's comparison
Bonnie Rock	23.5	a
Southern Cross	24.5	a
Merredin	27.1	b
Salmon Gums	27.3	bc
Perenjori	27.7	bc
Hyden	28.2	bc
Mullewa	28.4	c
Dalwallinu	29.6	d

Row spacing and nitrogen had significant effects on individual grain weight, but accounted for little of the variation (less than one percent). When the simulation results were averaged across all other treatments individual grain weight from the wider row spacing RS_{60} was 27.2 mg compared to 26.8 for narrower row spacing RS_{23}. The split N (27.5 mg) treatment produced a significantly greater individual grain weight than the two 'upfront' treatments (26.8 mg for $20_{N\ Upfront}$ and 26.7 for $50_{N\ Upfront}$), which were statistically the same.

Analysis within each location

The broader analysis above found there to be location by time and location by phenology interactions so additional analysis was undertaken within each location to further explore the effect of Location on grain yield and individual grain weight. Locations were grouped according to geography as illustrated in Figure 6.3.

<u>Northern parts</u>

Phenology accounted for the greatest amount of variation in yield in the analysis (six percent ($P < 0.001$) at Mullewa), with the short-seasoned genotype out yielding the long by 24 percent. Grain yield declined by 12 percent in the post-1974 period ($P < 0.001$), accounting for two percent of the variation. RS_{23} was higher yielding than RS_{60} by nine percent.

Phenology was the only factor that had a significant effect on individual grain weight ($P <0.001$), accounting for 34 percent of the variation with the short-seasoned genotype producing grains 42 percent heavier than the long-season genotype (Table 6.8).

Of all the locations Perenjori suffered the greatest yield loss after 1974. Grain yield dropped by 22 percent after 1974 and the difference between the two time periods accounted for seven percent of the variation ($P < 0.001$). Phenology was important, accounting for six percent of the variation in grain yield (short-season 2014 kg/ha versus long-season 1608 kg/ha, significant at $P < 0.001$). Phenology had a very large effect on individual grain weight, accounting for 38 percent of variation (33.1 versus 22.2 mg).

Table 6.8: Effect of time, nitrogen, row spacing and phenology on grain yield and individual grain weight in northern parts of low rainfall southwest Australian wheatbelt

Treatment		Mullewa		Perenjori	
		Grain yield (kg/ha)	Ind. grain weight (mg)	Grain yield (kg/ha)	Ind. grain weight (mg)
Time	Pre 1975	1965	29.1	2037	29.2
	Post 1974	1736	27.6	1585	26.1
	Sig	*<.001*	*ns*	*<.001*	*<.001*
	% of var.	*2%*	*1%*	*7%*	*3%*
N	20N Upfront	1764	28.1	1738	27.4
	50N Upfront	1913	28.0	1865	27.4
	50N Tact	1875	29.0	1830	28.2
	Sig	*ns*	*ns*	*ns*	*ns*
	% of var.	*1%*	*0%*	*0%*	*0%*
Row Spacing	RS23	1928	28.3	1886	27.5
	RS60	1773	28.5	1736	27.8
	Sig	*0.006*	*ns*	*0.006*	*ns*
	% of var.	*1%*	*0%*	*1%*	*0%*
Phenology	Short	2049	33.3	2014	33.1
	Long	1652	23.4	1608	22.2
	Sig	*<.001*	*<.001*	*<.001*	*<.001*
	% of var.	*6%*	*34%*	*6%*	*38%*

Eastern parts

In the eastern parts, time had the opposite effect to what it did in northern parts with grain yield increasing post-1974. For Bonnie Rock grain yield increased by eight percent (1509 kg/ha when averaged across all other treatments versus 1401 kg/ha for the pre-1975 climate) ($P < 0.05$).

Averaged across both time treatments (i.e. pre-1975 and post-1974), there were no significant differences between the nitrogen treatments. Phenology accounted for six percent of the variation and had a highly significant effect on grain yield ($P < 0.001$). The long-seasoned genotype yielded an average of 1269 kg/ha versus 1641 kg/ha for the short-seasoned genotype. Row spacing also had a significant effect on grain yield with RS_{23} (1510 kg/ha) achieving a greater average grain yield than RS_{60} (1400 kg/ha). There were no significant interactions among factors.

Phenology was the only factor that influenced individual grain weight to a significant level ($P < 0.001$) and accounted for 16 percent of the variation. The shorter season genotype produced an average individual grain weight of 26.5 mg compared to 20.4 mg. Treatment means can be

viewed in Table 6.9. As with grain yield there were no significant interactions affecting individual grain weight.

Southern Cross had the largest increase in grain yield after 1974 of any location. The modelling suggested that yields increased by 18 percent and time accounted for two percent of variation in grain yield. Phenology caused the largest amount of variation of all the factors (four percent) and with the short-seasoned genotype being higher yielding ($P < 0.001$). All N treatments produced very similar grain yields when averaged across all other treatments.

Once again, individual grain weight was heavily influenced by phenology (18 percent of variation, $P < 0.001$), while time also had a significant effect ($P < 0.001$) with average grain weights increasing post-1974 (25.5 mg versus 23.5 mg pre-1975). Nitrogen and row spacing had no significant effect on individual grain weight. There was a time by phenology interaction ($P < 0.01$) with individual grain weight increasing proportionately more in the short-seasoned variety after 1975 (29.8 mg post-1974 and 26.2 mg pre-1975 versus 21.3 mg and 20.8 mg in the long-seasoned variety).

Table 6.9: Effect of time, nitrogen, row spacing and phenology on grain yield and weight in eastern parts of low rainfall southwest Australian wheatbelt

Treatment		Bonnie Rock		Southern Cross	
		Grain yield (kg/ha)	Ind. grain weight (mg)	Grain yield (kg/ha)	Ind. grain weight (mg)
Time	Pre 1975	1401	23.0	1322	23.5
	Post 1974	1509	23.9	1564	25.5
	Sig	*0.04*	*0.066*	*<.001*	*<.001*
	% of var.	*0%*	*0%*	*2%*	*2%*
N	20N Upfront	1411	23.5	1401	24.5
	50N Upfront	1489	23.1	1479	24.2
	50N Tact	1465	23.8	1450	24.8
	Sig	*ns*	*ns*	*ns*	*ns*
	% of var.	*0%*	*0%*	*0%*	*0%*
Row Spacing	RS23	1510	23.3	1504	24.3
	RS60	1400	23.6	1382	24.7
	Sig	*0.035*	*ns*	*0.025*	*ns*
	% of var.	*1%*	*0%*	*1%*	*0%*
Phenology	Short	1641	26.5	1601	28.0
	Long	1269	20.4	1285	21.0
	Sig	*<.001*	*<.001*	*<.001*	*<.001*
	% of var.	*6%*	*16%*	*4%*	*18%*

Central parts

Grain yield declined at Dalwallinu after 1975 ($P < 0.01$). Once again phenology had the largest impact on grain yield accounting for four percent of the variation and being highly significant ($P < 0.001$). The short-seasoned genotype yielded an average of 2242 kg/ha compared to1954 kg/ha for the long. Row spacing accounted for one percent of the variation ($P < 0.001$); RS_{23} had an average yield of 2183 kg/ha while RS_{60} was lower at 2013 kg/ha. Nitrogen also had a significant impact on grain yield ($P < 0.01$) with $50_{N\ Upfront}$ out-yielding $20_{N\ Upfront}$ (Table 6.10).

At Merredin, phenology and time had the largest impact on grain yield (three and two percent respectively). The short-seasoned genotype produced a 16 percent better yield when averaged across all other treatments than the long ($P < 0.001$). Grain yield declined by 14 percent in the post-1974 period ($P < 0.001$). Row spacing had a significant impact on grain yield ($P < 0.01$) with RS_{23} increasing yield by eight percent over RS_{60}. Treatment means can be viewed in Table 6.10.

Table 6.10: Effect of time, nitrogen, row spacing and phenology on grain yield and weight in central parts of low rainfall southwest Australian wheatbelt

Treatment		Dalwallinu		Merredin	
		Grain yield (kg/ha)	Ind. grain weight (mg)	Grain yield (kg/ha)	Ind. grain weight (mg)
Time	Pre 1975	2172	30.3	1918	27.4
	Post 1974	2024	29.0	1688	26.8
	Sig	*0.004*	*0.004*	*<.001*	*ns*
	% of var.	*1%*	*1%*	*2%*	*0%*
N	20N Upfront	1990 a	29.3	1726	26.9
	50N Upfront	2181 b	29.2	1862	26.9
	50N Tact	2133 ab	30.3	1821	27.6
	Sig	*0.008*	*ns*	*Ns*	*ns*
	% of var.	*1%*	*0%*	*1%*	*0%*
Row Spacing	RS23	2183	29.5	1875	26.9
	RS60	2013	29.8	1731	27.3
	Sig	*< 0.001*	*ns*	*0.008*	*ns*
	% of var.	*1%*	*0%*	*1%*	*0%*
Phenology	Short	2242	35.8	1936	31.8
	Long	1954	23.4	1670	22.5
	Sig	*< 0.001*	*< 0.001*	*<.001*	*<.001*
	% of var.	*4%*	*50%*	*3%*	*27%*

Southern parts

Hyden saw an increase in grain yield in the 1975-2009 period ($P < 0.05$), which came mostly from an increase in grains per m^2 given that individual grain weight didn't change**.** All main effects accounted for about one percent of the variation in grain yield. The short-seasoned genotype yielded eight percent more than the long-season genotype at 1948 kg/ha compared to 1801 kg/ha. The narrow row spacing treatment RS_{23} out-yielded RS_{60} (1946 kg/ha versus 1802 kg/ha). The effect of nitrogen was not significant.

Phenology accounted for 30 percent of the variation in individual grain weight with the short-seasoned genotype producing grains 45 percent heavier than the long season genotype. There was an interaction between time and phenology also due to the differential between short and long-seasoned genotypes becoming greater after 1975. Treatment yields, significance levels and percentage of variance can be viewed in Table 6.11.

Overall, Salmon Gums responded very little to most treatments. There were no significant differences between the two time periods for either grain yield and individual grain weight. Phenology affected grain size ($P < 0.001$) but not grain yield.

Table 6.11: Effect of time, nitrogen, row spacing and phenology on grain yield and weight southern parts of low rainfall southwest Australian wheatbelt

Treatment		Hyden		Salmon Gums	
		Grain yield (kg/ha)	Ind. grain weight (mg)	Grain yield (kg/ha)	Ind. grain weight (mg)
Time	Pre 1975	1811	28.2	1602	27.4
	Post 1974	1938	28.2	1492	27.2
	Sig	*0.02*	*ns*	*ns*	*Ns*
	% of var.	*1%*	*0%*	*0%*	*0%*
N	20N Upfront	1786	27.9	1476	27.1
	50N Upfront	1943	27.9	1597	27.1
	50N Tact	1894	28.7	1568	27.8
	Sig	*ns*	*ns*	*ns*	*ns*
	% of var.	*1%*	*0%*	*0%*	*0%*
Row Spacing	RS23	1946	27.9	1602	27.1
	RS60	1802	28.4	1492	27.6
	Sig	*0.008*	*ns*	*ns*	*ns*
	% of var.	*1%*	*0%*	*0%*	*0%*
Phenology	Short	1948	33.3	1549	30.7
	Long	1801	23.0	1545	23.9
	Sig	*0.007*	*<.001*	*ns*	*<.001*
	% of var.	*1%*	*30%*	*0%*	*14%*

Phenology by row spacing interaction

There was a phenology by row spacing interaction: the yield advantage of narrow rows was generally greater at higher grain yields. Figure 6.8 illustrates the differential in grain yield between RS_{23} and RS_{60} pooled across all locations, years and N treatments, with the Y axis being the advantage or disadvantage in yield of narrow rows; (RS_{23} > RS_{60} are positive values; RS_{23} < RS_{60} are negative values). Overall there is little difference between grain yields (less that 100 kg/ha) when the yield of the narrow row spacing is less than 1500 kg/ha. The response for the two phenology types is also similar until the yield of the narrow row spacing reaches 1500 kg/ha after which yield advantage of narrow rows for the long-season genotype shows a much flatter and more variable response while for the short-seasoned genotype the advantage continues to increase as RS_{23} yield increases. For grain yield greater than 3 t/ha there is a large yield penalty (> 300 kg/ha) in the wide rows in the short-seasoned genotype.

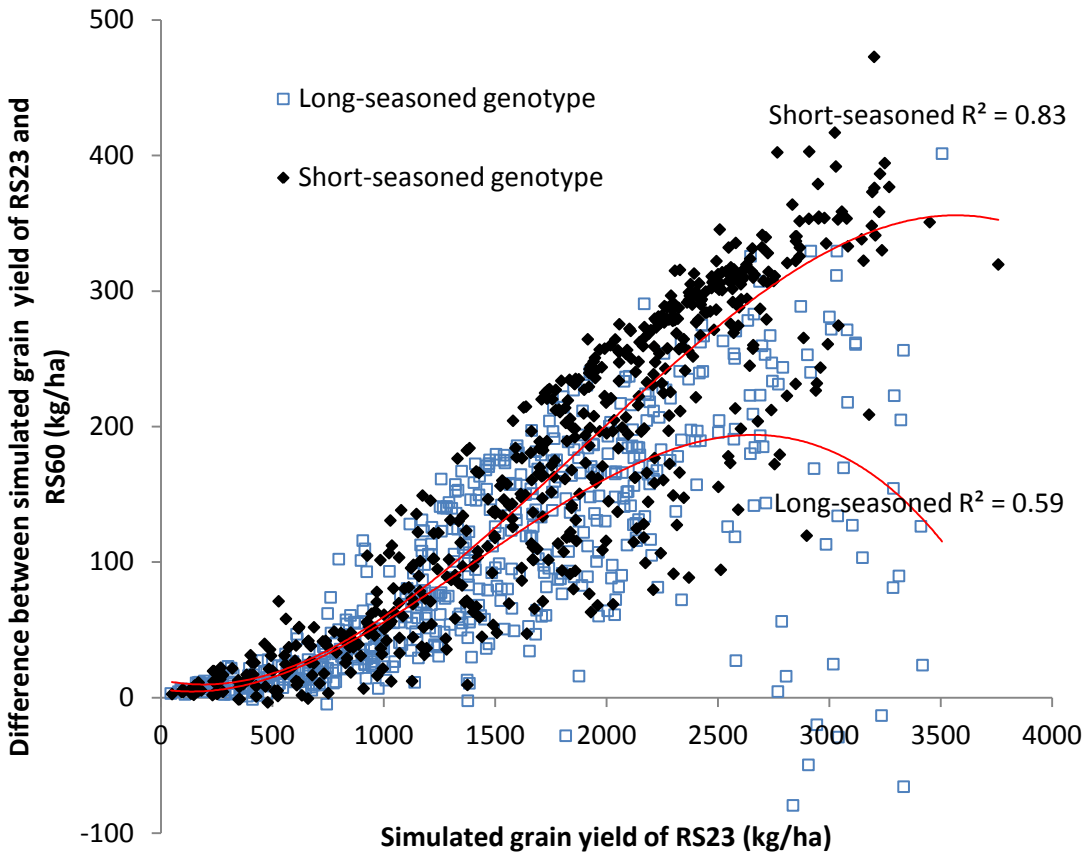


Figure 6.8: Simulated grain yield differential between RS_{23} and RS_{60} for short-seasoned and long-seasoned genotypes at all locations. Trendlines are third order polynomial regressions created for each genotype.

This trend could also be derived for individual locations where the long-seasoned genotype performed well. At Hyden, for example, there was a clear advantage in having the long-seasoned genotype in wide rows, but at Bonnie Rock, where the yield of the long-seasoned genotype was substantially lower than the short season genotype, grain yield in the long-

seasoned genotype did not exceed the point at which the differential trended down (about 2500 kg/ha) (Figure 6.9).

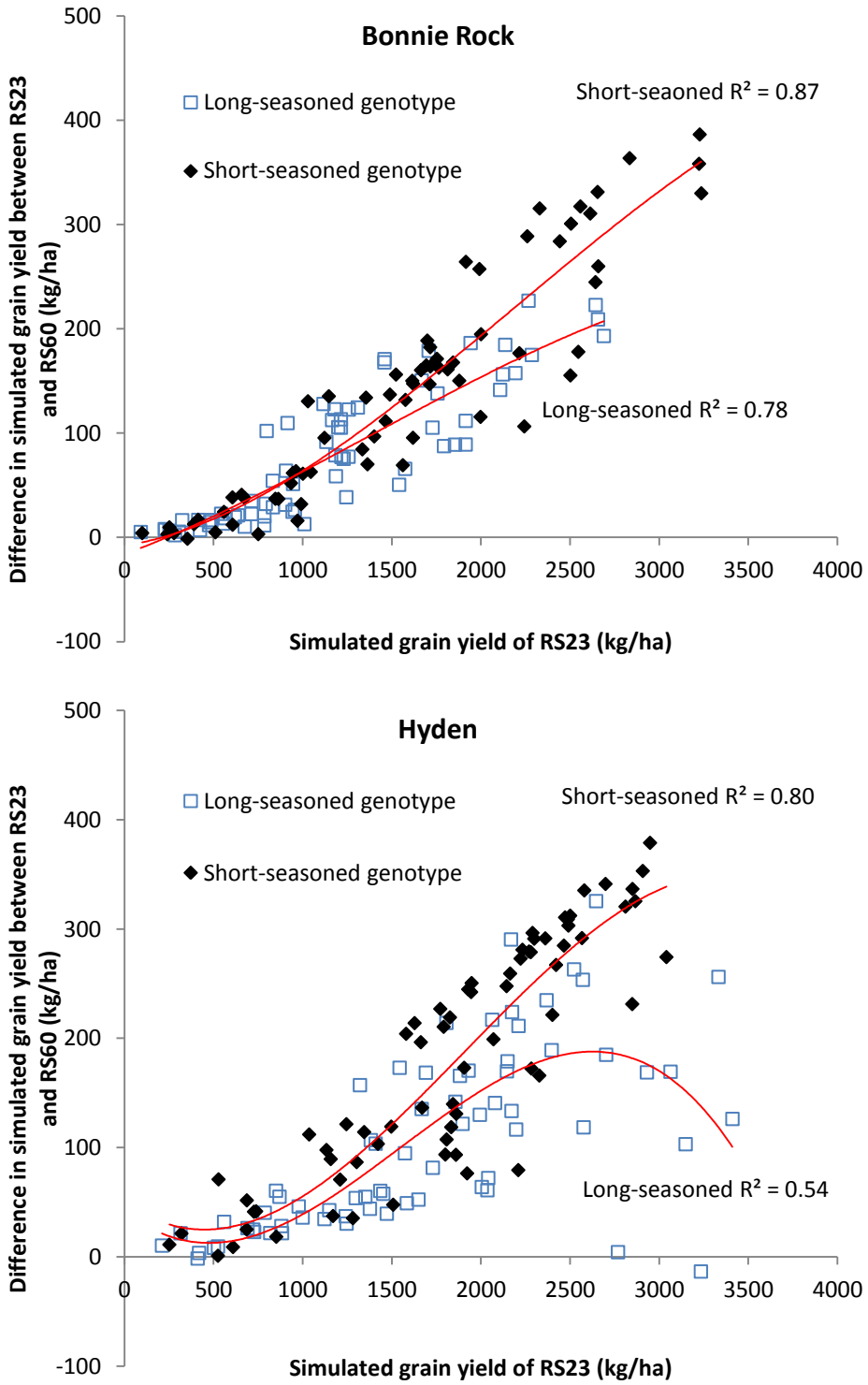


Figure 6.9: Simulated grain yield differential between RS_{23} and RS_{60} for short-seasoned and long-seasoned genotypes at Hyden and Bonnie Rock. Trendlines are third order polynomial regressions created for each genotype.

6.3.2 Plausible future climate simulations

Modelling the effect of the two plausible futures on grain yield and individual grain weight resulted in substantially lower yields at all locations when compared to the 1975-2009 period on which they were based (Table 6.12 and Table 6.13). The pessimistic future scenario always recorded significantly lower yields than the optimistic ($P < 0.01$ for all locations). The grain yield of the short-seasoned genotype often declined more than the yield of the long-seasoned genotype in the optimistic future scenario while individual grain weight increased (Table 6.12).

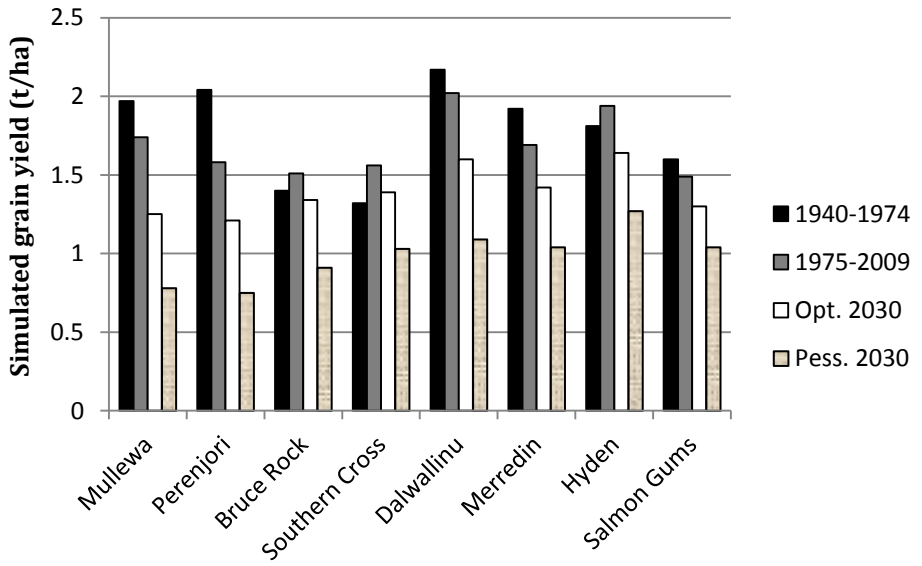


Figure 6.10: Effect of historical and plausible future climate on simulated grain yield at eight locations.

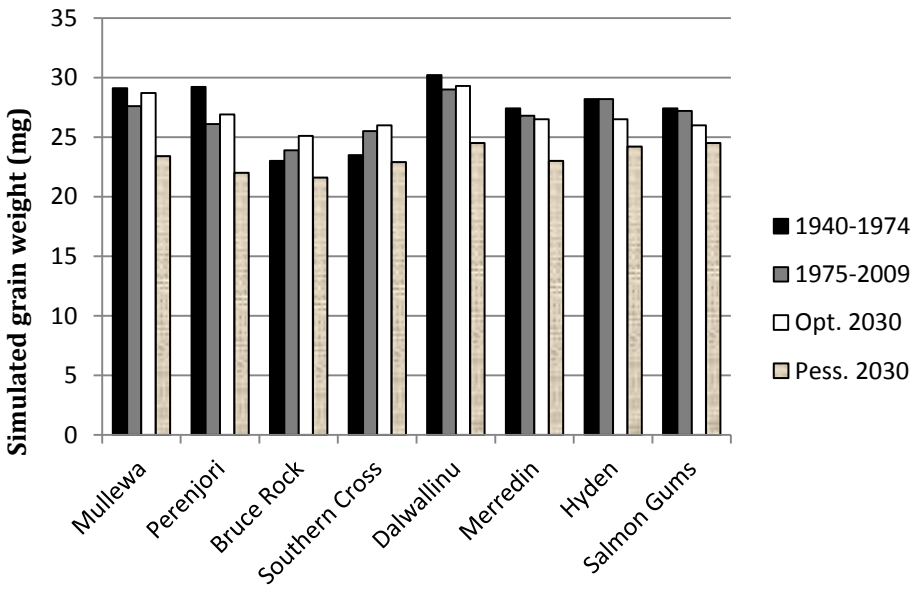


Figure 6.11: Effect of historical and plausible future climate on simulated individual grain weight at eight locations

Table 6.12: Effect of historical and plausible future climates, N, phenology and row spacing on simulated wheat yields (t/ha) at eight locations

Time	Other	Label	Northern		Eastern		Central		Southern	
			Mul.	Per.	B.R.	S.C.	Dal.	Mer.	Hy.	SG
1940-1974	N	20 upfront	1.87	1.95	1.35	1.28	2.07	1.81	1.73	1.52
		50 upfront	2.04	2.09	1.44	1.36	2.25	2.00	1.87	1.65
		Tactical	1.99	2.07	1.41	1.33	2.20	1.95	1.83	1.63
	Phenology	Long	1.81	1.85	1.24	1.17	2.06	1.82	1.73	1.62
		Short	2.13	2.23	1.57	1.48	2.29	2.01	1.89	1.59
	Row Spacing	23	2.05	2.12	1.45	1.38	2.27	1.99	1.89	1.66
		60	1.88	1.95	1.35	1.27	2.08	1.84	1.73	1.54
Mean			**1.97**	**2.04**	**1.40**	**1.32**	**2.17**	**1.92**	**1.81**	**1.60**
1975-2009	N	20 upfront	1.66	1.52	1.47	1.52	1.91	1.64	1.84	1.43
		50 upfront	1.79	1.64	1.54	1.60	2.12	1.73	2.01	1.54
		Tactical	1.76	1.59	1.52	1.57	2.04	1.69	1.96	1.51
	Phenology	Long	1.50	1.37	1.30	1.40	1.85	1.52	1.87	1.47
		Short	1.97	1.80	1.72	1.73	2.20	1.86	2.01	1.51
	Row Spacing	23	1.81	1.65	1.57	1.63	2.10	1.76	2.01	1.54
		60	1.66	1.52	1.45	1.50	1.95	1.62	1.87	1.44
Mean			**1.74**	**1.58**	**1.51**	**1.56**	**2.02**	**1.69**	**1.94**	**1.49**
Optimistic Future 2030	N	20 upfront	1.22	1.19	1.31	1.36	1.54	1.39	1.58	1.25
		50 upfront	1.28	1.25	1.37	1.42	1.65	1.45	1.70	1.34
		Tactical	1.25	1.21	1.34	1.40	1.60	1.42	1.65	1.31
	Phenology	Long	1.35	1.21	1.23	1.29	1.61	1.29	1.55	1.27
		Short	1.16	1.22	1.44	1.50	1.58	1.55	1.74	1.34
	Row Spacing	23	1.31	1.27	1.40	1.45	1.67	1.48	1.70	1.35
		60	1.19	1.16	1.28	1.33	1.53	1.36	1.58	1.25
Mean			**1.25**	**1.21**	**1.34**	**1.39**	**1.60**	**1.42**	**1.64**	**1.30**
Sig.	Time		***	***	***	***	***	***	***	***
	N		*	n.s.	n.s.	n.s.	***	*	**	n.s.
	Phenology		***	***	***	***	***	***	***	n.s.
	Row Spacing		***	***	***	***	***	***	***	**
	Time*Phen.		***	***	n.s.	n.s.	***	n.s.	n.s.	n.s.
Pessimistic Future 2030	N	20 upfront	0.77	0.74	0.89	1.01	1.07	1.02	1.24	1.01
		50 upfront	0.79	0.76	0.92	1.05	1.12	1.06	1.31	1.08
		Tactical	0.78	0.74	0.91	1.03	1.09	1.04	1.27	1.04
	Phenology	Long	0.73	0.66	0.79	0.92	0.99	0.90	1.18	0.97
		Short	0.83	0.83	1.02	1.14	1.19	1.18	1.37	1.12
	Row Spacing	23	0.81	0.78	0.95	1.07	1.14	1.08	1.32	1.08
		60	0.75	0.72	0.87	0.99	1.05	1.00	1.22	1.01
Mean			**0.78**	**0.75**	**0.91**	**1.03**	**1.09**	**1.04**	**1.27**	**1.04**
Sig.	Time		***	***	***	***	***	***	***	***
	N		*	n.s.	n.s.	n.s.	**	n.s.	**	n.s.
	Phenology		***	***	***	***	***	***	***	n.s.
	Row Spacing		***	***	**	***	***	***	***	**
	Time*Phen.		n.s.	**	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

n.s.	Not significant	Mul.	Mullewa	Dal.	Dalwallinu
*	P < 0.1	Per.	Perenjori	Mer.	Merredin
**	P < 0.05	B.R.	Bonnie Rock	Hy	Hyden
***	P < 0.01	S.C.	Southern Cross	S.G.`	Salmon Gums

Table 6.13: Effect of historical and plausible future climates, N, phenology and row spacing on simulated individual grain weight (mg) at eight locations

Time	Other	Label	Northern		Eastern		Central		Southern	
			Mul.	Per.	B.R.	S.C.	Dal.	Mer.	Hy.	SG
1940-1974	N	20 upfront	28.8	28.9	22.9	23.5	30.0	27.0	27.9	27.1
		50 upfront	28.7	28.8	22.8	23.3	29.8	27.2	27.9	27.1
		Tactical	29.9	29.8	23.3	23.8	30.9	28.1	28.8	28.0
	Phenology	Long	24.1	23.7	19.8	20.8	23.6	22.9	23.6	24.1
		Short	34.2	34.7	26.2	26.2	36.9	31.9	32.8	30.6
	Row Spacing	23	29.0	29.0	22.8	23.3	30.1	27.2	27.9	27.1
		60	29.3	29.4	23.2	23.7	30.4	27.6	28.4	27.7
Mean			**29.1**	**29.2**	**23.0**	**23.5**	**30.2**	**27.4**	**28.2**	**27.4**
1975-2009	N	20 upfront	27.4	26.0	24.0	25.6	28.6	26.8	27.9	27.1
		50 upfront	27.3	25.9	23.5	25.2	28.6	26.5	27.9	27.0
		Tactical	28.1	26.5	24.2	25.9	29.8	27.1	28.7	27.7
	Phenology	Long	22.8	20.8	21.0	21.3	23.2	22.0	22.5	23.7
		Short	32.5	31.5	26.9	29.8	34.8	31.6	33.9	30.8
	Row Spacing	23	27.5	26.0	23.8	25.4	28.8	26.7	27.9	27.0
		60	27.8	26.2	24.1	25.7	29.2	27.0	28.4	27.5
Mean			**27.6**	**26.1**	**23.9**	**25.5**	**29.0**	**26.8**	**28.2**	**27.2**
Optimistic Future 2030	N	20 upfront	28.9	27.0	25.3	26.1	29.4	26.6	26.4	25.9
		50 upfront	28.4	26.6	24.8	25.7	28.8	26.3	26.2	25.8
		Tactical	28.9	27.1	25.3	26.3	29.7	26.7	26.8	26.4
	Phenology	Long	22.4	20.0	20.6	20.9	22.5	21.1	20.9	22.2
		Short	35.1	33.8	29.7	31.1	36.1	31.9	32.1	29.9
	Row Spacing	23	28.6	26.8	24.9	25.9	29.1	26.4	26.3	25.8
		60	28.8	27.0	25.3	26.2	29.4	26.6	26.6	26.3
Mean			**28.7**	**26.9**	**25.1**	**26.0**	**29.3**	**26.5**	**26.5**	**26.0**
Sig.	Time		***	***	***	***	**	n.s.	***	**
	N		n.s.	n.s.	n.s.	n.s.	*	n.s.	n.s.	n.s.
	Phenology		***	***	***	***	***	***	***	***
	Row Spacing		n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
	Time*Phenology		***	***	***	***	**	n.s.	*	n.s.
Pessimistic Future 2030	N	50 upfront	23.5	22.1	21.7	23.1	24.6	23.1	24.3	24.4
		Tactical	23.2	21.9	21.4	22.6	24.3	22.8	24.0	24.3
			23.4	22.0	21.7	23.0	24.7	23.1	24.5	24.7
	Phenology	Long	16.9	17.1	18.1	18.8	18.8	18.7	19.6	21.1
		Short	29.8	26.9	25.0	27.0	30.3	27.4	28.9	27.8
	Row Spacing	23	23.0	21.8	21.5	22.7	24.3	22.8	24.1	24.3
		60	23.7	22.1	21.7	23.1	24.7	23.2	24.4	24.7
Mean			**23.4**	**22.0**	**21.6**	**22.9**	**24.5**	**23.0**	**24.2**	**24.5**
Sig.	Time		***	***	***	***	***	***	***	***
	N		n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
	Phenology		***	***	***	***	***	***	***	***
	Row Spacing		n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
	Time*Phen.		***	n.s.	n.s.	***	n.s.	n.s.	*	n.s.

n.s.	Not significant	Mul.	Mullewa	Dal.	Dalwallinu
*	P < 0.1	Per.	Perenjori	Mer.	Merredin
**	P < 0.05	B.R.	Bonnie Rock	Hy	Hyden
***	P < 0.01	S.C.	Southern Cross	S.G.`	Salmon Gums

Northern parts

Mullewa experienced large declines in grain yield under both future climates (Table 6.12 and Table 6.13); the probability distribution of yields for contrasting genotypes and under different climate scenarios are shown in Figure 6.13. There was a large time by phenology interaction in both models ($P < 0.001$) with the short-seasoned genotype suffering a larger yield penalty than the long-seasoned genotype in the projected climates (Table 6.12). The optimistic future (OpF) had a climate more conducive to crop production than the pessimistic future (PessF), with simulated yields being significantly higher in OpF ($P < 0.001$). As with the analysis involving observed data, all main effects had a significant effect on grain yield, with the exception of nitrogen.

Individual grain weight was affect by time under both futures ($P < 0.01$ for OpF and $P < 0.001$ PessF). Individual grain weight was affected by a time by phenology interaction under both future climates. The main cause of this was an increase in individual grain weight in the short-seasoned genotype that didn't occur in the long-seasoned genotype (Table 6.13).

Perenjori showed very similar trends to Mullewa. Time, phenology and row spacing had significant effects on grain yield in both analyses (Table 6.12). There was a time by phenology interaction for both grain yield and individual grain weight for the same reasons as at Mullewa; a greater decrease in grain yield for short-seasoned genotype in the future climates and greater individual grain weights compared to the long-seasoned genotype (Table 6.13).

Eastern Parts

Grain yield simulated for Bonnie Rock was reduced under both future climates when compared to the 1975-2009 period, but more significantly under the pessimistic future ($P < 0.001$ versus $P < 0.01$). Figure 6.13 shows that the grain yield at 50 percent probability is similar for 1940-2009 and OpF periods but OpF has far fewer years that yield over 2 t/ha and none over 2.5 t/ha, compared with 20 percent of years yielding over 2.5 t/ha in 1940-2009. Yields generated from PessF were significantly lower than those generated from the optimistic future ($P < 0.001$). There were no significant interactions in the analysis and phenology and row spacing had a significant impact on yield when averaged across all other treatments and time periods (Table 6.12). While the time by phenology interaction was not significant, the short-seasoned genotype tended to have a greater decline in grain yield under the milder outputs generated from OpF, particularly at yields over 2 t/ha (Figure 6.13). PessF produced large decline in yield for both phenologies.

There was a significant ($P < 0.01$) interaction between phenology and time for individual grain weight in OpF ($P < 0.001$) but not in PessF. As was the case with other locations, the

short-seasoned variety had an increase in individual grain weight in the future climate as a result of faster phenology so that grain fill occurred earlier when soil water was less limiting.

Time had an impact on grain yield at Southern Cross with PessF producing lower grain yields that OpF ($P < 0.001$). In the OpF scenario the future climate resulted in simulated grain yields that equalled the 1940-1974 period. In PessF analysis the yields for the future climate were significantly lower than those of 1940-1974. There were no interactions relating to grain yield. There was an interaction between time and phenology for individual grain weight as there was at Bonnie Rock.

Central parts

All main factors had an effect on grain yield at Dalwallinu. The effect of time on yield was significant for both futures ($P < 0.001$), while PessF produced significantly lower grain yields than OpF ($P < 0.001$). In OpF there was an interaction between phenology and time ($P < 0.001$). During the future climate period the two phenologies had equal grain yield, while in the other two time periods (1940-1974 and 1975-2009), the short-seasoned genotype had higher grain yield (Table 6.12). The opposite trend occurred with individual grain weight with the short-seasoned genotype having relatively heavier individual grain weight than the long season genotype in the future climate. There was a N treatment by phenology interaction for individual grain weight in the OpF analysis with the split N treatment producing greater simulated individual grain weights than the N applied upfront treatment in the long-season genotype but not the short (Figure 6.12).

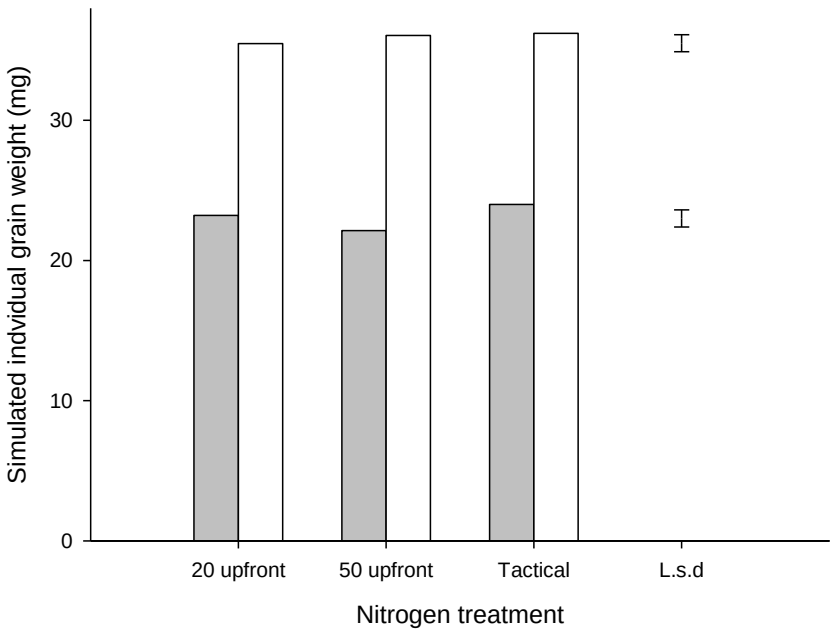


Figure 6.12: Interaction of N treatment and phenology on individual grain weight at Dalwallinu in optimistic future analysis. Grey bars indicate long-season genotype and white bars short-season genotype

Merredin had an almost linear decline in grain yield over the three time periods, particularly when OpF was used for the future climate; the step down from OpF to PessF followed the same trend and was significant ($P < 0.001$) (Table 6.12). All main treatments had a significant impact on grain yield but there were no interactions. In the OpF scenario time had no impact on individual grain weight, while it did under PessF (Table 6.13).

Southern parts

All main effects had a significant effect on grain yield and were consistent across other treatments (no interactions) at Hyden (Table 6.12). The OpF produced a greater grain yield than PessF ($P < 0.001$). Under both futures only time and phenology had a significant impact on individual grain weight ($P < 0.001$ on all accounts) (Table 6.13).

Salmon Gums had different results to all other location, including Hyden. It was the only location where phenology had no significant impact on grain yield under both future climates. Time was significant for both future climates ($P < 0.001$) (Table 6.12) and OpF produced significantly greater yields than PessF ($P < 0.001$). Phenology had a big effect on individual grain weight under both analyses ($P < 0.001$) (Table 6.13).

When looking at the graphs of the probability of exceeding a given grain yield (Figure 6.14), the cooler southern parts of the southwest Australian wheatbelt had about the same yields at 10 percent probability of exceedence across all climate scenarios, indicating that very good

years could still be possible under either an optimistic and pessimistic projection of climate change. There were greater differences between climates at the 50 percent probability of exceedence with the historical climate tending to have great yields (Figure 6.14).

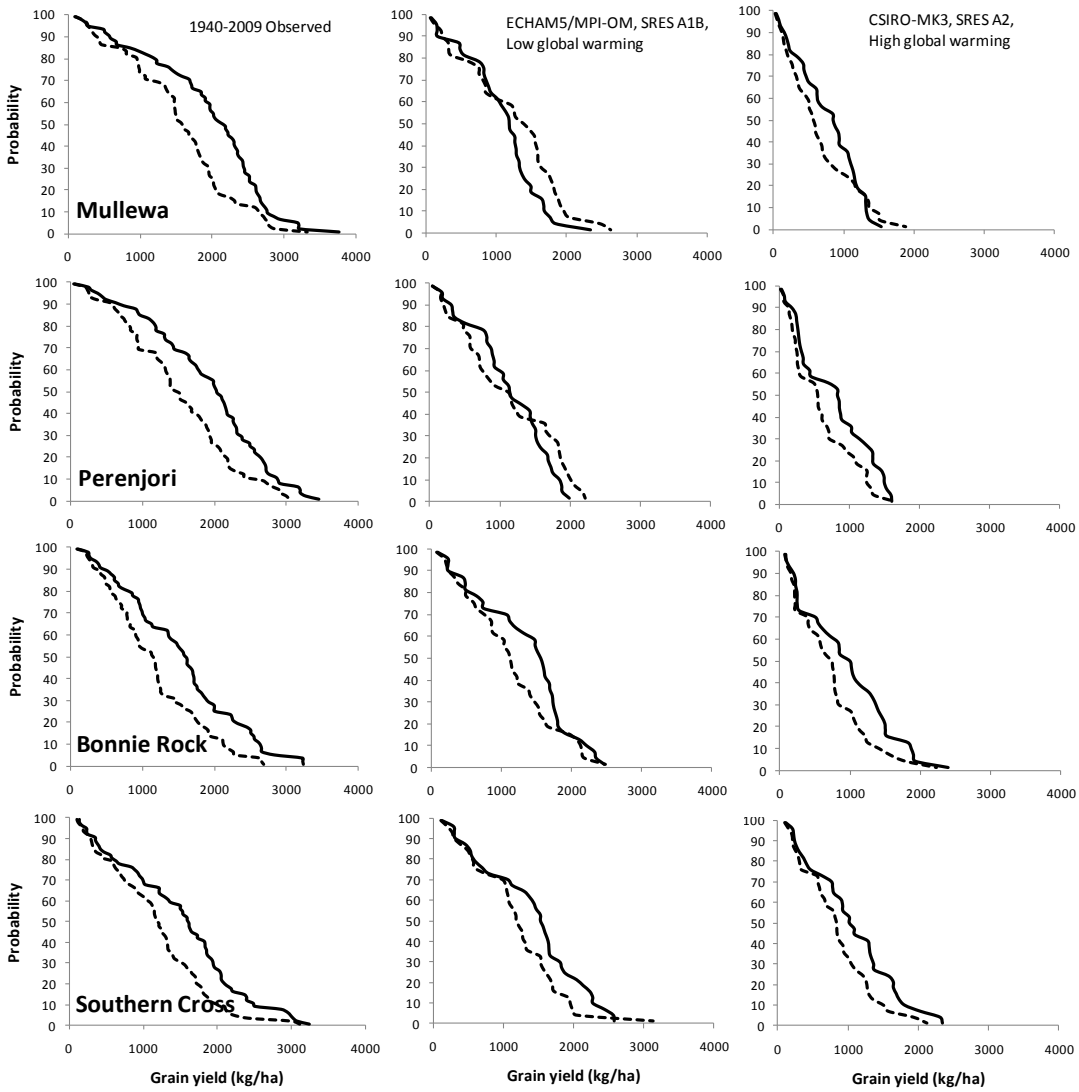


Figure 6.13: Probability of grain yield for short (solid line) and long-seasoned (dashed line) genotypes under historical, optimistic future (ECHAM5/MPI-OM, SRES A1B, low global warming) and pessimistic future (CSIRO-MK3, SRES A2, high global warming) for northern parts (Mullewa and Perenjori) and eastern parts (Bonnie Rock and Southern Cross) of low-rainfall southwest Australian wheatbelt.

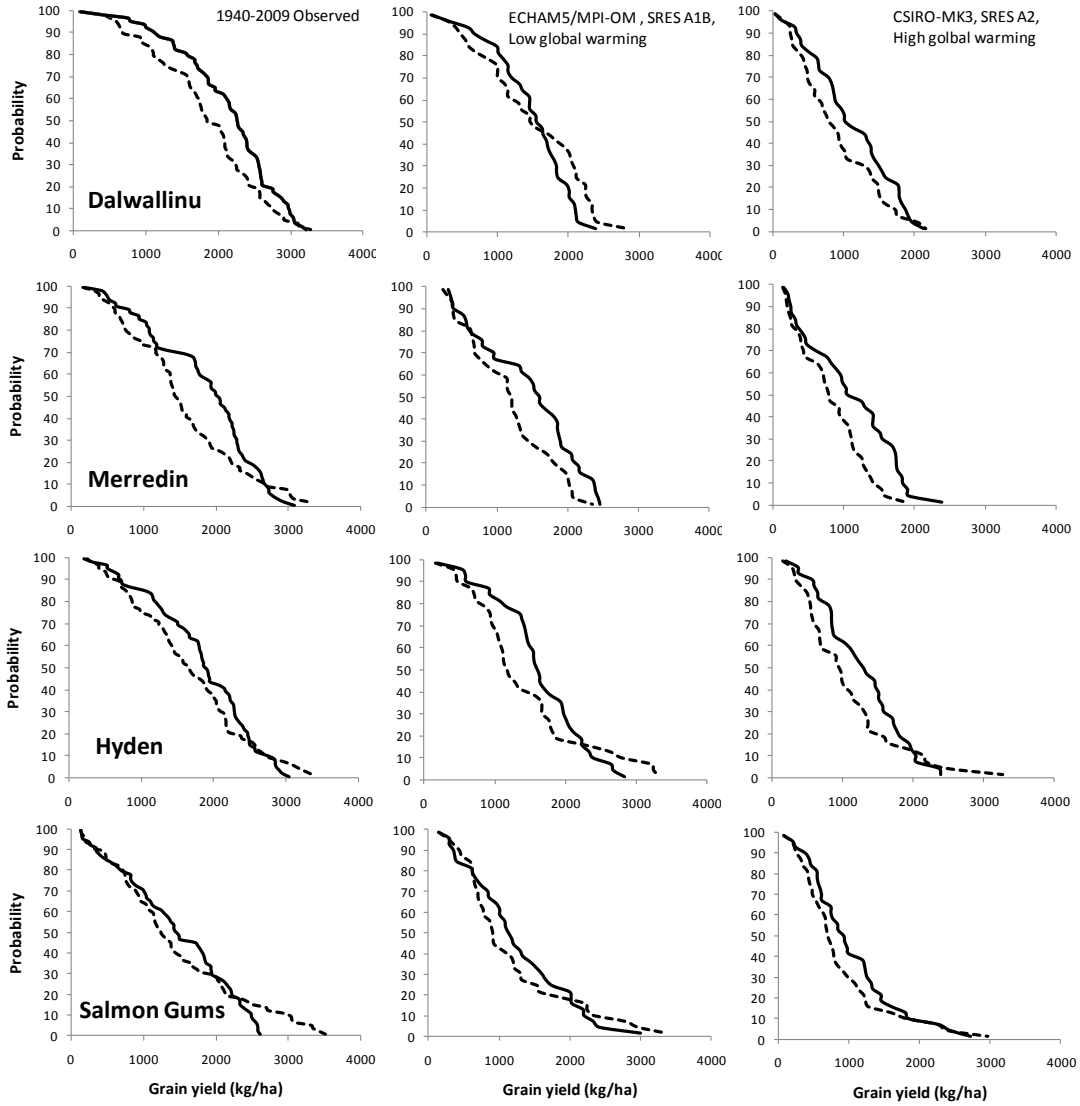


Figure 6.14: Probability of grain yield for short (solid line) and long-seasoned (dashed line) genotypes under historical, optimistic future (ECHAM5/MPI-OM, SRES A1B, low global warming) and pessimistic future (CSIRO-MK3, SRES A2, high global warming) for central parts (Dalwallinu and Merredin) and southern parts (Hyden and Salmon Gums) of low-rainfall southwest Australian wheatbelt.

Gross margins

All locations suffered a decline in gross margin (GM) under both future climate scenarios but generally to a lesser extent in the optimistic future. Mullewa and Perenjori in particular suffered huge declines in gross margin from $339/ha and $357/ha before 1975 to an average negative GM under the pessimistic future (Table 6.14).

Table 6.14: Gross margins by location for two historical time periods and two plausible future climates ($/ha)

Location	1940-1974	1975-2009	2030 Optimistic Future	Sig.	2030 Pessimistic Future	Sig.
Bonnie Rock	153	186	142	P < 0.01	27	P < 0.001
Dalwallinu	391	348	228	P < 0.001	74	P < 0.001
Hyden	284	316	232	P < 0.001	126	P < 0.001
Merredin	308	240	164	P < 0.001	60	P < 0.001
Mullewa	339	265	132	P < 0.001	-7	P < 0.001
Perenjori	357	217	119	P < 0.001	-15	P < 0.001
Salmon Gums	235	199	139	P < 0.001	69	P < 0.001
Southern Cross	145	209	166	P < 0.001	61	P < 0.001

The shorter-seasoned genotype consistently produced significantly higher gross margins under both future scenarios, due to better grain yield and individual grain weights.

Widening the row spacing lowered gross margin under both scenarios and at all locations at varying levels of significance. The row spacing effect tended to be lower at locations where average yield was lower. Nitrogen did not have a significant effect on gross margin at any location, in either of the future scenarios.

6.4 Discussion

6.4.1 Effect of historical and projected changes in climate

Changes in simulated grain yield as a result of changes in rainfall over the 1940-2009 period were specific to the regions examined in the low rainfall zone in southwest Australia**.** In the northern parts of the southwest Australian wheatbelt the decline in grain yield between the two periods (before and after 1975) was substantial and was coupled with increased variability. In eastern parts the trend was towards increased grain yield after 1974 mainly due to increases in out of season rainfall and little change in growing season rainfall, a finding consistent with that of Ludwig, Milroy, and Asseng (2009). In central parts the decline in growing season rainfall was larger and the increased out of season rainfall less significant. This resulted in smaller declines in grain yield. Ludwig, Milroy, and Asseng (2009) found there to be little effect on grain yield between the two periods for locations closer to the coast than used in this study and with higher average rainfall. In the southern parts of southwest Australia changes were not as substantial as in the northern and eastern parts. Hyden saw a mild increase in simulated grain yield and Salmon Gums no significant change**.**

However, both pessimistic and optimistic plausible future climates for the year 2030 resulted in decreased grain yields compared to the 1975-2009 period for all locations. Gross margins suffered greatly under both plausible futures and, importantly, there were no treatments that interacted with time to suggest that gross margins could be improved by adoption of any of the tested treatments. The short-seasoned genotype in particular suffered a larger yield loss than the long-seasoned genotype in the optimistic future, which probably reflects early maturity and insufficient time to build biomass and therefore sink size and yield potential. These results emphasise the importance of the phenology of future genotypes to ensure they flower in the desired time windows under expected future climatic conditions, as indicated by Howden, Gifford, and Meinke (2010).

6.4.2 The confounding effect of frost

The effect of frost was not included in this study and is likely to interact with phenology. Frost is estimated to cost Western Australian grain growers $50 million p.a. in direct losses and $150 million p.a. in opportunity costs (Belford 2009). An obvious method to avoid predicted increased temperature and water stress in spring would be to have the wheat crop flower earlier. Thus the simulated faster maturity of the long-seasoned variety in the future climates could be why that genotype didn't decline in grain yield as much as might have been expected. With less change in crop development it would be expected that greater yield losses would occur due to increased temperatures and less rain during grainfill. However, if frost damage occurs, grain yield will likely suffer with earlier flowering dates. The exact effect of climate change on frost incidence and severity in southwest Australia is unknown at his point. Torok and Nicholls (1996) have documented that minimum temperatures in Australia have risen since about 1950 and Stone, Nicholls, and Hammer (1996) suggest that frost incidence and duration have declined in north-east Australia, but information for southern Australia is lacking. Investigations into the effect of increased CO_2 on frost suggest that elevated CO_2 promotes frost damage in evergreen tree seedlings due to higher ice nucleation temperature (Lutze et al. 1998). Therefore it is not known if earlier phenology and or earlier planting could be used to counteract the effects of predicted increased drought and heat stress during grain fill under climate change. It is therefore important that future research investigates a) the likely effects of climate change on frost, and b) alternative strategies to avoid terminal heat and drought stress.

6.4.3 Effects of row spacing

Most literature dealing with the effect of row spacing on wheat yield suggests that as row spacing increases, grain yield decreases. This is particularly the case in mediterranean climates where rainfall is growing season dominant and narrower rows help reduce

evaporative losses from the soil and allow the crop to use more of the excess winter soil water before it drains from the root zone (Eberbach and Pala 2005; Tompkins, Fowler, and Wright 1991). Investigations into rainfall trends suggested increased out-of-season rainfall and decreased growing season rainfall with climate change (section 2.4.1) It was hypothesized that this trend in rainfall distribution would make wide row spacing more competitive with narrow due to more efficient usage of soil water leading to improved yields and greater individual grain weights, as has also been recorded in the literature (Blackwell, Pottier, and Bowden 2006; Johnson, Richards, and Turner 1983). However, the modelling results showed no interaction between row spacing and time period. The 1975-2009 climate did not show sufficient change in rainfall distribution (relative to 1940 – 1974) to significantly lessen the differential in grain yield between wide and narrow row spacings. There was still no interaction when the future climates were used in the investigation. This was because the higher temperatures shortened time to crop maturity. This would favour narrow row spacings as Amjad and Anderson (2006) have shown that late maturity reduces the yield penalty in wide row spacing. In the yield range where farmers are likely to achieve good gross margins (say over 1.5 t/ha) there is a substantial yield penalty (often over 100 kg/ha) for row spacings as wide as used in this study (60 cm), which is unlikely to be outweighed by the practical benefits of reduced tractor horsepower requirement and increased seeding speeds and timeliness of sowing (Jones and O'Halloran 2006). It is difficult to put a dollar value on these practical benefits as it will vary substantially from farm to farm and from season to season. Jones and O'Halloran (2006) estimated that improved timeliness from doubling row spacing could result in extra yield resulting in an extra $5.18/ha with a 20 day sowing program and an average yield of 1.5 t/ha and farm gate price of $150/ha. They also estimated fuel savings to vary from $0.27 and $3/ha and reduction in seed costs about $4/ha. At an average yield of 1.5 t/ha this study suggests the yield reduction involved in changing row spacing from 23 cm to 60 cm would be about 100 kg/ha or $15/ha (using $150 farm gate price) and therefore exceed likely benefits.

Amjad and Anderson (2006) found signs of a phenology by row spacing interaction in the south-eastern region of the southwest Australian wheatbelt. They found that the yield penalty suffered by crops grown in wider rows was smaller in longer-seasoned genotypes. The same finding was apparent in this study. In addition, this study discovered that as yield increased passed a certain point (2500 kg/ha in this low-rainfall Mediterranean-type climate and on a shallow duplex soil) the yield penalty decreased for the long-seasoned genotype while with the short-seasoned genotype the response was more linear (the yield penalty increased as narrow row spacing yield increased). However, the decline in yield and increase in the rate of

crop development in the future climates meant the yields of crops in the wide row spacings didn't reach the yields when they became similar to the narrow row spacing again.

Soil water was reset after each year's simulation to avoid confounding effects. Given wide rows resulted in more residual water left behind after crop maturity in this study, it might be considered that this would offer rotational effects. However, when wide rows were grown on wide rows in the field experiments, water use did not increase in the second year as a similar amount of residual soil water remained. The effect of residual water in wide rows on other cropping systems, involving multiple crops and row spacings, is a question for a different study.

The interaction of row spacing with frost requires more research, with only industry literature available on the topic. Jones and O'Halloran (2006) suggest wide rows could increase frost risk due to increased canopy temperature fluctuation, while Rebbeck and Knell (2007) found no difference in frost damage across differing row spacings.

6.4.4 Perspective

It is important to recognise that this simulation study was conducted on only one soil type on which the necessary calibrations had been carried out, so these results cannot be used in general terms. However, the soil type is typical of much of the cropping area in the eastern wheatbelt of southwest Australia (Russell 2005), and the conclusions reached here are likely to be realistic for this region. For responses on other soil types and in different regions, further calibration would be required. The study by Ludwig, Milroy, and Asseng (2009) suggested that a duplex soil (as was used in this study) was more resilient to reductions in winter rainfall than sand or loam soils. However, the results of this study are worrying for wheat farmers in the marginal regions who have already experienced extremely variable seasons in recent years. Of particular concern is the apparent lack of impact of the management options tested here to increase or even maintain yields in a hotter and drier climate.

This chapter has shown that the difference in climate before and after 1975 has affected simulated wheat yields differently across low rainfall areas of southwest Australia. What was more consistent was the high yielding climate of the 1990s across all parts of low rainfall southwest Australia. Of the seven decades included in this study the 1990s showed numerically greater grain yield across all parts of the test area (Figure 6.15). Given that the eight sites included in this study cover a large part of the southwest Australian wheatbelt, it is likely that some of the extraordinary increase in average grain yields in the area in the 1990s, as mentioned in Anderson et al. (2005), were due to favourable growing seasons. The reliability of rain in the 1990s meant wheat could be sown early and with high levels of inputs

and with great investment in machinery. During the 2000s, and likely going forward, this approach could result in unprofitable systems if there is a higher percentage of unfavourable seasons. Gross margins in the cereal growing regions of southwest Australia will likely benefit from more tactical cropping enterprises rather than the adoption of one or two management options. Costs can be reduced by sowing only when stored soil water levels guarantee a reasonable start to the year and by reducing fertiliser application at least until the season promises a return on that input. It is unlikely that the efficiencies (faster sowing speeds and improved timeliness of sowing, reduced horsepower requirement and cost of tractor and implement) and practical benefits (inter-row spraying of knockdown herbicides and trash flow of stubble) of wide rows (Jones and O'Halloran 2006) will result in increased profitability because of the significant yield penalties seen in high yield (and hence high return) years.

A possible management approach to lower production risk under predicted drier future climates is an extended fallow period to store soil water. This is likely to lower input costs such as nitrogen fertiliser (Cantero-Martinez, O'Leary, and Connor 1995) and increase yields, particularly on ‘heavier’ soil types (Oliver, Robertson, and Weeks 2010). Of course, this will require an altered business structure with reduced working capital as a smaller number of crops in a rotation will limit the capacity to repay debt and there will be no income from that paddock during the fallow period. An extended fallow period will allow more water storage and therefore lower production risk than a typical legume pasture in a mixed farming operation.

For many years wheat cultivars have been selected from field plots grown on narrow rows, possibly selecting for genotypes more suited to that production system. If genotypes were selected for performance in wider rows, a genotype more suited to this production system could be identified. If this was so, farmers may be able to gain from the benefits of wide rows without suffering a yield penalty. A possible ideotype for wide rows is suggested in the discussion chapter of this thesis.

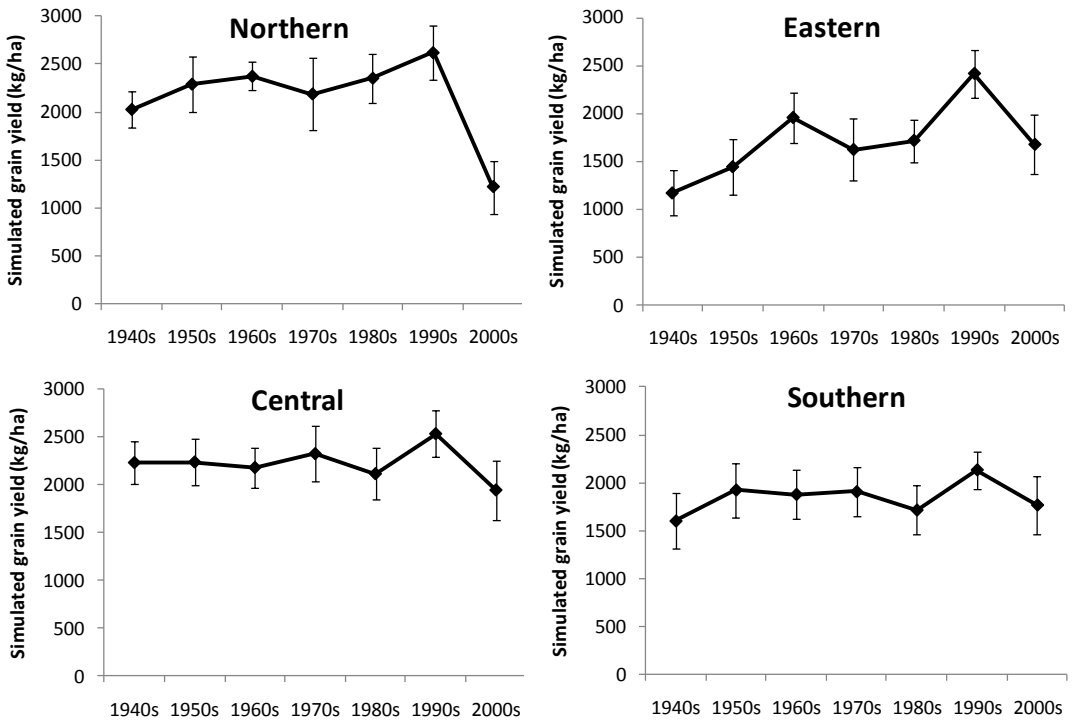


Figure 6.15: Simulated grain yield by decade according to region (23 cm row spacing, short-season genotype and tactical nitrogen). Error bars indicate standard error of the mean.

6.5 Conclusions

Soil and crop parameters with the crop model APSIM were calibrated from data taken from field experiments and simulations were set up and run with a view to determine the effects of historical and projected climate change at eight locations in the southwest wheatbelt in Australia. Also included in the analysis were the effects of row spacings, nitrogen and crop phenology treatments.

The effects of climate before and after 1975 were variable depending on location. However, both of the projected future climates for 2030 resulted in large reductions in grain yield for all locations when compared to the 1975-2009 period due to decreased growing season rainfall and warmer temperatures. Neither of the management factors included in the simulations interacted with time period or future climate treatments, suggesting that altering these factors won't result in improved grain yields if the projected climates eventuate. The elevated temperatures in the futures climates sped up phenology in the two genotypes and resulted in short-seasoned and long-seasoned genotypes having more similar yields in comparison to the historical climate (when the short-seasoned genotype tended to have substantially greater yields). This finding was more prevalent in the more optimistic future climate and was probably due to the short-seasoned genotype maturing too early and not having enough time

to accumulate biomass and sink-size. The more pessimistic future had large negative effects on both long and short season genotypes.

There was a phenology by row spacing interaction observed in the simulations of historical climate data that suggested longer-seasoned genotypes suffer a smaller yield penalty (than short-seasoned genotypes) in wide rows, particularly in grain yields over 2500 kg/ha.

This chapter also identified gaps in knowledge that will likely be important in adapting a system to a drying climate. One of those is the effect of climate change on frost in the grain growing regions of southwest Australia. This knowledge will help determine whether shortening the growing time of wheat is a plausible method to avoid predicted increases in high temperatures during grainfill. If frost incidence and severity is likely to decrease then it is likely that an earlier flowering will be beneficial. If frost incidence and severity stays the same or increases then flowering date will need to stay the same to avoid frost damage and other means are required to adapt to expected increases in terminal heat and drought stress.

Also suggested in this chapter is that more research is needed on adapting genotypes to wider row spacings so that farmers can capitalise on the practical benefits of wide row spacings (reduced machinery and fuel costs, faster sowing speeds and more optimal sowing times) while not suffering large yield penalties. An ideotype for wide rows is discussed in the following chapter.

Chapter seven

Discussion

"A river cuts through rock, not because of its power, but because of its persistence"

- Jim Watkins.

7. Discussion

Field experiments and simulation modelling studies in this thesis were undertaken to answer three key hypotheses:

I. *Increased out of season rainfall and decreased growing season rainfall will result in reduced wheat yields due to reduced individual grain size.*

II. *Growing wheat on wide row spacings will reduce biomass and water use before anthesis resulting in increased individual grain weight and yield when the degree of reliance on out of season rainfall is increased.*

III. *Wheat genotypes will respond differently to wide row spacings according to their early vigour and tillering ability under competition (more plants per metre row).*

This discussion will bring together findings from field experiments and computer simulations with relevant literature to address these hypotheses. Given the ancillary benefits of wide rows, this chapter will discuss situations in which wide rows are likely to yield similar to narrow row spacings and an ideotype for wheat in wide rows is presented.

7.1 The effect of changes in rainfall distribution on wheat production in marginal areas of the southwest Australian wheatbelt

Hypothesis I. Increased out of season rainfall and decreased growing season rainfall will result in reduced wheat yields due to reduced individual grain size.

Hypothesis one was found to be largely supported by the findings of this study, however, not consistently. The field experiments showed that with good water storage (47 mm) in the soil at seeding a good crop yield could still result, even with historically low growing season rainfall (2 t/ha with 121 mm growing season rainfall, section 5.3.6). Simulated grain yields using historical climate data also suggested that yields could be maintained, and in some instances increased, if there was good water storage at the start of the growing season. Of course, this depended on the extent of the decline in growing season rainfall and the increase in out of season rainfall. Where the out of season rainfall had increased substantially more than the decline in growing season rainfall (such as in eastern parts of southwest Australia after 1975), and no soil water was lost to summer weeds, grain yields could actually increase. However, in Merredin where the reduction in growing season rainfall after 1975 (32 mm) was similar to the increase in out of season rainfall (26 mm) grain yields decreased . In the simulations involving plausible future climates, increases in out of season rainfall were small

and dependent on location, while reductions in seasonal rainfall were relatively large. The effect of this (together with increases in temperature) resulted in large decreases in grain yield at all locations.

7.1.1 Simulated yields in relation to historic changes in rainfall

A marked change in rainfall patterns has been observed in the southwest of Australia since the mid-1970s (Bates et al. 2008) but there has been no investigation into the change in rainfall and the effect on wheat yield in the most water limited parts of the southwest wheatbelt for the same period. The crop modelling software Agricultural Production Systems Simulator (APSIM) was used in conjunction with historical and interpolated temperature, rainfall and solar radiation data from eight locations in low-rainfall (≤ 325 mm long-term annual average rainfall) regions of the southwest Australian wheatbelt to determine wheat yield and individual grain weight before and after 1975. The APSIM model was calibrated using soil water and crop growth and development data collected from the field.

Figure 6.3 shows the differences in recorded monthly rainfall and average minimum and maximum temperature before and after 1975. Most of the change in rainfall occurred as reductions in June and July rainfall, a finding consistent with that of Ludwig, Milroy and Asseng (2009) who studied locations in higher rainfall zones. Historically, the proportion of the rainfall in these months (relative to annual rainfall) is greatest in the northern parts of the southwest Australian wheatbelt and because the amount of spring rainfall is comparatively low, a reduction in winter rainfall is more likely to affect grain yields, which proved to be the case in the APSIM simulations (Chapter 6).

In northern parts (Perenjori and Mullewa) changes in climate resulted in a simulated decline in wheat yield of 17 percent (when averaged across both sites) and a large (43 percent) increase in coefficient of variation (CV) for yield after 1974. The change in individual grain weight was not as substantial but did trend down after 1974. The effect on individual grain weight was statistically significant at Perenjori but not Mullewa.

In central parts, winter rainfall was not as important to crop production, as more spring rainfall (compared to northern parts) reduces the reliance of the crop on stored winter rain for grain filling. Rainfall outside June and July tended to increase after 1974, further softening the seasonal contrast in rainfall, and while the resulting simulated grain yields declined after 1974, it was to a lesser extent than in northern parts. In central parts an average 9.5 percent decrease in grain yield was simulated, although Dalwallinu had a 42 percent increase in CV of wheat yield. Merredin had little change in variability. Individual grain weights were partly responsible for the drop in yield in that they were numerically lower after 1974, but this was not statistically significant.

There were no obvious trends in rainfall in southern parts. While June rainfall tended to reduce after 1974 at both locations (Hyden and Salmon Gums), neither growing season nor out of season rainfall changed by much, and changes in grain yield were smaller than those in other parts. At Hyden the simulations suggested a small increase in yield of seven percent while at Salmon Gums a decrease of the same amount was simulated. Individual grain weight mirrored grain yield and did not change to any great extent after 1974.

Eastern locations within the study area showed a different trend to those already mentioned with simulated grain yields suggesting climate after 1974 was more favourable for crop production than before. When averaged across both locations (Bonnie Rock and Southern Cross), grain yield increased by 13 percent with little change in variability. June and July rainfall was also lower after 1975 in eastern parts but was offset by increased rainfall in other months to the point that simulated grain yields increased after 1975. Individual grain weights trended up in eastern locations and were statistically significant at Southern Cross.

While APSIM accounts for evaporation from the soil, the model assumes no soil water usage by weeds. So while this finding would indicate that a shift in rainfall towards more out of season rainfall (coupled with a slight increase in annual rainfall) can result in increased grain yield, this would only be the case if summer weeds were controlled after large rainfall events to preserve the maximum amount of out of season rainfall for winter crop production (Browne et al. 2010).

In environments of marginal rainfall, good water storage in the soil has a large impact on wheat yields, with the relative effect depending on the amount of seasonal rain and soil type (Oliver, Robertson, and Weeks 2010). An investigation into the value of subsoil water by Kirkegaard et al. (2007) determined that under moderate post-anthesis stress, each millimetre of subsoil water used could be converted into 59 kg/ha of grain. The field experiments in my study showed that when good water storage was achieved (about 50 mm in the 2009 experiment), wheat yields of over 2 t/ha were achieved on a shallow soil (~100 cm), even when growing season rainfall (May to October) was less than 125 mm and there was no rainfall after July.

The study by Ludwig, Milroy, and Asseng (2009) found that a reduction in winter rainfall doesn’t necessarily result in reduced wheat yields, because supply of water at that time often exceeds demand by the crop and excess soil water may be lost to deep drainage. My study concentrated on locations with lower rainfall than those used by Ludwig, Milroy, and Asseng but the size of the decline in June and July rainfall after the mid-seventies was the same (20 percent). The effect of this reduction in winter rainfall was generally greater in my study

because winter rainfall is more important at locations where rainfall is lower, and soil water is more limiting to yield (Stephens and Lyons 1998b). Wang, Wang and Liu (2011) also found that wheat yields at drier sites in the eastern states of Australia were more sensitive to climate change than wetter sites.

7.1.2 Simulated yields in relation to projected changes in climate

In order to gauge the impact of projected climate change beyond 2009 on wheat yield and individual grain weight, two climate scenarios were used to indicate plausible changes in temperature and rainfall by the year 2030 for each of the eight locations (Chapter 6).

When APSIM was run using the weather data generated by these models, it suggested that grain yields would fall as a result of increased temperature and reduced rainfall, if it was assumed that there was no adaptation via crop genetics or management systems. Under the conditions of the two future climate scenarios the declines in grain yields and gross margins were calculated with grain prices and the cost of inputs at present day levels (section 6.2.4). Under the 'pessimistic' future the effects on yields and returns were larger than for the 'optimistic' future, to the point where the average gross margin in northern parts of the southwest Australian wheatbelt was negative under the 'pessimistic' scenario.

Included in the modelling study were two genotypes – short-seasoned and long-seasoned. Wheat development is largely driven by temperature (Angus et al. 1981) so with the predicted increase in temperature after 2009, the phenological development of wheat increased in the simulations and the short-seasoned genotype, that performed well in the historical analysis, matured very early in the growing season; this resulted in reduced biomass and grain yields in the 'optimistic' future. The reduction in rainfall and increased temperature during grainfill for the 'pessimistic' future resulted in genotypes of both long and short phenology suffering large declines in grain yield and individual grain weight. Even if the 'optimistic' future eventuates, breeding efforts are required to slow down development of wheat varieties through a more moderate response to thermal time or greater sensitivity to photoperiod. The need for adapting wheat phenology under rising temperatures has also been mentioned by Howden, Gifford, and Meinke (2010). Sadras and Monzon (2006) conducted a simulation study (using APSIM and CERES-wheat) which focused on detecting changes in maturity of wheat in Australia and Argentina and found that historical rises in temperature had already most likely resulted in reduced times to flowering and maturity.

Adding complication to the choice of optimal flowering time of wheat is the frequency of occurrence, severity, and timing of frost. If frost incidence was to increase in the future, then varieties maturing earlier could be at a greater risk of a grain yield penalty. If frost incidence was to decrease then an earlier maturity date might be beneficial in protecting the crop from

hot and dry weather during grain filling. Luo et al. (2009) suggested that earlier sowing could help negate the effects of climate change in South Australia, but didn't consider frost and ran simulations with added water at sowing to induce germination at the desired time. Howden, Gifford, and Meinke (2010) suggested that the incidence of frost is likely to decline as temperatures rise. However, there is evidence to suggest that rising atmospheric CO_2 could interact with frost by raising the ice nucleation temperature (Lutze et al. 1998), which may negate the beneficial (in this regard) effects of rising temperature.

It is important to note that the crop model was run with the biological responses calibrated in the current climate and without the influences of projected increases in atmospheric CO_2 which can have a beneficial effect on wheat production due to increases in radiation use efficiency and transpiration efficiency (Drake, Gonzalez-Meler, and Long 1997). Asseng et al. (2004) investigated the interaction of elevated CO_2 with rising temperatures, under different water and N supply using APSIM modelling calibrated from field experiments. In general, the study suggested that elevated CO_2 was better for crop growth when N was not limiting and as with this study, elevated temperatures and increased water deficit resulted in yield penalties. As indicated by the authors, further research is required to validate the interaction of elevated CO_2 and rising temperatures. In another simulation study Ludwig and Asseng (2006) suggested that the benefit of CO_2 fertilisation would be greater in low rainfall parts of southwest Australia. There is likely to be some benefit to wheat production from increased atmospheric CO_2 but the optimum concentration and the complex interactions with rising temperature, changing N availability and change in rainfall are not well understood. While increased atmospheric CO_2 is likely to offset the yield decline resulting from decreased rainfall and increased temperature, there is no evidence to suggest any of the treatments discussed in this thesis will benefit compared to another as a result of increase CO_2. Therefore, the conclusions made would be unlikely to change with the inclusion of CO_2. There is some suggestion, however that genotypes may vary in their response to CO_2 (Tausz-Posch et al. 2012).

7.2 The effect of wide row spacings on grain yield and individual grain weight

Hypothesis II. Growing wheat on wide row spacings will reduce biomass and evapotranspiration before anthesis resulting in increased individual grain weight and yield when the degree of reliance on out of season rainfall is increased.

The first part of hypothesis two (*growing wheat on wide row spacings will reduce biomass and evapotranspiration pre-anthesis*) was validated by the experimental data. Widening the crop row spacing reduced biomass and slowed down water use in the crop so that more water was available after anthesis. However, it was often the case (in both experiments and simulations) that the crops grown on wide rows did not use all available water at depth, which reduced the total amount of evapotranspiration (ET) for the growing season compared to narrow rows (narrow rows were usually close to lower limit). While this water was in theory 'available' to the crop after anthesis, it wasn't used by the crop and only resulted in increased individual grain weight in one of the rainfall distribution treatments across the two years in the field experiments (growing season dominant treatment in 2009). While there were trends for increased individual grain weights in the wider row spacing in the simulations, it wasn't significant at any location.

Even though widening row spacing had the expected impact on biomass accumulation and water use, grain yield was consistently lower under wide rows and there was no interaction with the rainfall distribution treatments in the experiments or the different time periods (that had changes in rainfall distribution) in the simulations, therefore hypothesis two was rejected. Figure 7.1 brings together simulated grain yields with experimental data and data from a long-term row spacing experiment near experimental site (Reithmuller, pers comm), all showing simular responses when widening row spacing about two fold.

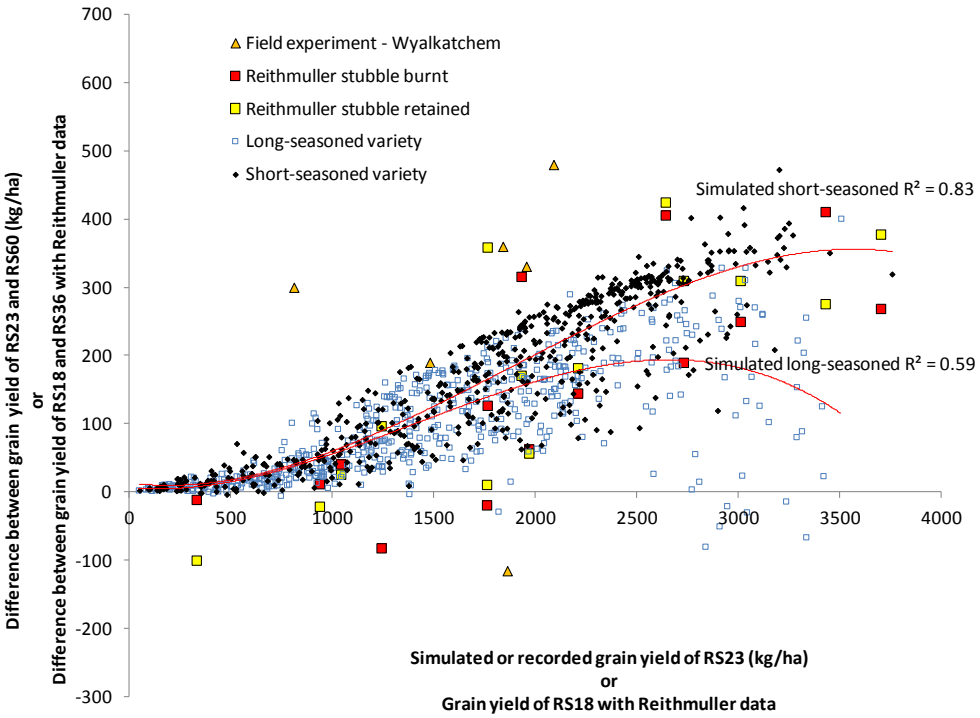


Figure 7.1: Difference in grain yield between RS_{23} and RS_{60} in long-term historic simulations and Wyalkatchem in the field experiments. Also, difference in grain between RS_{18} and RS_{36} in long-term row spacing experiment (Reithmuller, pers comm).

Given that there was no relative advantage in using wide rows under future climate scenarios, this part of the discussion deals mainly with the main effects of row spacing.

In theory, the residual water in the soil at harvest under wide rows could benefit a following crop, but while there was additional starting water in the wide row plots in the second experimental year (in the order of 13 mm) this failed to result in additional yield because water use in the second year was equal for both row spacings (i.e. the residual soil water under the wide rows persisted in the second year also). It is possible that when the soil filled to capacity (with winter rain), the additional soil water that was available at sowing, was lost to the crop through deep drainage. When the average residual water of each row spacing treatment was entered as the starting water in the long-term simulations, little advantage in grain yield was seen in wide rows compared to the narrow rows. The effect of residual water in wide rows on other cropping systems, involving multiple crops and row spacings, is a question for a different study. Attempts to improve grain yield in wide rows should aim at increasing water use at depth.

Whilst evaporation wasn't directly measured in the field experiments, greater water-use-efficiency (grain yield per unit of ET) in the narrow rows suggested there was greater partitioning of growing season ET to E in the wide rows. When transpiration was estimated using a transpiration efficiency of 50 kg/ha.mm for total dry matter production (Jones 2009),

the proportion of T was higher in narrow row spacings in both experiments. Other studies that have measured ET partitioning across varying row spacings have found wider rows to lose more soil water to evaporation than narrow rows (Eberbach and Pala 2005; Johnson, Witters, and Ciha 1981; Tompkins, Fowler, and Wright 1991). Therefore any attempt to increase yields under wide rows spacings, should attempt to reduce evaporation and therefore increase water used through transpiration.

When the same number of seeds are sown in fewer rows (constant seed rate per unit area across wider row spacings) more plants are compressed into each of the rows, and thus the intensity of competition between plants within the wider spaced rows is increased and starts earlier. In these experiments this resulted in fewer tillers per plant and therefore per area, which in turn reduced the number of heads at harvest, a finding consistent with other studies investigating the effects of row spacing on wheat (Chen et al. 2008; Doyle 1980; Johnson, Witters, and Ciha 1981; Kleemann and Gill 2010). The number of spikelets per head was also reduced in wide rows and was not offset by an increase in the number of grains per spikelet. The reduced head number and spikelet number thus resulted in a large reduction in sink size. The reduction in grains per metre square in widening row spacings is a common response mentioned in the literature (Chen et al. 2008; Johnson, Witters, and Ciha 1981; Kleemann and Gill 2010; Tompkins, Fowler, and Wright 1991). Wide rows did lower the amount of assimilates put into infertile tillers and on occasion increased harvest index. Individual grain weight tended to be greater in wide rows but not to significant levels unless there was severe water stress after anthesis. There are mixed responses of grain weight to row spacing in the literature (Blackwell, Pottier, and Bowden 2006; Chen et al. 2008; Chen et al. 2010; Johnson, Witters, and Ciha 1981; Kleemann and Gill 2010; Tompkins, Fowler, and Wright 1991). The differences are likely due to differences in rainfall after anthesis, with narrow rows able to better capture late rainfall and wide rows benefitting from more available soil water when there is little or no rainfall after anthesis. The sum of the yield components equated to reduced grain yields in the wide row spacing treatment in most circumstances. Increasing head density would aid yield in wide rows through multiple means; increased sink size, larger canopy with reduced evaporation and greater water extraction.

When grain yields were simulated over the past 70 years at the eight marginal locations, crops on 23 cm row spacing systems had a grand mean yield of 1804 kg/ha compared to 1666 kg/ha in 60 cm row spacing. Generally speaking, the yield penalty due in wide rows was proportional to the yield of the narrow row spacing treatment, i.e. when the grain yield in the narrow row spacing increased, so did the yield differential between the two row spacings, a finding consistent with other studies conducted over multiple sites and seasons in southwest Australia (Amjad and Anderson 2006; Shackley 2000).

It is a common belief among producers and farm consultants that producers in marginal regions of the southwest Australian wheatbelt make most of their profit in 20 percent of seasons (which are generally the wettest years in low rainfall areas). It is imperative in a high risk operation to maximize production and profits in these seasons. Simulated yields between row spacings were compared in the top yielding 14 seasons out of 70 (20 percent) from 1940 to 2009. In the top 20 percent of years, when average yield was 2766 kg/ha for 23 cm row spacing, the yield advantage for narrow row spacings was 224 kg/ha compared to the wide row spacings; and 117 kg/ha in all other years when average yield was 1654 kg/ha for 23 cm row spacing. This result was calculated across all locations, phenologies and N treatment. A yield penalty of 224 kg/ha could result in an annual opportunity cost of over $250,000 to a cropping enterprise of 5,000 hectares, assuming a farm gate wheat price of $225.

The APSIM simulations failed to capture the 'edge effect' that can result in a yield advantage in wide rows in very dry seasons. The inability of the model to simulate low yields in terminal drought has been reported previously in southwest Australia (Asseng et al. 1998) so it is not surprising that it failed to capture a more complex effect at low yield levels. It is unlikely that even a relatively large yield advantage at very low yields will make a large difference to the profitability of an enterprise in a very poor season. For example, if a 15 percent increase in yield occurred in wider rows at an average yield of 500 kg/ha (as suggested could happen at Merredin in 36 cm row spacing versus 18 cm in section 2.3.2 of this thesis), using the example above the benefit would be ~$85,000. Therefore there is much more to lose than there is to gain in widening row spacing too far.

7.3 Factors affecting the performance of crops on wide row spacings

It is clear that producers consider more than the effects on grain yield when deciding on what row spacing to use in wheat production. Anecdotal evidence suggests that crop row spacing in marginal parts of the southwest Australian wheatbelt have increased over the past 15 years as no-till farming has been widely adopted (GRDC 2011). While papers published in scientific journals often refer to 18 cm being a typical row spacing used for spring wheat in southern Australia, the reality is that 18 cm row spacing is the exception rather than the rule in southwest Australia and is a remnant of years gone by when combine seeders were commonplace. Combine seeders with 18 cm row spacings are rarely used in the wheatbelt of southwest Australia now and very rarely used in lower rainfall parts where no-till airseeder bars are more common, with tine spacings of around 30 cm (GRDC 2011).

A simple analysis was conducted on seeder bar options made by manufacturers common in Western Australia (namely Auseeder DBS, Bourgault, Ezee-on, Flexi-coil, Gason, Horwood Bagshaw, John Deere, Morris, Primary-Precision Seeder Bar). Of the 96 seeder bar options listed by these manufacturers in Machinery Farm Annual 2010, only 13 had tine spacings of less than 20 cm. The average available tine spacing was 26 cm and the range was 15 to 41 cm. Row spacings seem to be getting still wider due to practical benefits and positive interactions with precision agriculture and no-till systems such as increased ease of inter-row sowing, spraying and nitrogen applications and sowing through stubble. Lowering costs is another potential benefit through reduced cost of expensive per-row equipment such as advanced disc-seeder modules and parallelogram tines, and reduced cost of fuel through less drag and perhaps a smaller tractor requirement resulting in lower upfront cost of the machine and reduced ongoing fuel costs. Arguably, the greatest benefit of wider rows is potential yield benefit associated with timeliness of sowing (Anderson, Heinrich, and Abbotts 1996), through increased seeding speeds, assuming at least part of operation is sown after break and not all dry sown (Jones and O'Halloran 2006).

Given the ancillary benefits associated with wide rows (Table 7.1), and farmers' inclination to increase row spacing, it may be worthwhile investigating the situations in which wide rows may produce similar yields to narrow rows and therefore what systems are likely to fit better with wide rows.

Table 7.1: Advantages and disadvantages of wide row spacings

Advantages	Disadvantages
Timeliness of sowing through faster sowing speeds and less refills due to reduced seeding rate Ease of interrow sowing Ability to interrow spray Reduced fuel costs through less draft and smaller tractor requirement Reduced costs of seeding machine through less seeding modules	Yield reduction Reduced harvestability through possible crop lodging Increased weed competition

7.3.1 Situations favouring wide rows

In water limited environments, having water available after anthesis is very important to crop yield (Passioura 1977). This study (Chapters 4 and 5), as well as others, suggests that wide rows can slow water use by the wheat crop (Johnson, Witters, and Ciha 1981; Kleemann and Gill 2010; Winter and Welch 1987). Blackwell, Pottier, and Bowden (2006) showed that

slower water use by the crop through widening row spacing can increase grain yield in certain circumstances; when early growth is vigorous and post anthesis water is limiting. The discussion on what situations favour wide rows will be conducted in light of Figure 7.2, taken from Passioura (2002). The figure highlights the importance of the proportion of available water used before and after anthesis.

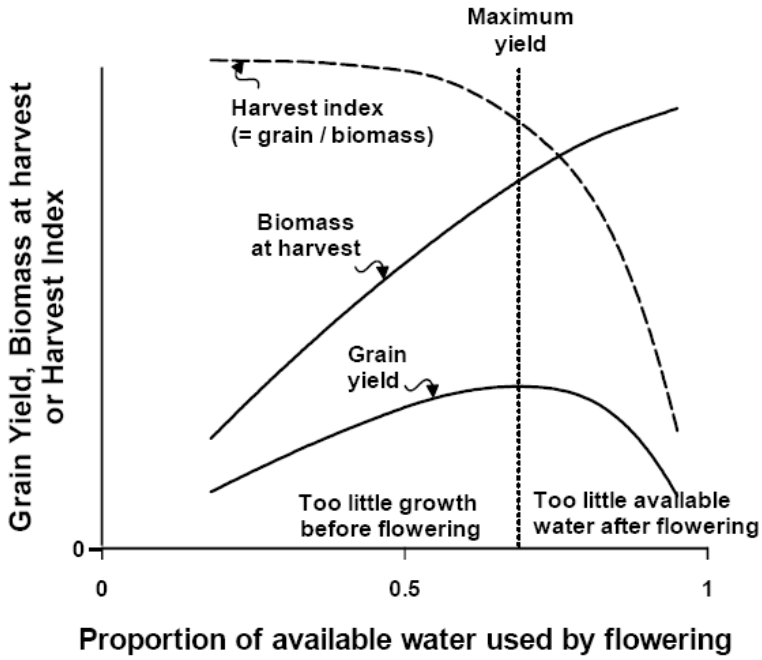


Figure 7.2: Schematic graph of grain yield of wheat, biomass at harvest, and harvest index in relation to proportion of the available water supply used by flowering. The scale of the y-axis is arbitrary (Passioura 2002).

Vigorous early growth and shallow soil

The study by Blackwell, Pottier, and Bowden (2006) provides some insights into circumstances that favour wide rows. Firstly, the crop was sown early (May 5) in the warmer northern part of the southwest Australian wheatbelt, encouraging vigorous early growth and water use. Secondly, the soil was shallow and limited rainfall after anthesis led to water deficit.

In contrast, my experiments conducted to investigate row spacing showed low early vigour due to low plant density and dry starts to the season (both experiments), deep sowing (2009 experiment), and late sowing (2008 experiment). This resulted in low water use and biomass production before anthesis and adequate water afterwards – a situation likely to favour narrow rows. It was also observed that nodal roots had a short stubby appearance generally associated with compacted soil (Reeves, Haines, and Coventry 1984). The site has a history of traffic (given it is one of a few sites in WA available for research requiring rainout shelters) and

organic carbon levels were low (0.86 percent at 0-10 cm and 0.62 percent at 10-20 cm). A soil classification conducted on the site by Russell (2005) suggested that the soil has a number of characteristics likely to inhibit root growth (full description provided in Chapter 3). Consistent with this, when the APSIM wheat model was calibrated for the site, parameters governing root growth needed to be altered to reduce the rate of water extraction so that simulated soil water content matched the observed data (Chapter 6). Crops grown on wide rows are more likely to yield similar to those in narrow rows when root front velocity is high and thus water use before anthesis is increased to a level where it may be too great in narrow rows and at more appropriate levels in wide row systems.

Conditions conducive to healthy root growth

This may be the reason why some leading growers, who have used a no-till system and controlled traffic for many years, can seemingly grow high yielding crops with exceptional water-use-efficiency on row spacings greater than 35 cm (Francis 2009). In a cropping system that minimizes compaction (through reduced tillage, controlled traffic and stubble retention) (Hamza and Anderson 2005), and minimises the effect of root disease, through inter-row seeding and good crop rotation (Bockus and Shroyer 1998), the result is increased root penetration and crop vigour. It is not then altogether surprising that high yields are achievable on wider than conventional rows as biomass and head density (and sink size) is not limiting yield as they would be in wide rows on a compacted, poorly rotated soil with a history of heavy cultivation.

Extended fallow

An extended fallow may also present circumstances where wider rows may be beneficial. Extended fallow will likely result in vigorous early growth provided the fallow has generated the expected benefits of reduced weed competition, a root disease break, good stored soil water and increased soil fertility (Oliver, Robertson, and Weeks 2010). All these factors should result in an adequate sink size in wide rows and unless there are large rainfall events after anthesis (which is unlikely in low rainfall areas), and a greater risk of haying off in narrow rows. Given the uncertainty and decline in rainfall post 1975 and particularly after 2000, an extended fallow period could be implemented by farmers to lower production risk (Oliver, Robertson, and Weeks 2010) and lower input costs (chemical and fertiliser). However, there are herbicide costs associated with keeping the fallow clean of weeds and a loss of income from that paddock during the year the fallow is implemented. Wider row spacings would also probably lower fuel costs (through less draft) and the cost of machinery through fewer tines/disc modules and maybe a smaller tractor.

In partially replicated plots adjacent to the 2009 experiment, results showed that the extra biomass produced by wheat on fallow plots compared to wheat on wheat plots resulted in

increased harvest index (17 percent) and individual grain weight (18 percent) in wide rows and a trend for increased grain yield in the genotype Wyalkatchem (five percent). Harvest Index and individual grain weight also tended to be higher in the wider rows in the genotype Silverstar, but grain yield tended to decline in wide rows. This genotype by row spacing interaction was consistent in the other rainfall distributions and will be discussed further in section 7.3.2.

Other factors

Large inter-row spaces associated with wide rows result in reduced light interception by the crop (light interception was reduced by 37 percent on average in wide rows in 2008) and reduced competition against weeds (Borger, Hashem, and Pathan 2010). Work by Borger, Hashem, and Pathan (2010) in southwest Australia has suggested that by orientating crop rows east-west rather than north-south competition with weeds is enhanced due to increased light interception by the crop, and grain yield can be increased. This option was not tested in this thesis. Orientating crop rows east-west could be employed by growers using wide rows to reduce reliance on herbicides to control weeds as well as to improve grain yields.

Consideration should also be given to reducing evaporation in the inter-row space and increasing the partitioning of ET to transpiration. Of course, the conditions conducive to good early vigour already discussed in this section should result in more inter-row shading. Another obvious tactic is stubble retention and inter-row sowing so that the stubble of last year's crop shades the inter-row of the current year's crop. Stubble levels of over 2 t/ha can slow down the rate of evaporation of water from the soil (Bond and Willis 1970) and therefore increase the chance of the crop having access to it. However, there is also evidence to suggest that large amounts of residue can intercept small rainfall events and prevent water from entering the soil (Cook et al. 2006). Other more novel (but expensive) approaches such as using polymers could also be considered (Fernández et al. 2001).

7.3.2 An ideotype for wide rows

Hypothesis III. Wheat cultivars will respond differently to wide row spacings according to their early vigour and tillering ability under competition (more plants per metre row).

As has already been suggested, there are grounds to accept hypothesis three and conclude that there is genetic variation in response to row spacing.

In the above sections I discussed situations in which wider rows are more likely to produce grain yields comparable to narrow rows. The discussion comes down to two main factors; a)

optimising the balance of water use before and after anthesis, and b) not limiting grain yield through limited sink size in wide rows. Contributing to these two factors are vigorous early growth and shallow soil. A continuation of this is an ideotype that may help to increase yields and add the practical benefits already discussed in this chapter. Given that producers are seemingly widening row spacing in wheat does it not make sense that breeders should produce cultivars that suit this system? Section 0 mentions three areas that should be focused on to increase yields under wide rows; increased head density, decreased evaporation, and increased water extraction.

In 2008 five varieties were tested and a row spacing by variety interaction was recorded for grain yield. A contributing factor seemed to be phenology, with Halberd, the longest-season variety, showing a smaller penalty in wide rows than Silverstar, the shortest-season variety (19 percent and 41 percent decline in grain yield in wide rows respectively). This finding was consistent with that of Amjad and Anderson (2006) in the southern parts of the southwest wheatbelt where the longer-seasoned variety Camm performed better in wider rows than other varieties. The 2008 experiment also found that varieties that tended to have greater light interception at stem elongation (Halberd and Westonia) tended to perform better in wide rows.

In 2009 the two top yielding genotypes in wide rows from the 2008 experiment were not used and the row spacing by variety interaction was not as large. In this experiment Wyalkatchem tended to be better performing than Silverstar in wide rows with less reduction in head density (nine percent versus 19 percent), a greater increase in grain weight (11 percent versus two percent) and a trend toward better grain yield (17 percent decline in wide rows compared to 24 percent).

It is likely that a vigorous root system will play a role in improving yield in wide rows. In both the 2008 and 2009 experiments there was more residual water left in the wide rows (24 and 14 mm respectively), mostly at a depth of about 50 cm. Kirkegaard (2007) showed that water used after anthesis is very valuable to grain yield, especially under terminal drought (up to 59 kg/ha per mm transpired). A root system that allowed use of the residual soil water late in the season would very likely increase individual grain weight and grain yield in wide rows, provided sink size wasn't limiting.

A more lateral root system might also aid in accessing water and nitrogen in wide row systems and result in greater source and sink size. Silverstar had a tendency for faster vertical soil exploration when grown in a highly competitive environment (i.e. increased plant density in a wide row), as can be seen in Figure 5.12. Work by Manschadi et al. (2008) found that the seminal root angle of Wyalkatchem tended to be greater than Silverstar while Silverstar had a

greater number of seminal roots. The work by Manschadi et al. also revealed that wheat genotypes can differ in root architecture and branching properties even from within a group of similar genetic backgrounds and this can be evident in the early stages of growth (33 days after emergence). Such a finding suggests that breeding for greater lateral soil exploration in wide rows should be possible.

In summary, it is theorised that for increased water use, reduced evaporation and improved sink size a vigorous, heavy tillering variety is required with a root system capable of good lateral soil exploration. If these areas could be improved to match performance on narrow rows farmers could enjoy the practical benefits of wide rows without the detraction of yield decline.

7.4 Conclusion and further research

This study showed that the most consistent and clear trend in climate in the marginal parts (annual rainfall ≤ 325 mm) of the southwest Australian wheatbelt has been the reduction in June and July rainfall. The effect on wheat yield was dependent on the size of this reduction and the increase in out of season rainfall (November to April). Both optimistic and pessimistic projections in climate for 2030 resulted in reductions in yield for all locations (in the absence of CO_2 fertilisation and adaption to genetics and management). A significant concern for producers is that none of the tactics tested in this thesis are likely to result in improved yield in a drying climate.

Increasing row spacing slowed water use by the crop and left water available for use after anthesis. However, the genotypes used in this study failed to benefit from this additional available water under the management used in the field experiments and simulations. Without the benefit from extra post anthesis water use, the wider row spacing failed to increase grain yield, even under terminal drought, and there was no evidence that the wide row system would perform relatively better than conventional row spacings under future climate scenarios.

It is proposed that a genotype that is better able to make use of additional post anthesis water in wide rows, reduce water loss through evaporation through the soil, and produce a sink size so that the plant has the capacity to benefit from post anthesis water use will yield better under wide rows.

Therefore it is suggested that future research on this area focus on the following:

- The effects on the interaction of the changes in climatic factors predicted for southwest Australia, namely increase occurrence of drought, elevated atmospheric CO_2 and increased temperatures.

- Developing wheat varieties that reduce yield reductions under wide rows so that wheat producers can benefit from the practical benefits of wide rows without the yield reductions.
- The effects of predicted climate on the occurrence, timing and severity of frost so that future optimal flowering dates can be established.
- Developing high yielding varieties with adapted phenology (either through slower response to thermal time or increased photoperiod sensitivity) that suit future optimal flowering dates.

References

ABARE. 2009. *Australian commodity statistics 2009*. http://www.abare.gov.au/publications_html/data/data/data.html (accessed May 26, 2011).

ABARE. 2010. *Australian crop report* Report no 154: Australian Bureau of Agricultural and Resource Economics. http://www.abare.gov.au/publications_html/crops/crops_10/crops_10.html (accessed 17 April 2010).

Abrecht, D., and T. Calder. 1994. *A modular field plot irrigation system*. ISSN 1037-9789: Division of Plant Industries, Department of Agriculture, Western Australia.

Ainsworth, E. A., and S. P. Long. 2005. What have we learned from 15 years of free-air CO2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO2. *New Phytologist* 165 (2): 351-372. Wiley Online Library. http://onlinelibrary.wiley.com (accessed May 6, 2011).

Amjad, M., and W. K. Anderson. 2006. Managing yield reductions from wide row spacing in wheat. *Australian Journal of Experimental Agriculture* 46 (10): 1313-1321. CSIRO Publishing. http://www.publish.csiro.au (accessed April 19, 2007).

Anderson, W. K., A. Heinrich, and R. Abbotts. 1996. Long-season wheats extend sowing opportunities in the central wheat belt of Western Australia. *Australian Journal of Experimental Agriculture* 36 (2): 203-208. CSIRO Publishing. http://www.publish.csiro.au (accessed April 7, 2011).

Anderson, W. K., and F. C. Hoyle. 1999. Nitrogen efficiency of wheat cultivars in a Mediterranean environment. *Australian Journal of Experimental Agriculture* 39 (8): 957-965. CSIRO Publishing. http://www.publish.csiro.au (accessed May 17, 2010).

Anderson, W. K., D. L. Sharma, B. J. Shackley, and M. F. D'Antuono. 2004. Rainfall, sowing time, soil type, and cultivar influence optimum plant population for wheat in Western Australia. *Australian Journal of Agricultural Research* 55 (9): 921-930. CSIRO Publishing. http://www.publish.csiro.au (accessed June 28, 2011).

Anderson, W. K., M. A. Hamza, D. L. Sharma, M. F. D'Antuono, F. C. Hoyle, N. Hill, B. J. Shackley, M. Amjad, and C. Zaicou-Kunesch. 2005. The role of management in yield improvement of the wheat crop: a review with special emphasis on Western Australia. *Australian Journal of Agricultural Research* 56 (11): 1137-1149. CSIRO Publishing. http://www.publish.csiro.au (accessed March 23, 2007).

Anderson, W. K. 2010. Closing the gap between actual and potential yield of rainfed wheat. The impacts of environment, management and cultivar. *Field Crops Research* 116 (1-2): 14-22. Science Direct. http://www.sciencedirect.com (accessed April 23, 2010).

Angus, J. F., D. H. Mackenzie, R. Morton, and C. A. Schafer. 1981. Phasic development in field crops II. Thermal and photoperiodic responses of spring wheat. *Field Crops Research* 4: 269-283. Science Direct. http://www.sciencedirect.com (accessed February 15, 2011).

Angus, J.F., and A.F. van Herwaarden. 2001. Increasing water use and water use efficiency in dryland wheat. *Agronomy Journal* 93:209-298.

Araus, J. L., G. A. Slafer, M. P. Reynolds, and C. Royo. 2002. Plant Breeding and Drought in C_3 Cereals: What Should We Breed For? *Annals of Botany* 89: 925-940. Oxford Journals. http://www.oxfordjournals.org (accessed July 17, 2007).

Asseng, S., B. A. Keating, I. R. P. Fillery, P. J. Gregory, J. W. Bowden, N. C. Turner, J. A. Palta, and D. G. Abrecht. 1998. Performance of the APSIM-wheat model in Western Australia. *Field Crops Research* 57 (2): 163-179. http://www.sciencedirect.com (accessed May 6, 2010).

Asseng, S., and A. F. van Herwaarden. 2003. Analysis of the benefits to wheat yield from assimilates stored prior to grain filling in a range of environments. *Plant and Soil* 256 (1): 217-229. SpringerLink. http://www.springerlink.com/ (accessed July 17, 2007).

Asseng, S., P. D. Jamieson, B. Kimball, P. Pinter, K. Sayre, J. W. Bowden, and S. M. Howden. 2004. Simulated wheat growth affected by rising temperature, increased water deficit and elevated atmospheric CO2. *Field Crops Research* 85 (2-3): 85-102. Science Direct. http://www.sciencedirect.com (accessed March 16, 2009).

Asseng, S., I. A. N. Foster, and N. C. Turner. 2011. The impact of temperature variability on wheat yields. *Global Change Biology* 17 (2): 997-1012. Wiley Online Library. http://onlinelibrary.wiley.com/ (accessed June 2, 2011).

Bates, B., P. Hope, B. Ryan, I. Smith, and S. Charles. 2008. Key findings from the Indian Ocean Climate Initiative and their impact on policy development in Australia. *Climatic Change* 89 (3): 339-354.

Belford, R. 2010. Final report prepared for the Grains Research and Development Corporation. “National Frost Workshop, Perth 4-6 November 2009”.

Bird, I. F., M. J. Cornelius, and A. J. Keys. 1977. Effects of Temperature on Photosynthesis by Maize and Wheat. *Journal of Experimental Botany* 28 (3): 519-524. Oxford Journals. http://www.oxfordjournals.org (accessed June 28, 2011).

Blackwell, P., S. Pottier, and B. Bowden. 2006. Response to winter drought by wheat on shallow soil with low seeding rate and wide row spacing. In *Agribusiness Crop Updates, 2006*. Perth, WA. Department of Agriculture and Food, Western Australia.

Blum, A., and Y. Pnuel. 1990. Physiological attributes associated with drought resistance of wheat cultivars in a Mediterranean environment. *Australian Journal of Agricultural Research* 41 (5): 799-810. CSIRO Publishing. http://www.publish.csiro.au (accessed March 21, 2007).

Blum, A. 1998. Improving wheat grain filling under stress by stem reserve mobilisation. *Euphytica* 100 (1): 77-83. SpringerLink. http://www.springerlink.com (accessed July 17, 2007).

Blum, A., J. Zhang, and H. T. Nguyen. 1999. Consistent differences among wheat cultivars in osmotic adjustment and their relationship to plant production. *Field Crops Research* 64 (3): 287-291. Science Direct. http://www.sciencedirect.com (accessed March 21, 2007).

Bly, A. G., and H. J. Woodard. 2003. Foliar nitrogen application timing influence on grain yield and protein concentration of hard red winter and spring wheat. *Agronomy Journal* 95 (2): 335-338. ProQuest. http://www.proquest.co.uk/en-UK (accessed June 1, 2011).

Bockus, W. W., and J. P. Shroyer. 1998. The impact of reduced tillage on soilborne plant pathogens. *Annual Review of Phytopathology* 36: 485-500. Annual Reviews. http://www.annualreviews.org (accessed May 23, 2011).

Botwright, T.L., A.G. Condon., G.J. Rebetzke., and R.A. Richards. 2002. Field evaluation of early vigour for genetic improvement of grain yield in wheat. *Australian Journal of Agricultural Research* 53:1137-1145.

BOM. 2010. *Australian climate variability and change - trend maps*. http://www.bom.gov.au/cgibin/climate/change/trendmaps.cgi?map=rain&area=wa&season=0112&period=1970 (accessed April 15, 2010).

BOM, and CSIRO. 2010. *Climate Change in Australia*. www.climatechangeinaustralia.com.au (accessed May 6, 2011).

BOM. 2011. *Climate data online*. http://www.bom.gov.au/climate/data/ (accessed June 2, 2011).

Bond, J. J., and W. O. Willis. 1970. Soil evaporation rate: first stage drying as influenced by surface residue and evaporation potential. *Proceedings of the Soil Science Society of America* 34: 924-928.

Borger, C., A. Hashem, and S. Pathan. 2010. Manipulating crop row orientation to suppress weeds and increase crop yield. *Weed Science* 58 (2): 174-178. Allen Press. http://allenpress.com/ (accessed Feb 21, 2011).

Browne, C., J. Hunt, S. Craig, A. Whitbread, and D. Mowat. 2010. Improving winter crop productivity through increased capture and storage of summer fallow rain. In *Food Security from Sustainable Agriculture' 15th Agronomy Conference*, edited by H. Dove and R. Culvenor. Lincoln, New Zealand.

Burger, W. C. 1981. Why are there so many kinds of flowering plants? *BioScience* 31 (8): 572-581. http://www.jstor.org/stable/1308218 (accessed 19 April 2010).

Cantero-Martinez, C., G. J. O'Leary, and D. J. Connor. 1995. Stubble retention and nitrogen fertilisation in a fallow-wheat rainfed cropping system. 1. Soil water and nitrogen conservation, crop growth and yield. *Soil and Tillage Research* 34 (2): 79-94. Science Direct. http://www.sciencedirect.com (accessed June 28, 2011).

Cattivelli, L., F. Rizza, F.-W. Badeck, E. Mazzucotelli, A. M. Mastrangelo, E. Francia, C. Mare, A. Tondelli, and A. M. Stanca. 2008. Drought tolerance improvement in crop plants: An integrated view from breeding to genomics. *Field Crops Research* 105 (1-2): 1-14. Science Direct. http://www.sciencedirect.com (accessed March 27, 2008).

Chaves, M. M., J. S. Pereira, J. Maroco, M. L. Rodrigues, C. P. P. Ricardo, M. L. Osorio, I. Carvalho, T. Faria, and C. Pinheiro. 2002. How plants cope with water stress in the field. Photosynthesis and Growth. *Annals of Botany* 89: Oxford Journals. http://www.oxfordjournals.org (accessed July 17, 2007).

Chen, C., K. Neill, D. Wichman, and M. Westcott. 2008. Hard red spring wheat response to row spacing, seeding rate, and nitrogen. *Agronomy Journal* 100: 1296-1302. ProQuest. http://www.proquest.co.uk/en-UK (accessed May 3, 2010).

Chen, S., X. Zhang, H. Sun, T. Ren, and Y. Wang. 2010. Effects of winter wheat row spacing on evapotranspiration, grain yield and water use efficiency. *Agricultural Water Management* 97 (8): 1126-1132. Science Direct. http://www.sciencedirect.com (accessed June 16, 2011).

Cook, H.F., G.S.B. Valdes., and H.C. Lee. 2006. Mulch effects on rainfall interception, soil physical characteristics and temperature under Zea may L. *Soil and Tillage Research* 91:227-235.

Condon, A.G., R.A. Richards., G.J. Rebetzke., and G.D. Farquhar. 2004. Breeding for high water-use efficiency. *Journal of Experimental Botany* 55:2447-2460.

Darinkel, A. 1978. Patterns of tillering and grain production of winter wheat at a wide range of densities. *Netherlands Journal of Agricultural Science* 26:383-398.

Darwinkel, A. 1983. Ear formation and grain yield of winter wheat as affected by time of nitrogen supply. *Netherlands Journal of Agricultural Science* 31 (3): 211-225.

Davidson, J. L., and J. W. Birch. 1978. Responses of a standard Australian and a Mexican wheat to temperature and water stress. *Australian Journal of Agricultural Research* 29 (6): 1091-1106. CSIRO Publishing. http://www.publish.csiro.au (accessed August 13, 2007).

Del Cima, R., M. D'Antuono, and W. K. Anderson. 2004. The effects of soil type and seasonal rainfall on the optimum seed rate for wheat in Western Australia. *Australian Journal of Experimental Agriculture* 44: 585-594. CSIRO Publishing. http://www.publish.csiro.au (accessed May 17, 2010).

Delroy, N.D., and J.W. Bowden.1986. Effect of deep ripping, the previous crop, and applied nitrogen on the growth and yield of a wheat crop. *Australian Journal of Experimental Agriculture* 26:469-479.

Dodig, D., M. Zoric, D. Knezevic, S. R. King, and G. Surlan-Momirovic. 2008. Genotype x environment interaction for wheat yield in different drought stress conditions and agronomic traits suitable for selection. *Australian Journal of Agricultural Research* 59 (6): 536-545. CSIRO Publishing http://www.publish.csiro.au (accessed June 11, 2008).

Dolling, P. J., I. R. P. Fillery, P. R. Ward, S. Asseng, and M. J. Robertson. 2006. Consequences of rainfall during summer-autumn fallow on available soil water and subsequent drainage in annual-based cropping systems. *Australian Journal of Agricultural Research* 57: 281-296. CSIRO Publishing. http://www.publish.csiro.au (accessed June 7, 2011).

Donald, C. M. 1968. The breeding of crop ideotypes. *Euphytica* 17: 385-403.

Donald, C. M. 1979. A barley breeding programme based on an ideotype. *The Journal of Agricultural Science* 93: 261-269.

Doyle, A. D., and R. A. Fischer. 1979. Dry matter accumulation and water use relationships in wheat crops. *Australian Journal of Agricultural Research* 30 (5): 815-829. CSIRO Publishing. http://www.publish.csiro.au (accessed October 30, 2007).

Doyle, A. D. 1980. Effect of row spacing on wheat yield. *The Journal of the Australian Institute of Agricultural Science* 46 (2): 125-127.

Drake, B. G., M. A. Gonzalez-Meler, and S. Long. 1997. More efficient plants: A consequence of rising atmospheric CO2? *Annual Review of Plant Physiology and Plant Molecular Biology* 48: 609-639. http://www.annualreviews.org/doi/abs/10.1146/annurev.arplant.48.1.609 (accessed April 13, 2010).

Duggan, B. L., R. A. Richards, A. F. van Herwaarden, and N. A. Fettel. 2005. Agronomic evaluation of a tiller inhibition gene (tin) in wheat. I. Effect on yield, yield components, and grain protein. *Australian Journal of Agricultural Research* 56: 169 - 178. CSIRO Publishing. http://www.publish.csiro.au (accessed March 21, 2007).

Eastham, J., and P.J. Gregory. 2000. The influence of crop management on the water balance of lupin and wheat crops on a layered soil in a Mediterranean climate. *Plant and Soil* 221:239-251.

Eberbach, P., and M. Pala. 2005. Crop row spacing and its influence on the partitioning of evapotranspiration by winter-grown wheat in Northern Syria. *Plant and Soil* 268 (1): 195-208. SpringerLink. http://www.springerlink.com (accessed August 14, 2007).

Evans, L. T., and R. A. Fischer. 1999. Yield potential: Its definition, measurement, and significance. *Crop Science* 39 (6): 1544-1551. http://www.mendeley.com/research/yield-potential-its-definition-measurement-and-significance-1/ (accessed June 28, 2011).

FAO. 2006. *World agriculture: towards 2030/2050*. Rome: Global Perspectives Studies Unit. Food and Agriculture Organisation of the United Nations.

FAO. 2011. *FAOSTAT*. http://faostat.fao.org/ (accessed May 3, 2011).

Farquhar, G. D., and R. A. Richards. 1984. Isotopic composition of plant carbon correlates with water-use efficiency of wheat genotypes. *Functional Plant Biology* 11 (6): 539-552. CSIRO Publishing http://www.publish.csiro.au (accessed July 17, 2007).

Farre, I., I. Foster, and S. Charles. 2007. Future wheat yields in the West Australian wheatbelt. In *Agribusiness Crop Updates 2007*. Perth, WA. Department of Agriculture and Food, Western Australia.

Fawcett, R. G. 1964. Effect of certain conditions on yield of crop plants. *Nature* 204: 858-860.

Fernández, J. E., F. Moreno, J. M. Murillo, M. V. Cuevas, and F. Kohler. 2001. Evaluating the effectiveness of a hydrophobic polymer for conserving water and reducing weed infection in a sandy loam soil. *Agricultural Water Management* 51 (1): 29-51. Science Direct. http://www.sciencedirect.com (accessed February 21, 2011).

Fischer, R.A., I. Aguilar., R. Maurer., and S. Rivers. 1976. Density and row spacing effects on irrigated short wheats at low latitude. *Journal of Agricultural Science* 87:137-147.

Fischer, R. A., and R. Maurer. 1978. Drought resistance in spring wheat cultivars. I. Grain yield responses. *Australian Journal of Agricultural Research* 29 (5): 897-912. CSIRO Publishing. http://www.publish.csiro.au (accessed August 13, 2007).

Fischer, R. A., and J. T. Wood. 1979. Drought resistance in spring wheat cultivars. III.* Yield associations with morpho-physiological traits. *Australian Journal of Agricultural Research* 30 (6): 1001-1020. CSIRO Publishing. http://www.publish.csiro.au (accessed August 13, 2007).

Fischer, R. A., and Y. M. Stockman. 1980. Kernel number per spike in wheat (Triticum aestivum L.): responses to anthesis shading. *Australian Journal of Plant Physiology* 7: 169-180. CSIRO Publishing. http://www.publish.csiro.au (accessed June 23, 2011).

Fischer, R. A. 1999. Physiological and numerical components of wheat yield. In *Wheat: Ecology and Physiology of Yield Determination*, ed. E. H. Satorre and G. A. Slafer. Binghamton, NY: Food Products Press.

Fischer, R. A. 2009. Farming systems of Australia: Exploiting the synergy between genetic improvement and agronomy. In *Crop Physiology: Applications for Genetic Improvement and Agronomy*, ed. V. O. Sadras and D. F. Calderini. Burlington, USA: Elsevier Inc.

Fischer, R. A. 2011. Wheat physiology: a review of recent developments. *Crop & Pasture Science* 62: 95-114. CSIRO Publishing. http://www.publish.csiro.au (accessed June 9, 2011).

Flenet, R., J.R. Kiniry., J.E. Board., M.E. Westgate., and D.C. Reicosky. 1996. Row spacing effects on light extinction coefficients of corn, sorghum, soybean, and sunflower. *Agronomy Journal* 88:185-190.

Foster, I. 2000. Environment. In *The Wheat Book: Principles and Practice*, ed. W. K. Anderson and J. R. Garlinge. Perth: Department of Agriculture, Western Australia.

Foulkes, M. J., R. Sylvester-Bradley, R. Weightman, and J. W. Snape. 2007. Identifying physiological traits associated with improved drought resistance in winter wheat. *Field Crops Research* 103 (1): Science Direct. http://www.sciencedirect.com (accessed June 29, 2007).

Francis, P. 2009. Wimmera farmer sets new benchmarks for grain water use efficiency *Australian Farm Journal*, November 2009. 6-9

French, R. J., and J. E. Schultz. 1984. Water use efficiency of wheat in a Mediterranean-type environment. I The relation between yield, water use and climate. *Australian Journal of Agricultural Research* 35: 743 - 764. CSIRO Publishing. http://www.publish.csiro.au (accessed March 21, 2007).

GRDC. 2011. *Crop placement and row spacing fact sheet: A systems approach to row spacing (Western Region)*. http://www.grdc.com.au/uploads/documents/GRDC_FS_CropPlacement_West2.pdf (accessed June 28, 2011).

Gregory, P.J., and J Eastham. 1996. Growth of shoots and roots, and interception of radiation by wheat and lupin crops on a shallow, duplex soil in response to time of sowing. *Australian Journal of Agricultural Research* 47:427-447.

Halse, N. J., E. A. N. Greenwood, P. Lapins, and C. A. P. Boundy. 1969. An analysis of the effects of nitrogen deficiency on the growth and yield of a Western Australian wheat crop. *Australian Journal of Agricultural Research* 20: 987-998.

Hamblin, A. P., and D. Tennant. 1987. Root length density and water uptake in cereals and grain legumes: how well are they correlated. *Australian Journal of Agricultural Research* 38 (3): 513-527. CSIRO Publishing. http://www.publish.csiro.au (accessed March 21, 2007).

Hammer, G.L., Z. Dong., G. McLean., A. Doherty., C. Messina., J. Schussler., C. Zinselmeier., S. Paszkiewicz., and M Cooper. 2009. Can changes in canopy and/or root system architecture explain historical maize yield trends in the U.S. corn belt? *Crop Science* 49:299-312.

Hamza, M. A., and W. K. Anderson. 2005. Soil compaction in cropping systems: A review of the nature, causes and possible solutions. *Soil and Tillage Research* 82 (2): 121-145. Science Direct. http://www.sciencedirect.com (accessed May 23, 2011).

Harlan, J. 1976. Genetic resources in wild relatives of crops. *Crop Science* 16 (3): 329-333. ProQuest. http://www.proquest.co.uk/en-U (accessed April 19, 2010).

Hochman, Z., D. Holzworth, and J. Hunt. 2009. Potential to improve on-farm wheat yield and WUE in Australia. *Crop & Pasture Science* 60: 708-719. CSIRO Publishing. http://www.publish.csiro.au (accessed May 27, 2011).

Howden, M., and R. N. Jones. 2004. Risk assessment of climate change impacts on Australia's wheat industry. *4th International Crop Science Congress*. Brisbane, Australia: The Regional Institute Ltd. http://www.cropscience.org.au/icsc2004/symposia/6/2/1848_howdensm.htm (accessed March 16, 2009).

Howden, S. M., R. G. Gifford, and H. Meinke. 2010. Grains. In *Adapting agriculture to climate change: Preparing Australian agriculture, forestry and fisheries for the future*, ed. C. Stokes and M. Howden. Collingwood, VIC: CSIRO.

IOCI. 2002. *Indian Ocean Climate Initiative: Climate variability and change in south west Western Australia*. Perth. http://www.ioci.org.au/ (accessed March 17, 2009).

IPCC. 2007. *Fourth Assessment Report: Climate Change 2007*. Intergovernmental Panel on Climate Change. http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf (accessed April 12, 2010).

Isbell, R. F. 1993. *A classification system for Australian soils*. Technical report 2/1993: CSIRO.

Johnson, J.W. 1988. Optimzing row spacing and seeding rate for soft red winter-wheat. *Agronomy Journal* 80:164-166.

Johnson, D. A., R. A. Richards, and N. C. Turner. 1983. Yield, water relations, gas exchange, and surface reflectances of near-isogenic wheat lines differing in glaucousness. *Crop Science* 23: 318-325.

Johnson, R. C., R. E. Witters, and A. J. Ciha. 1981. Apparent photosynthesis, evapotranspiration, and light penetration in two contrasting hard red winter wheat canopies. *Agronomy Journal* 73: 419-422.

Jones, B., and N. O'Halloran. 2006. *Farming the Mallee with GPS Guidance*. Walpeup: Victorian Government Department of Primary Industries.

Jones, B. 2009. A new approach to estimate the components of water-use. In GRDC Water-use-efficiency Newsletter, Issue 1:6-8.

Jones, C. A., and J. R. Kiniry. 1986. *CERES-Maize: A simulation model of maize growth and development*. College Station, Texas: Texas A&M University Press.

Karrou, M. 1998. Observations on effect of seeding pattern on water-use efficiency of durum wheat in semi-arid areas of Morocco. *Field Crops Research* 59 (3): 175-179. Science Direct. http://www.sciencedirect.com (accessed October 29, 2007).

Keating, B. A., P. S. Carberry, G. L. Hammer, M. E. Probert, M. J. Robertson, D. Holzworth, N. I. Huth, J. N. G. Hargreaves, H. Meinke, Z. Hochman, G. McLean, K. Verburg, V. Snow, J. P. Dimes, M. Silburn, E. Wang, S. Brown, K. L. Bristow, S. Asseng, S. Chapman, R. L. McCown, D. M. Freebairn, and C. J. Smith. 2003. An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy* 18 (3-4): 267-288. Science Direct. http://www.sciencedirect.com (accessed March 21, 2007).

Kerr, N., K. Siddique, and R. Delane. 1992. Early sowing with wheat cultivars of suitable maturity increases grain yield of spring wheat in a short season environment. *Australian Journal of Agricultural Research* 32 (6): 717-723. CSIRO Publishing. http://www.publish.csiro.au (accessed 23 April 2010).

Kimball, B.A., P.J. Pinter., R.L. Garcia., R.L. LaMorte., G.W. Wall., D.J. Hunsaker., G. Wechsung., F. Wechsung., and T. Kartschall. 1995. Productivity and water use of wheat under free-air CO_2 enrichment. *Global Change Biology* 1:429-442.

Kimball, B.A., C.F. Morris., P.J. Pinter., G.W. Wall., D.J. Hunsaker., F.J. Adamsen., R.L. LaMorte., S.W. Leavitt., T.L. Thompson., A.D. Matthias., and T.J. Brooks. 2001. Elevated CO_2, drought and soil nitrogen effects on wheat grain quality. *New Phytologist* 150:295-303.

Kirby, E. J. M., K. H. M. Siddique, M. W. Perry, D. Kaesehagen, and W. R. Stern. 1989. Variation in spikelet initiation and ear development of old and modern Australian wheat varieties. *Field Crops Research* 20 (2): 113-128. Science Direct http://www.sciencedirect.com (accessed June 1, 2011).

Kirkegaard, J. A., and J. M. Lilley. 2007. Root penetration rate - benchmark to identify soil and plant limitations to rooting depth in wheat. *Australian Journal of Experimental Agriculture* 47: 590-602. Science Direct. http://www.sciencedirect.com (accessed June 29, 2007).

Kirkegaard, J. A., J. M. Lilley, G. N. Howe, and J. M. Graham. 2007. Impact of subsoil water use on wheat yield. *Australian Journal of Agricultural Research* 58: 303-315. CSIRO Publishing. http://www.publish.csiro.au (accessed April 13, 2007).

Kirkegaard, J.A., and J.R. Hunt. 2010. Increasing productivity by matching farming system management and genotype in water-limited environments. *Journal of Experimental Botany* 61:4129-4143.

Kleemann, S. G. L., and G. S. Gill. 2010. Influence of row spacing on water use and yield of rain-fed wheat (Triticum aestivum L.) in a no-till system with stubble retention. *Crop & Pasture Science* 61 (11): 892-898. CSIRO Publishing http://www.publish.csiro.au (accessed February 19, 2011).

Koohafkan, P., and B. A. Stewart. 2008. *Water and Cereals in Drylands*. Sterling, Virginia Earthscan.

Lafond, G.P. 1994. Effects of row spacing, seeding rate and nitrogen on yield of barley and wheat under zero-till management. *Canadian Journal of Plant Science* 74: 703-711.

Lafond, G.P., and D.A. Derksen. 1996. Row spacing and seeding rate effects in wheat and barley under conventional fallow management system. *Canadian Journal of Plant Science* 76: 791-793.

Langer, R. H. M., and F. K. Y. Liew. 1973. Effects of varying nitrogen supply at different stages of the reproductive phase on spikelet and grain production and on grain nitrogen in wheat. *Australian Journal of Agricultural Research* 24: 647-656.

Lilley, J. M., and J. A. Kirkegaard. 2010. Benefits of increased soil exploration by wheat roots. In *'Food Security from Sustainable Agriculture' 15th Agronomy Conference* edited by H. Dove and R. Culvenor. Lincoln, New Zealand.

Littleboy, M., D. M. Silburn, D. M. Freebairn, D. R. Woodruff, G. L. Hammer, and J. K. Leslie. 1992. Impact of soil erosion on production in cropping systems .I. Development and validation of a simulation model. *Australian Journal of Soil Research* 30 (5): 757-774. CSIRO Publishing. http://www.publish.csiro.au (accessed June 28, 2011).

Long, S. P., E. A. Ainsworth, A. Rogers, and D. R. Ort. 2004. Rising atmospheric carbon dioxide: Plants FACE the future. *Annual Review of Plant Biology* 55: 591-628. Annual Reviews. http://www.annualreviews.org/ (accessed April 13, 2010).

Long, S., E. Ainsworth, A. Leakey, J. Nosberger, and D. Ort. 2006. Food for thought: Lower-than-expected crop yield stimulation with rising CO2 concentrations. *Science* 312 (5782): 1918-1921. http://www.sciencemag.org/cgi/content/short/312/5782/1918 (accessed May 17, 2010).

Loss, S. P. 1989. Frost injury to wheat. *Journal of Agriculture, Western Australia* 30: 32-34.

Loss, S. P., E. J. M. Kirby, K. H. M. Siddique, and M. W. Perry. 1989. Grain growth and development of old and modern Australian wheats. *Field Crops Research* 21 (2): 131-146. Science Direct. http://www.sciencedirect.com (accessed June 28, 2011).

Loss, S. P., and K. H. M. Siddique. 1994. Morphological and physiological traits associated with wheat yield increases in Mediterranean environments. *Advances in Agronomy* 52: 229-276.

Ludwig, F., and S. Asseng. 2006. Climate change impacts on wheat production in a Mediterranean environment in Western Australia. *Agricultural Systems* 90 (1-3): 159-179. Science Direct. http://www.sciencedirect.com (accessed June 5, 2008)

Ludwig, F., S. P. Milroy, and S. Asseng. 2009. Impacts of recent climate change on wheat production systems in Western Australia. *Climate Change* 92: 495-517. ProQuest. http://www.proquest.co.uk/en-U (accessed March 13, 2009).

Luo, Q., M. A. J. Williams, W. Bellotti, and B. Bryan. 2003. Quantitative and visual assessments of climate change impacts on South Australian wheat production. *Agricultural Systems* 77 (3): 173-186. Science Direct. http://www.sciencedirect.com (accessed June 28, 2011).

Luo, Q., W. Bellotti, M. Williams, and E. Wang. 2009. Adaptation to climate change of wheat growing in South Australia: Analysis of management and breeding strategies. *Agriculture, Ecosystems & Environment* 129 (1-3): 261-267. Science Direct. http://www.sciencedirect.com (accessed June 29, 2011).

Lutze, J., J. Roden, C. Holly, J. Wolfe, J. Egerton, and M. Ball. 1998. Elevated atmospheric [CO2] promotes frost damage in evergreen tree seedlings. *Plant, Cell and Environment* 21 (6): 631-635.

Manschadi, A., G. Hammer, J. Christopher, and P. deVoil. 2008. Genotypic variation in seedling root architectural traits and implications for drought adaptation in wheat (Triticum aestivum L.). *Plant and Soil* 303 (1): 115-129. SpringerLink. http://www.springerlink.com (accessed June 28, 2011).

McLean, G., J. Whish, R. Routley, I. Broad, and G. Hammer. 2003. *11th Australian Agronomy Conference, The effect of row configuration on yield reliability in grain sorghum. II Modelling the effects of row configuration* Geelong: The Australian Society of Agronomy http://www.regional.org.au/au/asa/2003/c/9/mclean.htm (accessed 18 May 2010).

McLeod, J.G., C.A., Campbell,Y. Gan., F.B. Dyck., and C. L. Vera. 1996. Seeding depth, rate and row spacing for winter wheat grown on stubble and chemical fallow in the semiarid prairies. *Canadian Journal of Plant Science.* 76:207-214.

Miralles, D.J., R.A. Richards., and G.A. Slafer. 2000. Duration of the stem elongation period influences the number of fertile florets in wheat and Barley. *Australian Journal of Plant Physiology* 27:931-940.

Monteith, J. L. 1977. Climate and the efficiency of crop production in Britain. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* 281 (980): 277-294. http://www.jstor.org/stable/2417832 (accessed 28 April 2010).

Monteith, J. L. 1986. How do crops manipulate water supply and demand?. *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences* 316 (1537): 245-259. http://www.jstor.org/stable/37505 (accessed June 28, 2011).

Morgan, J. M., and A. G. Condon. 1986. Water use, grain yield, and osmoregulation in wheat. *Functional Plant Biology* 13 (4): 523-532. CSIRO Publishing http://www.publish.csiro.au (accessed July 17, 2007).

Morgan, J. M., R. A. Hare, and R. J. Fletcher. 1986. Genetic variation in osmoregulation in bread and durum wheats and its relationship to grain yield in a range of field environments. *Australian Journal of Agricultural Research* 37 (5): 449-457. CSIRO Publishing. http://www.publish.csiro.au (accessed March 23, 2007).

Munns, R. 1988. Why Measure Osmotic Adjustment? *Functional Plant Biology* 15 (6): 717-726. CSIRO Publishing. http://www.publish.csiro.au (accessed July 17, 2007).

Nix, H. A. 1975. The Australian climate and its effect on grain yield and quality. In *Australian Field Crops, Volume 1: Wheat and Other Temperate Cereals*, ed. A. Lazenby and E. M. Matheson. Sydney: Angus and Robertson.

Norton, R., and N. Wachsmann. 2006. Nitrogen use and crop type affect the water use of annual crops in south-eastern Australia. *Australian journal of agricultural research* 57 (3): 257-267. CSIRO Publishing. http://www.publish.csiro.au (accessed June 28, 2011).

Oliver, Y., M. Robertson, P. Stone, and A. Whitbread. 2009. Improving estimates of water-limited yield of wheat by accounting for soil type and within-season rainfall. *Crop and Pasture Science* 60 (12): 1137-1146. CSIRO Publishing. http://www.publish.csiro.au (accessed May 3, 2011).

Oliver, Y. M., M. J. Robertson, and C. Weeks. 2010. A new look at an old practice: Benefits from soil water accumulation in long fallows under Mediterranean conditions. *Agricultural Water Management* 98 (2): 291-300. Science Direct. http://www.sciencedirect.com (accessed March 15, 2011).

Olsen, J., and J. Weiner. 2007. The influence of Triticum aestivum density, sowing pattern and nitrogen fertilization on leaf area index and its spatial variation. *Basic and Applied Ecology* 8 (3): 252-257. Science Direct. http://www.sciencedirect.com (accessed April 18, 2007).

Panozzo, J. F., and H. A. Eagles. 1998. Cultivar and environmental effects on quality characters in wheat. I. Starch. *Australian Journal of Agricultural Research* 49 (5): 757-766. CSIRO Publishing. http://www.publish.csiro.au (accessed June 28, 2011).

Panozzo, J., and H. Eagles. 1999. Rate and duration of grain filling and grain nitrogen accumulation of wheat cultivars grown in different environments. *Australian Journal of Agricultural Research* 50 (6): 1007-1015. CSIRO Publishing. http://www.publish.csiro.au (accessed June 28, 2011).

Panozzo, J., and H. Eagles. 2000. Cultivar and environmental effects on quality characters in wheat. II. Protein. *Australian Journal of Agricultural Research* 51 (5): 629-636. CSIRO Publishing. http://www.publish.csiro.au (accessed June 28, 2011).

Passioura, J. 1977. Grain yield, harvest index, and water use of wheat. *The Journal of the Australian Institute of Agricultural Science* 43: 117-120.

Passioura, J. B. 1983. Roots and drought resistance. *Agricultural Water Management* 7: 265-280. Science Direct. http://www.sciencedirect.com (accessed June 29, 2007).

Passioura, J. 2002. Environmental biology and crop improvement *Functional Plant Biology* 29: 537-549. CSIRO Publishing. http://www.publish.csiro.au (accessed May 16, 2010).

Passioura, J. 2004. Increasing crop productivity when water is scarce - From breeding to field management In *New Directions for a diverse planet: 4th International Crop Science Congress*, edited by R. A. Fischer. Brisbane, Australia. The Regional Institute Ltd.

Peltzer, S. C., A. Hashem, V. A. Osten, M. L. Gupta, A. J. Diggle, G. P. Riethmuller, A. Douglas, J. M. Moore, and E. A. Koetz. 2009. Weed management in wide-row cropping systems: a review of current practices and risks for Australian farming systems. *Crop & Pasture Science* 60 (5): 395-406. CSIRO Publishing. http://www.publish.csiro.au (accessed March 25, 2011).

Perry, M. W., and M. F. D'Antuono. 1989. Yield improvement and associated characteristics of some Australian spring wheat cultivars introduced between 1860 and 1982. *Australian Journal of Agricultural Research* 40 (3): 457-472. CSIRO Publishing. http://www.publish.csiro.au (accessed August 15, 2007).

Photiades, I., and A. Hadjichristodoulou. 1984. Sowing date, sowing depth, seed rate and row spacing of wheat and barley under dryland conditions. *Field Crops Research* 9: 151-162. Science Direct. http://www.sciencedirect.com (accessed April 18, 2007).

Puckridge, D. W., and C. M. Donald. 1967. Competition among wheat plants sown at a wide range of densities *Australian journal of agricultural research* 18: 193-211. CSIRO Publishing. http://www.publish.csiro.au (accessed 3 May 2010).

Quarrie, S. A., J. Stojanovic, and S. Pekic. 1999. Improving drought resistance in small-grained cereals: A case study, progress and prospects. *Plant Growth Regulation* 29: 1-21. SpringerLink. http://www.springerlink.com (accessed July 17, 2007).

Rebbeck, M.A. and G.A. Knell. 2007. "Managing Frost Risk: A Guide for Southern Australian Grains". SARDI and GRDC.

Rebetzke, G.J., A.J. Condon., R.A. Richards., and G.D. Farquhar. 2002. Selection for reduced carbon isotope discrimination increases aerial biomass and grain yield of rainfed bread wheat. *Crop Science* 42:739-745.

Rebetzke, G. J., T. L. Botwright, C. S. Moore, R. A. Richards, and A. G. Condon. 2004. Genotypic variation in specific leaf area for genetic improvement of early vigour in wheat. *Field Crops Research* 88 (2-3): 179-189. Science Direct. http://www.sciencedirect.com (accessed June 28, 2011).

Rebetzke, G. J., R. A. Richards, N. A. Fettell, M. Long, A. G. Condon, R. I. Forrester, and T. L. Botwright. 2007. Genotypic increases in coleoptile length improves stand establishment, vigour and grain yield of deep-sown wheat. *Field Crops Research* 100 (1): 10-23. Science Direct. http://www.sciencedirect.com (accessed June 29, 2007).

Reeves, T., P. Haines, and D. Coventry. 1984. Growth of wheat and subterranean clover on soil artificially compacted at various depths. *Plant and Soil* 80 (1): 135-138. Springerlink. http://www.springerlink.com (accessed April 7, 2011).

Reynolds, M. P., A. Majeeb-Kazi, and M. Sawkins. 2005. Prospects for utilising plant-adaptive mechanisms to improve wheat and other crops in drought and salinity prone environments. *Annals of Applied Biology* 146: 239-259.

Richards, R. 1983. Manipulation of leaf area and its effect on grain yield in droughted wheat. *Australian journal of agricultural research* 34 (1): 23-31. CSIRO Publishing. http://www.publish.csiro.au (accessed March 1, 2011).

Richards, R. A. 1988. A tiller inhibitor gene in wheat and its effect on plant growth. *Australian Journal of Agricultural Research* 39 (5): 749-757. CSIRO Publishing. http://www.publish.csiro.au (accessed July 30, 2007).

Richards, R. A., and J. B. Passioura. 1989. A breeding program to reduce the diameter of the major xylem vessel in the seminal roots of wheat and its effect on grain yield in rainfed environments. *Australian Journal of Agricultural Research* 40 (5): 943-950. CSIRO Publishing http://www.publish.csiro.au (accessed April 21, 2011).

Richards, R. A. 1991. Crop improvement for temperate Australia: Future opportunities. *Field Crops Research* 26 (2): 141-169. Science Direct. http://www.sciencedirect.com (accessed May 16, 2010).

Richards, R. A. 1996. Defining selection criteria to improve yield under drought. *Plant Growth Regulation* 20: 157-166.

Richards, R. A., and Z. Lukacs. 2002. Seedling vigour in wheat - sources of variation for genetic and agronomic improvement. *Australian Journal of Agricultural Research* 53 (1): 41-50. CSIRO Publishing. http://www.publish.csiro.au (accessed July 30, 2007).

Richards, R. A., G. J. Rebetzke, A. G. Condon, and A. F. van Herwaarden. 2002. Breeding Opportunities for Increasing the Efficiency of Water Use and Crop Yield in Temperate Cereals. *Crop Science* 42 (1): 111-121. ProQuest. http://www.proquest.co.uk/en-U (accessed August 21, 2007).

Richards, R. A. 2006. Physiological traits used in the breeding of new cultivars for water-scarce environments. *Agricultural Water Management* 80 (1-3): 197-211. Science Direct. http://www.sciencedirect.com (accessed March 21, 2007).

Richards, R. A., M. Watt, and G. J. Rebetzke. 2007. Physiological traits and cereal germplasm for sustainable agricultural systems. *Euphytica* 154: 409-425.

Richards, R. A. 2008. Genetic opportunities to improve cereal root systems for dryland agriculture. *Plant Production Science* 11 (1): 12-16. http://www.jstage.jst.go.jp/article/pps/11/1/12/_pdf (accessed June 28, 2011).

Ritchie, J. T. 1974. Atmospheric and soil water influences on the plant water balance. *Agricultural Meteorology* 14 (1-2): 183-198. Science Direct. http://www.sciencedirect.com (accessed March 1, 2011).

Ritchie, J. T. 1983. Efficient water use in crop production: Discussion on the generality of relations between biomass production and evapotranspiration. In *Limitations to Efficient Water Use in Crop Production*, ed. H. M. Taylor, W. R. Jordan and T. R. Sinclair. Madison, Wisconsin: American Society of Agronomy, Inc.

Roderick, M. L., and G. D. Farquhar. 2004. Changes in Australian pan evaporation from 1970 to 2002. *International Journal of Climatology* 24: 1077-1090. http://www.rsbs.anu.edu.au/Profiles/Graham_Farquhar/documents/214RoderickAustpan2004_000.pdf (accessed May 17, 2010).

Roderick, M.L., L.D. Rotstayn., G.D. Farquhar., and M.T. Hobbins. 2007. On the attribution of changing pan evaporation. *Geophysical Research Letters* 34.

Routley, R., I. Broad, G. McLean, J. Whish, and G. Hammer. 2003. *11th Australian Agronomy Conference The effect if row configuration on yield reliability in grain sorghum. I. Yield, water use efficiency and soil water extraction* Geelong: The Australian Society of Agronomy http://www.regional.org.au/au/asa/2003/c/9/routley.htm (accessed June 28, 2011).

Russell, J. J. 2005. *Major soils of the eastern wheatbelt to characterise soil moisture availability*. Technical report 187: Department of Agriculture, Western Australia.

Ruuska, S. A., G. J. Rebetzke, A. F. van Herwaarden, R. A. Richards, N. A. Fettel, L. Tabe, and L. D. Jenkins. 2006. Genotypic variation in water-soluble carbohydrate accumulation in wheat. *Functional Plant Biology* 33: 799 - 809. CSIRO Publishing. http://www.publish.csiro.au (accessed March 21, 2007).

Sadras, V. O., and J. F. Angus. 2006. Benchmarking water-use efficiency of rainfed wheat in dry environments. *Australian Journal of Agricultural Research* 57 (8): 847. CSIRO Publishing http://www.publish.csiro.au (accessed May 2, 2011).

Sadras, V. O., and J. P. Monzon. 2006. Modelled wheat phenology captures rising temperature trends: Shortened time to flowering and maturity in Australia and Argentina. *Field Crops Research* 99 (2-3): 136-146. Science Direct. http://www.sciencedirect.com (accessed February 15, 2011).

Sadras, V., and D. Rodriguez. 2007. The limit to wheat water-use efficiency in eastern Australia. II. Influence of rainfall patterns. *Australian Journal of Agricultural Research* 58 (7): 657-669. CSIRO Publishing. http://www.publish.csiro.au (accessed May 3, 2011).

Satorre, E. H. 1999. Plant density and distribution as modifiers of growth and yield. In *Wheat: Ecology and physiology of yield determination* ed. E. H. Satorre and G. A. Slafer. Binghampton, NY: Food Products Press.

Serraj, R., and T. R. Sinclair. 2002. Osmolyte accumulation: can it really help increase crop yield under drought conditions? *Plant, Cell & Environment* 25 (2): 333-341. Blackwell Synergy. http://www.blackwellpublishing.com (accessed July 17, 2007).

Setter, T. L. 2000. Germination, vegetative and reproductive growth. In *The Wheat Book: Practices and Principles*, ed. W. K. Anderson and J. R. Garlinge. Perth: Department of Agriculture, Western Australia.

Shackley, B. L. 2000. Crop Management. In *The Wheat Book: Principles and Practice*, ed. W. K. Anderson and J. R. Garlinge. Perth: Department of Agriculture, Western Australia.

Sharma, D. L., and W. K. Anderson. 2004. Small grain screenings in wheat: interactions of cultivars with season, site, and management practices. *Australian Journal of Agricultural Research* 55 (7): 797-809. CSIRO Publishing. http://www.publish.csiro.au (accessed May 26, 2011).

Sharma, D., M. D'Antuono, W. Anderson, B. Shackley, C. Zaicou-Kunesch, and M. Amjad. 2008. Variability of optimum sowing time for wheat yield in Western Australia. *Australian Journal of Agricultural Research* 59 (10): 958-970. CSIRO Publishing. http://www.publish.csiro.au (accessed April 23, 2010).

Siddique, K. H. M., R. K. Belford, M. W. Perry, and D. Tennant. 1989. Growth, Development and Light Interception of old and Modern Wheat Cultivars in a Mediterranean-type Environment. *Australian Journal of Agricultural Research* 40: 473-487. CSIRO Publishing http://www.publish.csiro.au (accessed July 22, 2008).

Siddique, K., D. Tennant, M. Perry, and R. Belford. 1990. Water-use and water-use efficiency of old and modern wheat cultivars in a Mediterranean-type environment. *Australian Journal of Agricultural Research* 41 (3): 431-447. CSIRO Publishing. http://www.publish.csiro.au (accessed 3 May 2010).

Simon, J. C., and G. Lemaire. 1987. Tillering and leaf area index in grasses in the vegetative phase. *Grass and Forage Science* 42 (4): 373-380. Wiley Online Library. http://onlinelibrary.wiley.com (accessed June 28, 2011).

Sinclair, T. R., and T. Horie. 1989. Leaf nitrogen, photosynthesis, and crop radiation use efficiency - A review. *Crop Science* 29 (1): 90-98.

Sinclair, T. R., and R. C. Muchow. 1999. Radiation use efficiency. *Advances in Agronomy* 65: 215-265.

Slafer, G., and H. Rawson. 1994. Sensitivity of wheat phasic development to major environmental factors: A re-examination of some assumptions made by physiologists and modellers. *Australian Journal of Plant Physiology* 21 (4): 393-426.

Spiertz, J. H. J., and N. M. De Vos. 1983. Agronomical and physiological aspects of the role of nitrogen in yield formation of cereals. *Plant and Soil* 75: 379-391.

Stapper, M., and R.A. Fischer. 1990. Genotype, sowing date and plant density influence on high-yielding irrigated wheat in southern NSW. II Growth, yield and nitrogen use. *Australian Journal of Agricultural Research* 41:1021-1041.

Stephens, D., and T. Lyons. 1998a. Rainfall-yield relationships across the Australian wheatbelt. *Australian Journal of Agricultural Research* 49 (2): 211-223. CSIRO Publishing. http://www.publish.csiro.au (accessed April 23, 2010).

Stephens, D., and T. Lyons. 1998b. Variability and trends in sowing dates across the Australian wheatbelt. *Australian Journal of Agricultural Research* 49 (7): 1111-1118. CSIRO Publishing. http://www.publish.csiro.au (accessed April 23, 2010).

Stone, R. C., N. Nicholls, and G. Hammer. 1996. Frost in northeast Australia: Trends and influences of phases of the southern oscillation. *Journal of Climate* 9 (8): 1896-1909.

Stoskopf, N. C. 1985. *Cereal Grain Crops*. Reston, Virginia: Reston Publishing Company, Inc.

Synnott, K. 1938. *The Farmers' Handbook*. Fifth ed. Sydney: Department of Agriculture, New South Wales.

Tanner, C. B., and T. R. Sinclair. 1983. Efficient water use in crop production: Research or re-search? In *Limitations to Efficient Water Use in Crop Production*, ed. H. M. Taylor, W. R. Jordan and T. R. Sinclair. Madison, Wisconsin: American Society of Agronomy, Inc.

Tausz-Posch, S., S. Senewera., R.M. Norton., G.J. Fitzgerald., and M Tausz. 2012. Can a wheat cultivar with high transpiration efficiency maintain its yield advantage over a near-isogenic cultivar under elevated CO_2. *Field Crop Research*. 133:160-166.

Tompkins, D. K., D. B. Fowler, and A. T. Wright. 1991. Water use by no-till winter wheat influence of seed rate and row spacing. *Agronomy Journal* 83: 766-769.

Torok, S., and N. Nicholls. 1996. A historical annual temperature dataset for Australia. *Australian Meteorological Magazine* 45 (4): 251-260. http://210.8.186.60/amm/docs/1996/torok.pdf (accessed April 23, 2010).

Tubiello, F. N., J. S. Amthor, K. J. Boote, M. Donatelli, W. Easterling, G. Fischer, R. M. Gifford, M. Howden, J. Reilly, and C. Rosenzweig. 2007. Crop response to elevated CO2 and world food supply - A comment on "Food for Thought..." by Long et al., Science 312: 1918-1921, 2006. *European Journal of Agronomy* 26 (3): 215-223.

Turner, N.C., and M. Nicholas. 1987. “Drought resistance of wheat for light-textured soils in a Mediterranean climate”. In *Drought Tolerance in Winter Cereals*, edited by P. Srivastava, E. Porceddu, E. Acevedo and S. Varma. John Wiley. Chitchester.

Turner, N.C. 2004. Agronomic options for improving rainfall-use efficiency of crops in dryland farming systems. *Journal of Experimental Botany* 55:2413-2425.

van Herwaarden, A. F., G. D. Farquhar, J. F. Angus, R. A. Richards, and G. N. Howe. 1998. 'Haying-off', the negative grain yield response of dryland wheat to nitrogen fertiliser. I. Biomass, grain yield, and water use. *Australian Journal of Agricultural Research* 49 (7): 1067-1082. CSIRO Publishing. http://www.publish.csiro.au (accessed September 4, 2007).

van Ittersum, M. K., S. M. Howden, and S. Asseng. 2003. Sensitivity of productivity and deep drainage of wheat cropping systems in a Mediterranean environment to changes in CO2, temperature and precipitation. *Agriculture, Ecosystems & Environment* 97 (1-3): 255-273. Science Direct. http://www.sciencedirect.com (accessed June 28, 2011).

Wall, G. W., and E. T. Kanemasu. 1990a. Carbon dioxide exchange rates in wheat canopies. Part I. Influence of canopy geometry on trends in leaf area index, light interception and instantaneous exchange rates. *Agricultural and Forest Meteorology* 49 (2): 81-102. Science Direct. http://www.sciencedirect.com (accessed April 18, 2007).

Wall, G. W., and E. T. Kanemasu. 1990b. Carbon dioxide exchange rates in wheat canopies. Part II. Photosynthetic and phytomass production efficiencies. *Agricultural and Forest Meteorology* 49 (2): 103-122. Science Direct. http://www.sciencedirect.com (accessed April 18, 2007).

Wang, J., E. L. Wang, and D. L. Liu. 2011. Modelling the impacts of climate change on wheat yield and field water balance over the Murray-Darling Basin in Australia. *Theoretical and Applied Climatology* 104: 285-300. www.cua.edu.cn (accessed June 27, 2011).

Ward, P.R., Hall, D.J.M., Micin, S.F., Whisson, K., Willis, T.M., Treble, K., and D Tennant. 2007. Water use by annual crops. 1. Role of dry matter production. *Australian Journal of Agricultural Research* 58:1159-1166.

Wardlaw, I. F., I. A. Dawson, P. Munibi, and R. Fewster. 1989. The tolerance of wheat to high temperatures during reproductive growth 1. Survey procedures and general response patterns. *Australian Journal of Agricultural Research* 40 (1): 1-13. CSIRO Publishing. http://www.publish.csiro.au (accessed June 28, 2011).

Wardlaw, I. F., and C. W. Wrigley. 1994. Heat tolerance in temperate cereals - An overview. *Australian Journal of Plant Physiology* 21 (6): 695-703. CSIRO Publishing. http://www.publish.csiro.au (accessed June 28, 2011).

Winter, S. R., and A. D. Welch. 1987. Tall and semidwarf wheat response to dryland planting systems. *Agronomy Journal* 79: 641-645.

Yunusa, I. A. M., R. K. Belford, D. Tennant, and R. H. Sedgley. 1993. Row spacing fails to modify soil evaporation and grain yield in spring wheat in a dry Mediterranean environment. *Australian Journal of Agricultural Research* 44 (4): 661-676. CSIRO Publishing. http://www.publish.csiro.au (accessed October 29, 2007).

Yunusa, I. A. M., R. H. Sedgley, R. K. Belford, and D. Tennant. 1993. Dynamics of water use in a dry Mediterranean environment I. Soil evaporation little affected by presence of plant canopy. *Agricultural Water Management* 24 (3): 205-224. Science Direct. http://www.sciencedirect.com (accessed March 27, 2008).

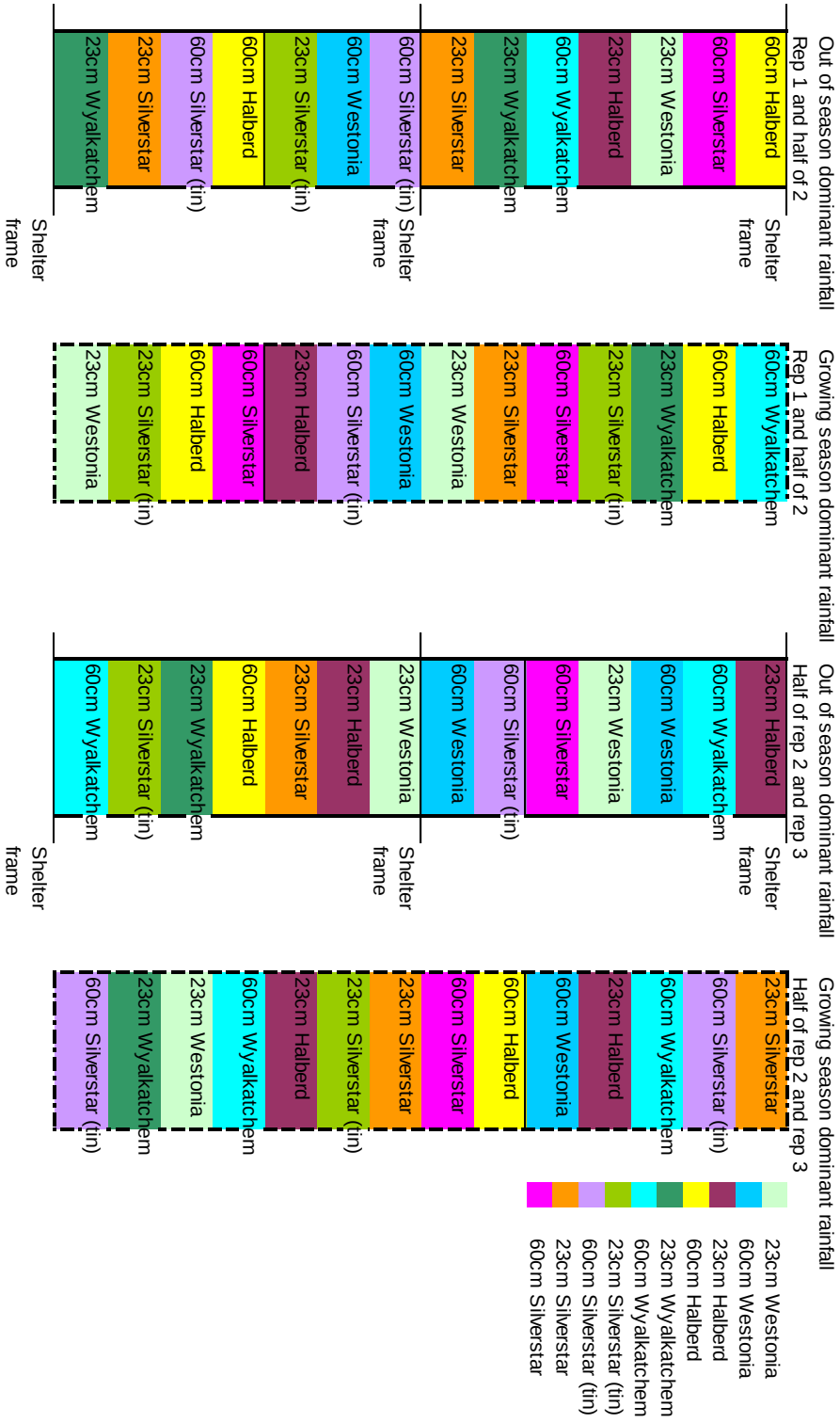
Zerner, M., and G. Gill. 2010. Stability of competitive ability in wheat genotypes across different weed species. In *Food Security from Sustainable Agriculture, 15th Agronomy Conference 2010*, edited by H. Dove and R. Culvenor. Loncoln, New Zealand.

Zhang, G. S., K. Y. Chan, A. Oates, D. P. Heenan, and G. B. Huang. 2007. Relationship between soil structure and runoff/soil loss after 24 years of conservation tillage. *Soil and Tillage Research* 92 (1-2): 122-128. Science Direct. http://www.sciencedirect.com (accessed March 1, 2011).

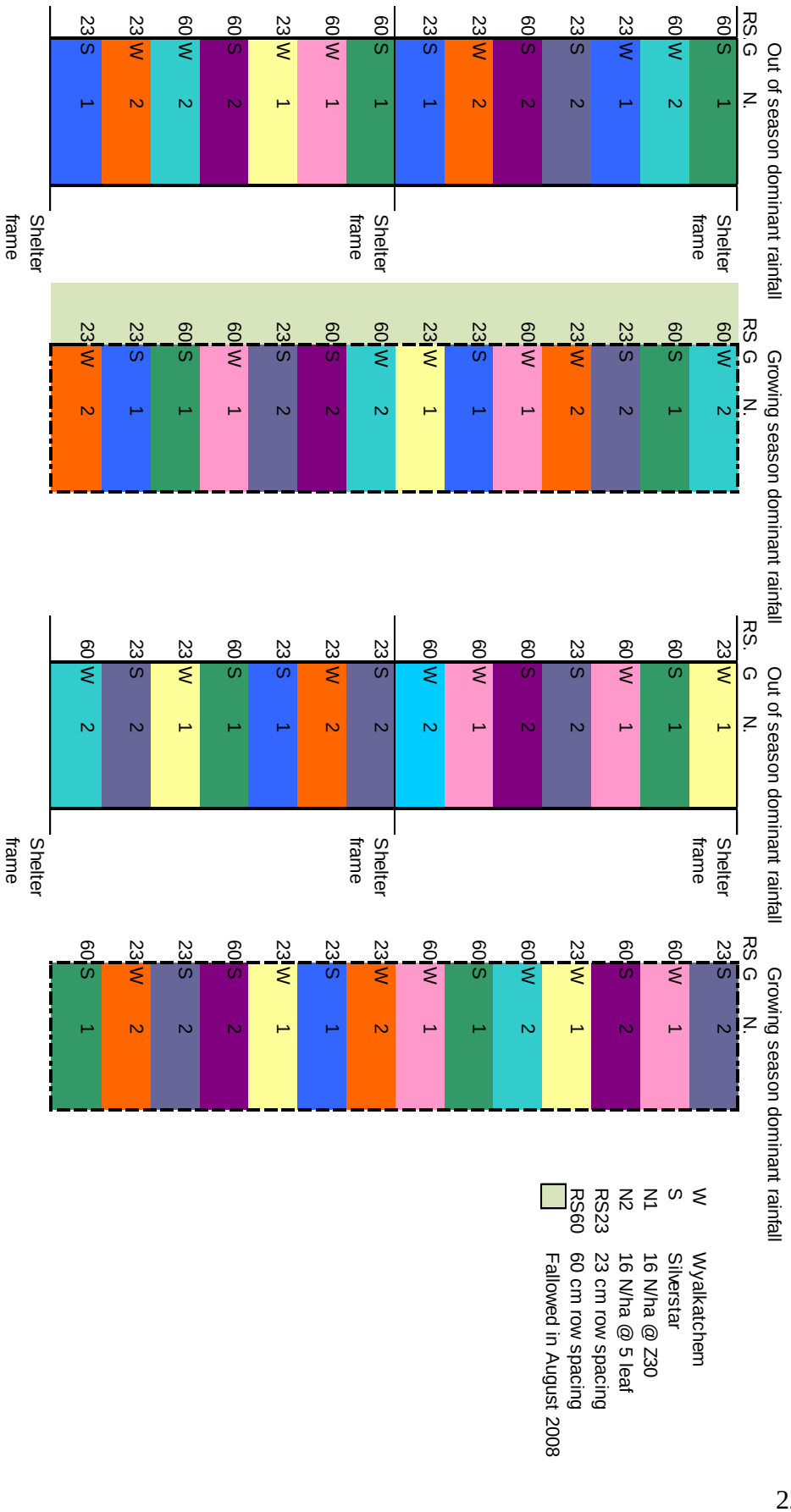
Zhang, H., N. Turner, N. Simpson, and M. Poole. 2010. Growing-season rainfall, ear number and the water-limited potential yield of wheat in south-western Australia. *Crop and Pasture Science* 61 (4): 296-303. CSIRO Publishing. http://www.publish.csiro.au (accessed March 16, 2011).

Appendix

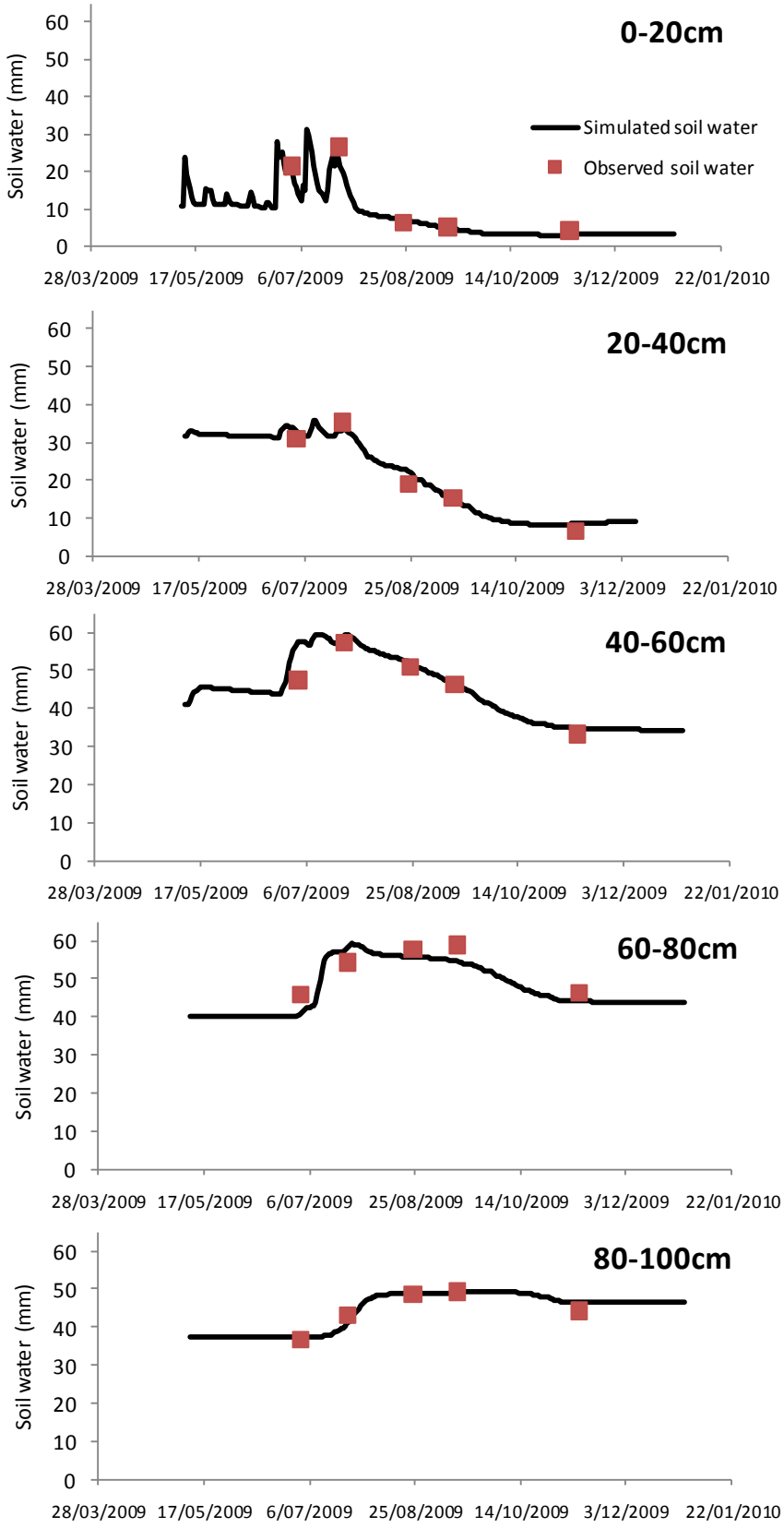
Appendix 1: Layout of 2008 field experiment at Merredin Research Station



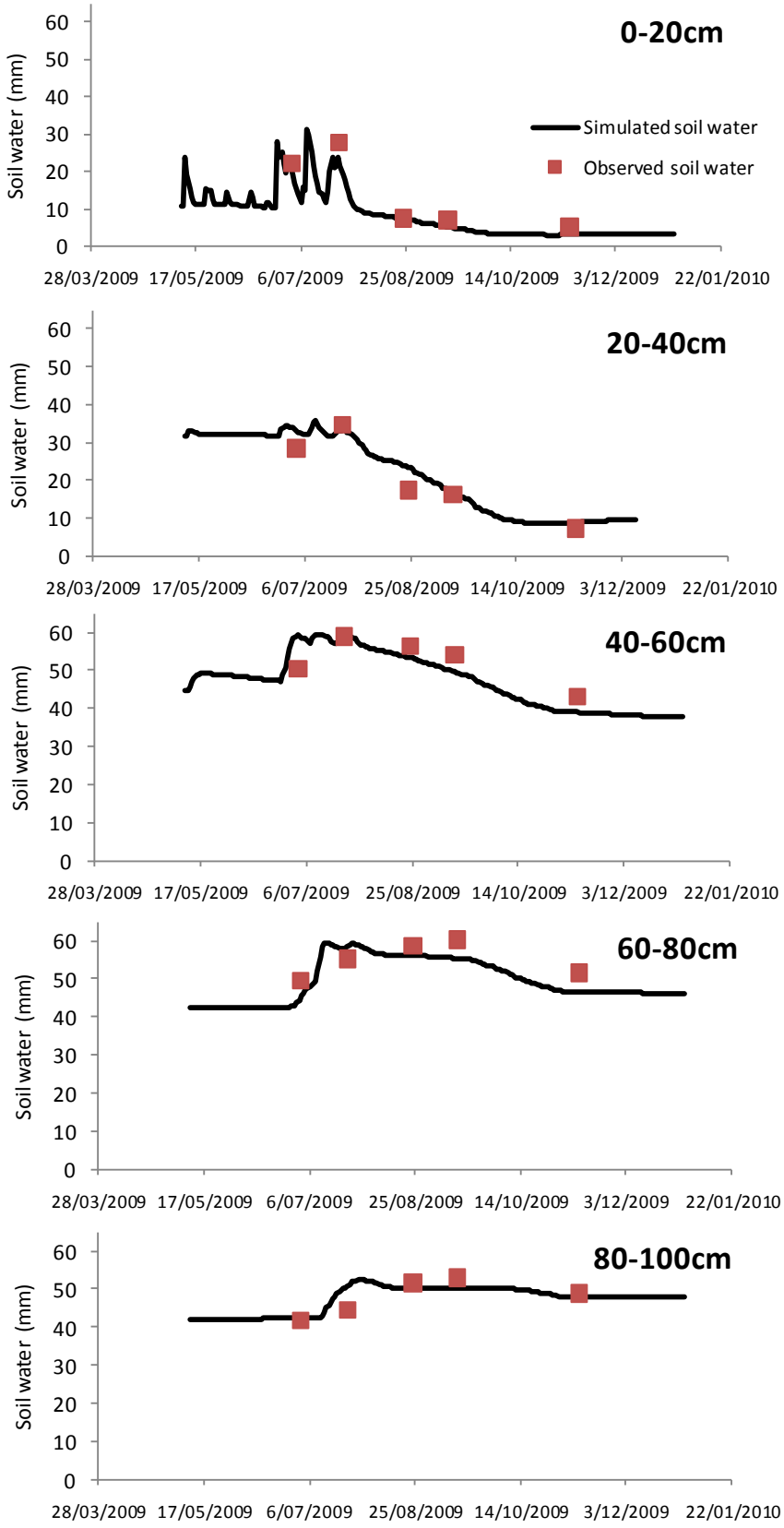
Appendix 2: Layout of 2009 field experiment at Merredin Research Station



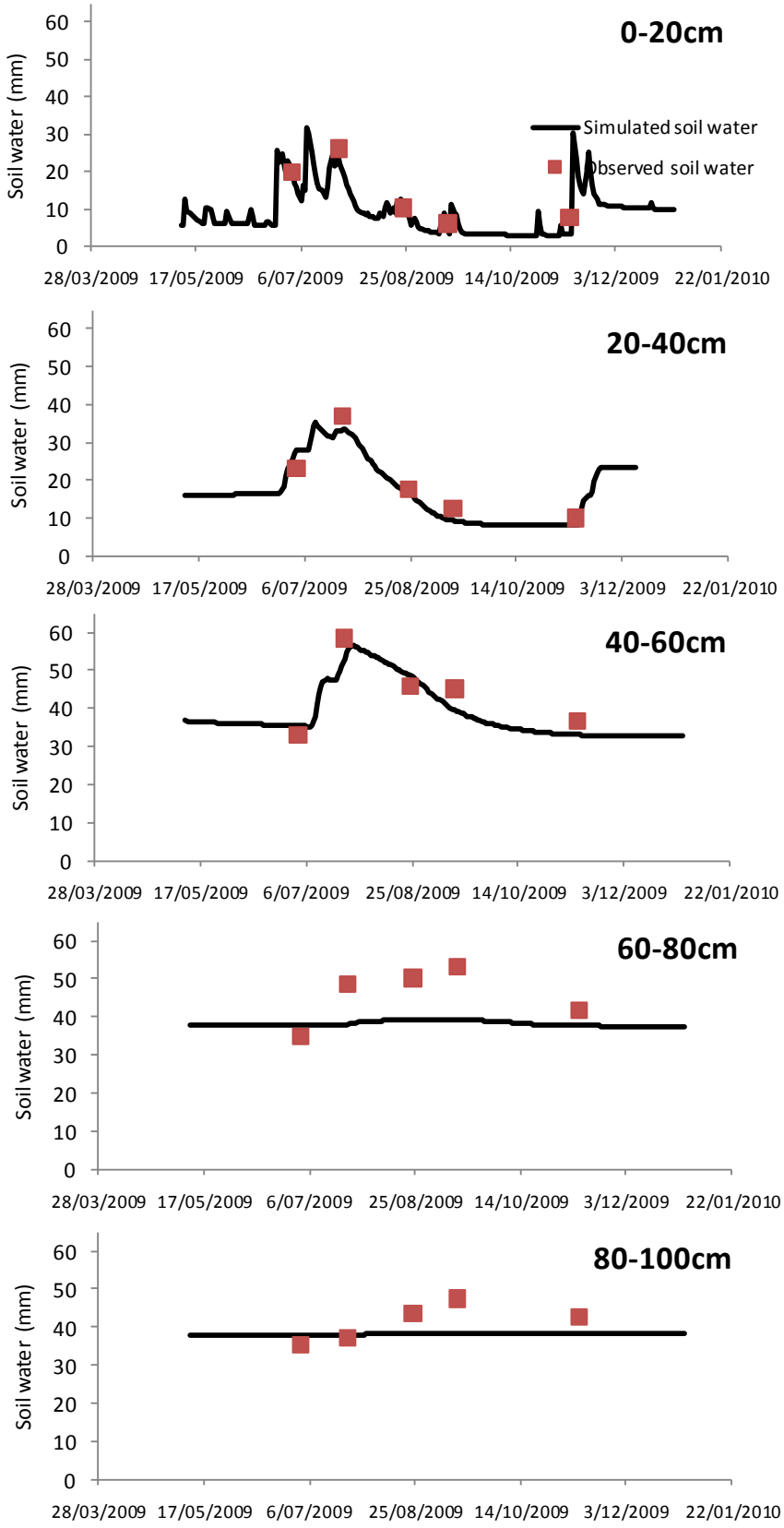
Appendix 3: Simulated versus observed value comparisons of soil water for out of season dominant rainfall and 23 cm row spacing.



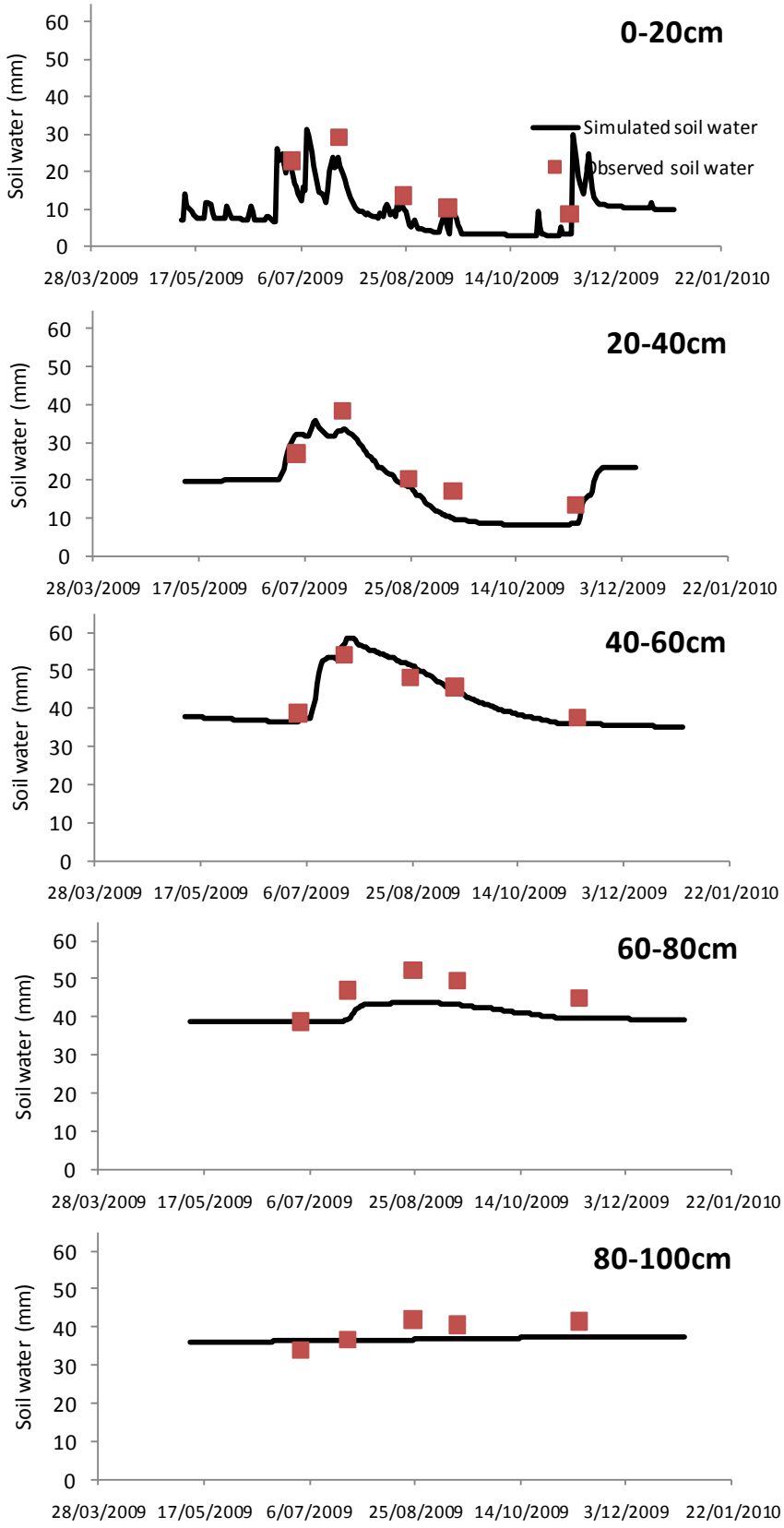
Appendix 4: Simulated versus observed value comparisons of soil water for out of season dominant rainfall and 60 cm row spacing.



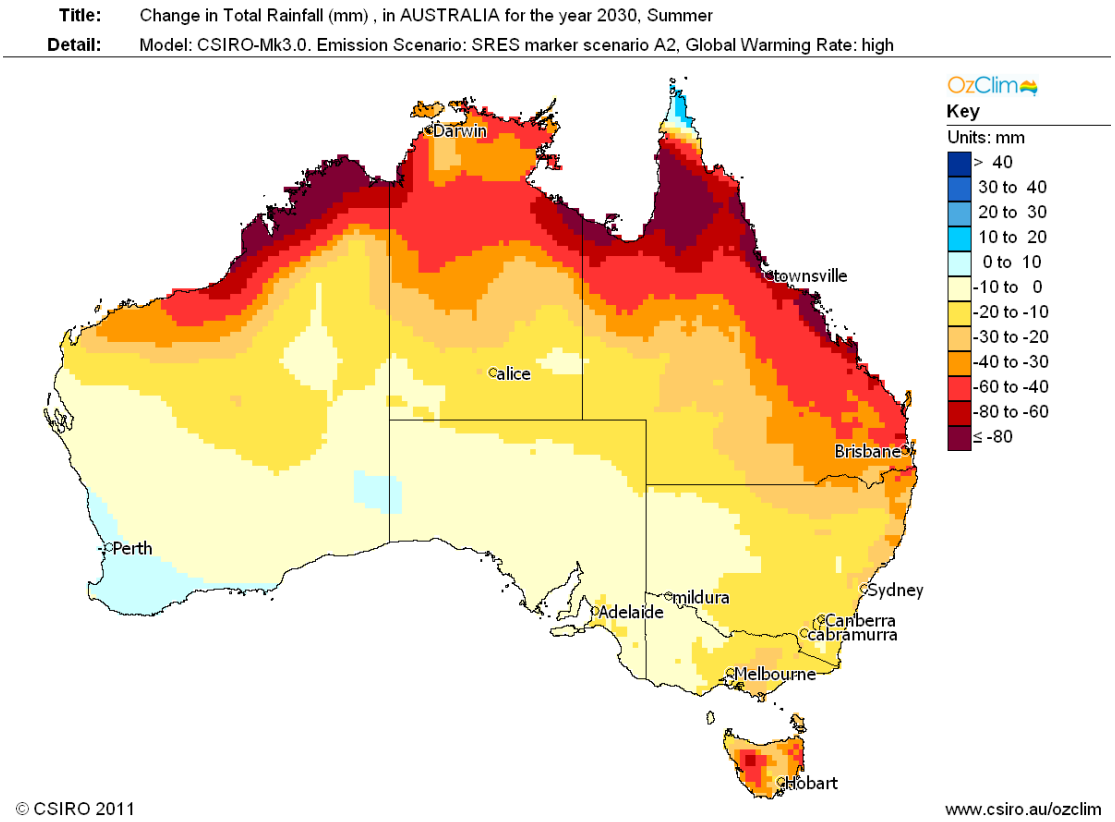
Appendix 5: Simulated versus observed value comparisons of soil water for growing season dominant rainfall and 23 cm row spacing.



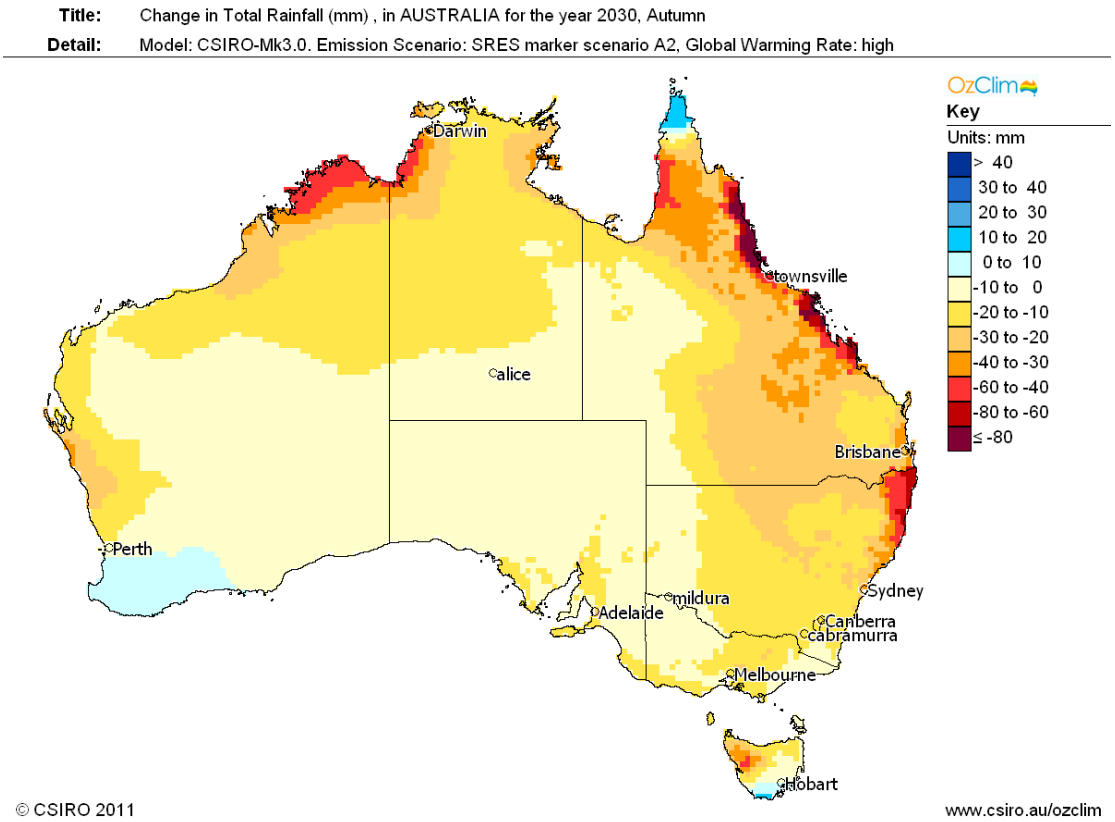
Appendix 6: Simulated versus observed value comparisons of soil water for growing season dominant rainfall and 60 cm row spacing.



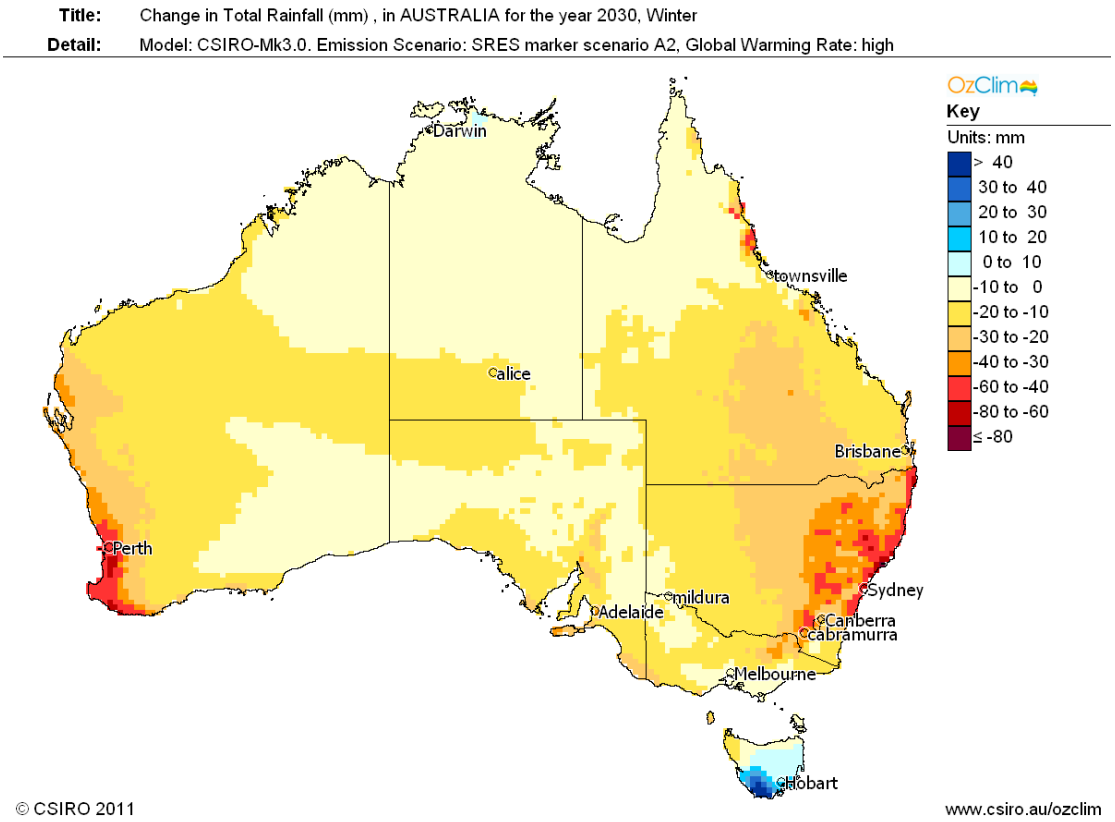
Appendix 7: Predicted change in summer rainfall by 2030 for 'pessimistic' future climate.



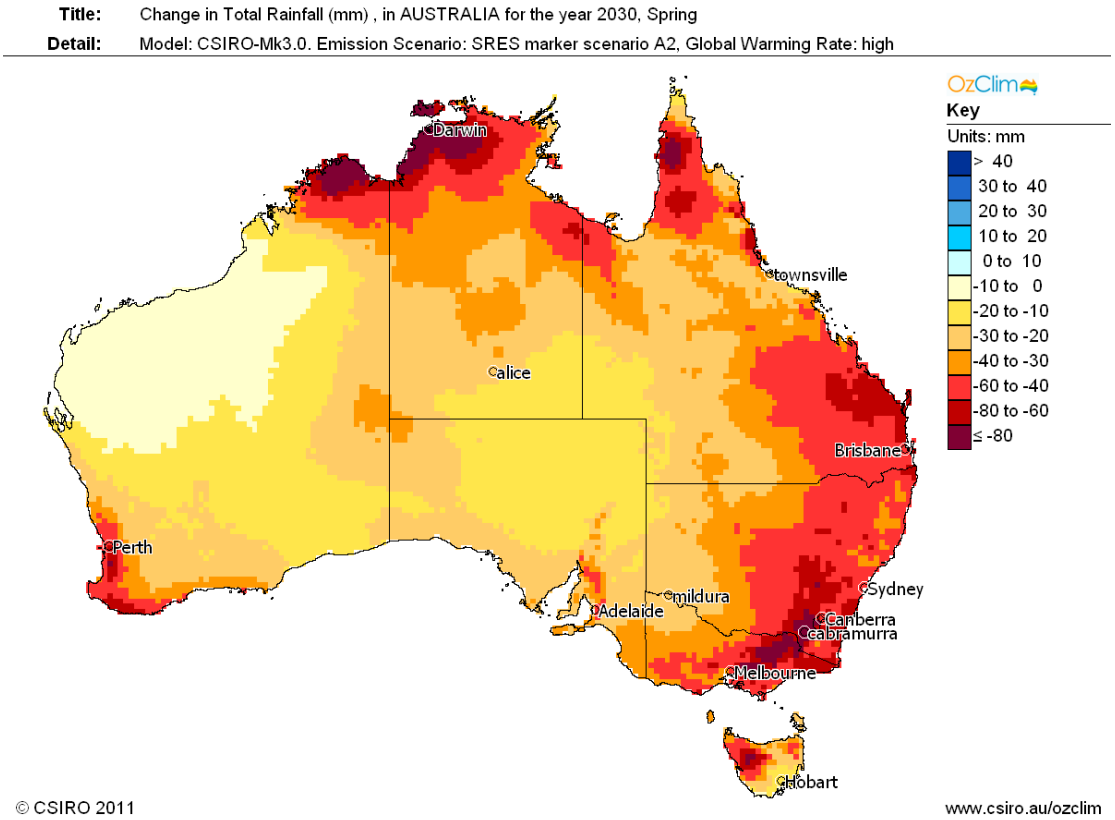
Appendix 8: Predicted change in autumn rainfall by 2030 for 'pessimistic' future climate.



Appendix 9: Predicted change in winter rainfall by 2030 for 'pessimistic' future climate.



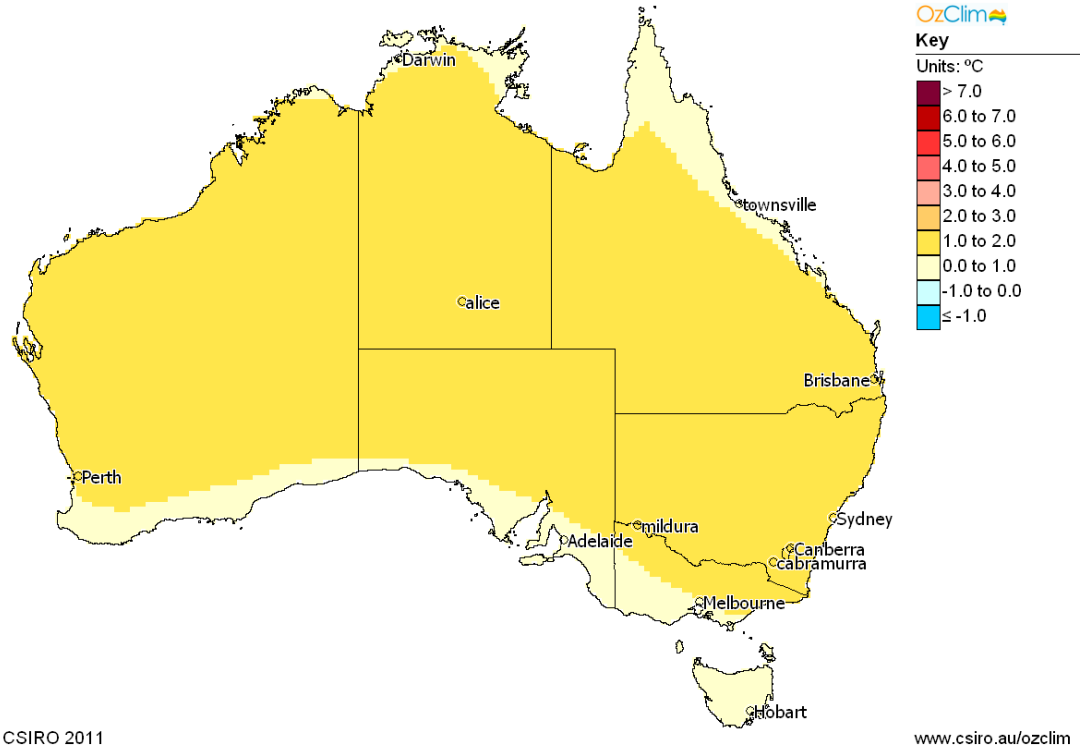
Appendix 10: Predicted change in spring rainfall by 2030 for 'pessimistic' future climate.



Appendix 11: Predicted change in annual mean temperature by 2030 for 'pessimistic' future climate.

Title: Change in Mean Surface Temperature (ºC) , in AUSTRALIA for the year 2030, Annual

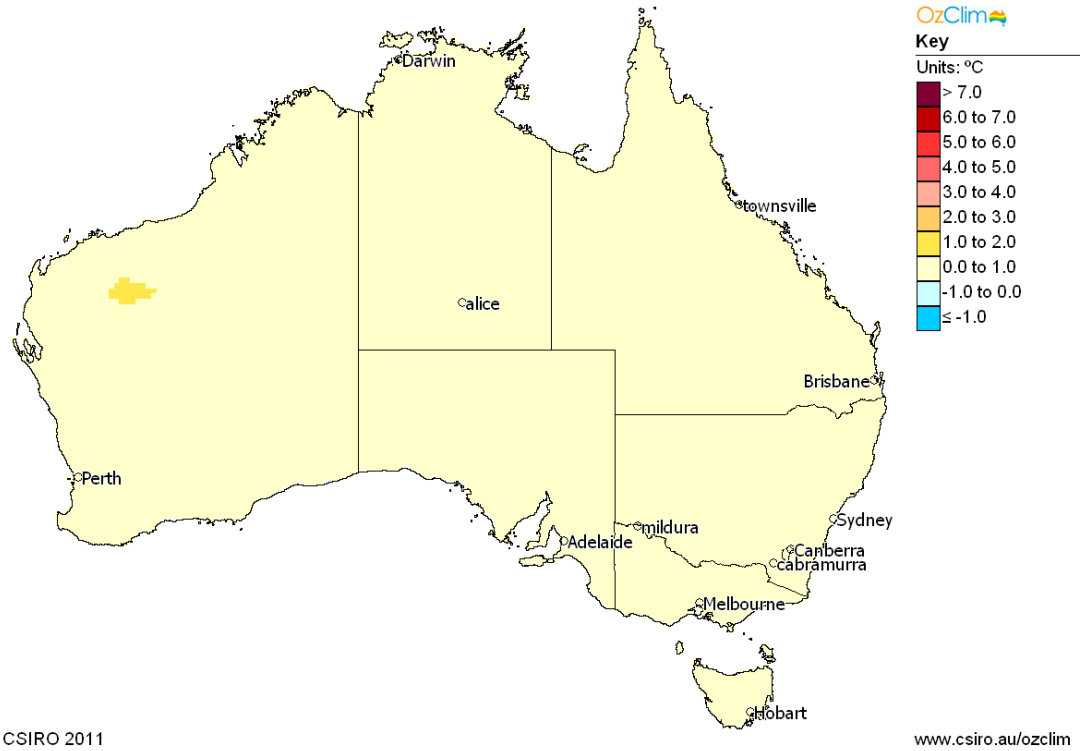
Detail: Model: CSIRO-Mk3.0. Emission Scenario: SRES marker scenario A2, Global Warming Rate: high



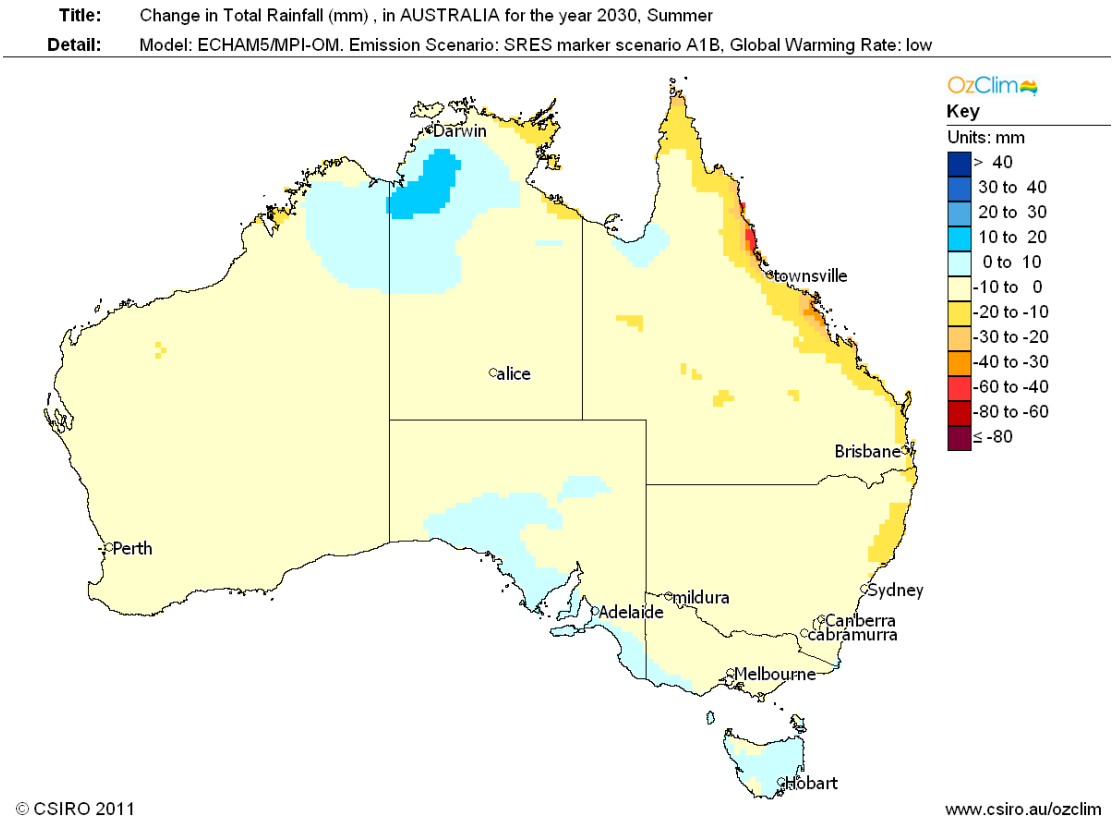
Appendix 12: Predicted change in annual mean temperature by 2030 for 'optimistic' future climate.

Title: Change in Mean Surface Temperature (ºC) , in AUSTRALIA for the year 2030, Annual

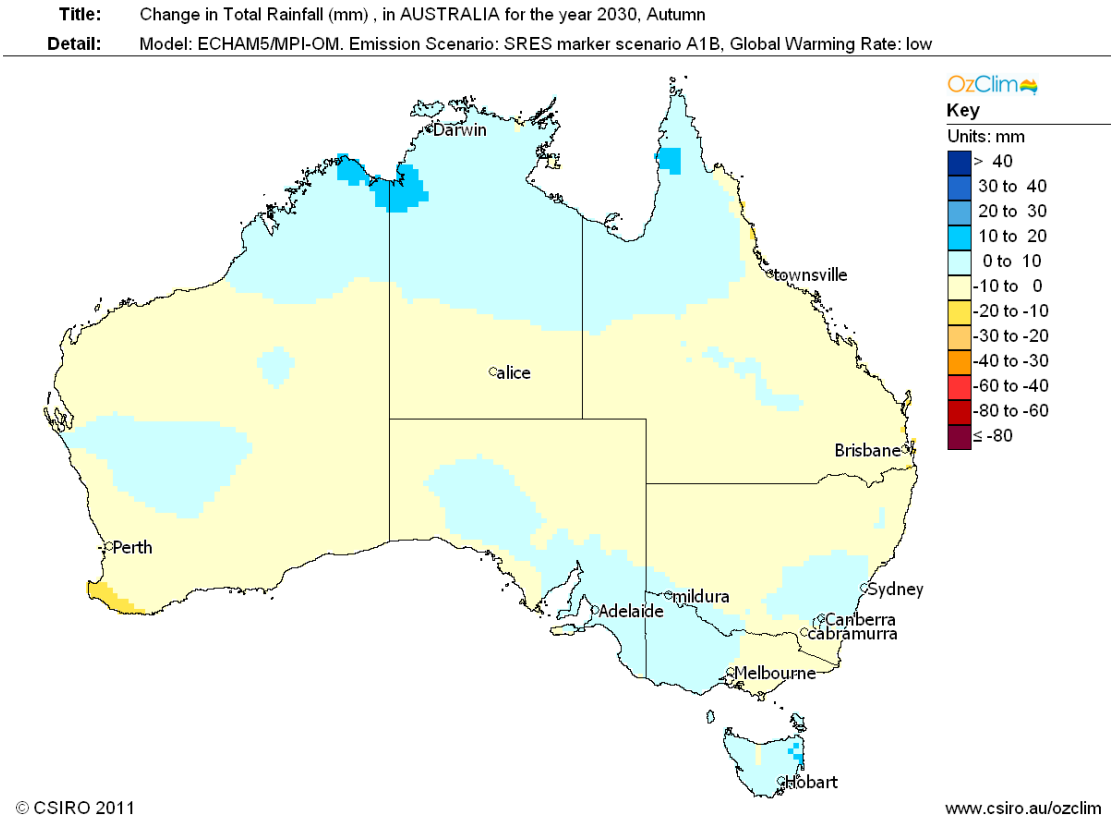
Detail: Model: ECHAM5/MPI-OM. Emission Scenario: SRES marker scenario A1B, Global Warming Rate: low



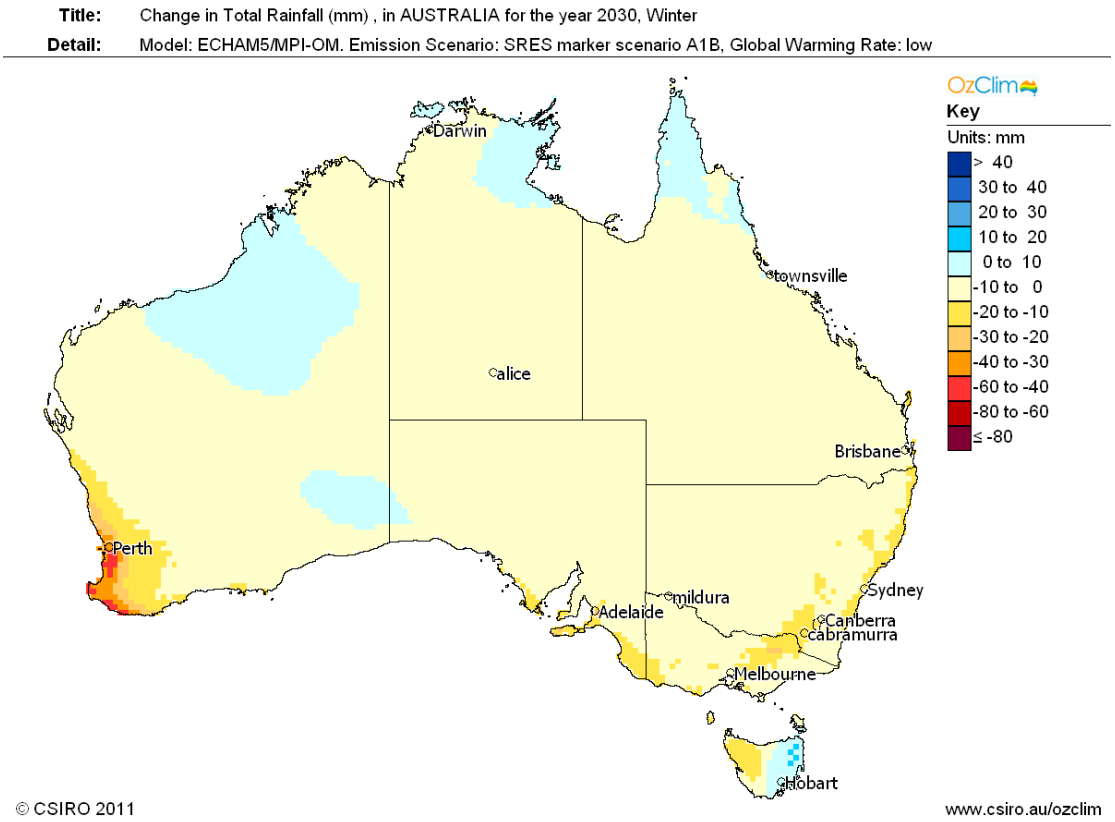
Appendix 13: Predicted change in summer rainfall by 2030 for 'optimistic' future climate.



Appendix 14: Predicted change in autumn rainfall by 2030 for 'optimistic' future climate.



Appendix 15: Predicted change in winter rainfall by 2030 for 'optimistic' future climate.



Appendix 16: Predicted change in spring rainfall by 2030 for 'optimistic' future climate.