Faculty of Health, Engineering and Sciences

School of Civil Engineering and Surveying

Improving water productivity of irrigated wheat in the northern grain production region of Australia

A dissertation submitted by

Allan Stewart Peake BAgrSc(Hons), MAgrSc

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Abstract

While cotton has traditionally been the dominant crop in irrigated broad-acre farming systems of subtropical Australia, high grain prices triggered a record area of irrigated wheat production in the winter of 2008. Unfortunately wheat yields were substantially lower than expected, probably due to widespread lodging (a disorder where crops fall over). And while irrigation water was plentiful for the 2008 season, the typical water availability for irrigated wheat production in the region involves water rather than land being the limiting factor to production.

Little research has been conducted on the potential yield, water use requirement or water productivity of irrigated spring wheat in the northern grain production region of eastern Australia, often referred to as the ‘northern grains region’. Such information would allow growers to assess lodging-related yield losses, compare the profitability of irrigated wheat against alternative crops, and determine the irrigation strategies that maximise economic returns. Additionally, there is uncertainty within the region over which agronomic techniques can be used to minimise the risk of lodging without reducing grain yield.

The overarching question to be addressed by this study is therefore: *what are the agronomic practices required to achieve maximum water productivity in irrigated wheat, across the northern grain production region of eastern Australia?* Two specific hypotheses were investigated in answering this question: (1) *that lodging constrains irrigated wheat yields in the northern grains region, and agronomic techniques can be used to control lodging, and* (2) *that when irrigation water availability is limited, maximum whole-farm crop water productivity for wheat is achieved by partially irrigating a larger crop area rather than fully irrigating a smaller area.* These hypotheses were investigated in the context of spring-wheat production systems within the northern grains region, where water rather than irrigable area is generally the limiting factor to crop production.

The APSIM (Agricultural Production Systems Simulator) model was used to determine the potential yield and water use requirement of irrigated spring wheat, but first required validation against field data. Crop production data (e.g. biomass and grain yield) were collected from 21 wheat crops throughout the northern grains region in 2008 and 2009, and recorded crop conditions and inputs (e.g. weather data, sowing dates, irrigation) were used to parameterise APSIM simulations for each crop.

APSIM predicted biomass production satisfactorily in 2008 but substantially over-predicted grain yield of lodged fields. The mean difference (yield gap) between APSIM-estimated potential yield and farmer-realised yield was 0.9 t ha^{-1} in non-lodged fields, and 2.5 t ha^{-1} in lodged fields. The average effect of lodging was therefore estimated as a decrease in grain yield of 1.6 t ha^{-1}, the difference between the yield gap calculated for lodged and non-lodged fields. In 2009 commercial fields generally experienced little lodging, probably due to the use of in-crop nitrogen (N) application to control canopy development. APSIM generally under-predicted biomass production and yield in these fields, suggesting that the N uptake parameters in APSIM may require adjustment. However, observed yields from fields of a quick-maturing cultivar that experienced little lodging were simulated accurately when N was assumed to be non-limiting. Further simulations of fully irrigated, quick maturing wheat using 50 years of climate data at six representative locations found that the potential yield of irrigated spring wheat in the northern grains region was

approximately 8 to 9 t ha^{-1}, and average growing season evapotranspiration of such crops was approximately 490 to 530 mm, depending on location.

The canopy management techniques of in-crop N application and reduced plant population are widely used in rainfed wheat production in temperate climates. However they are untested on irrigated wheat in the subtropics, and may not reduce lodging risk in the northern grains region without simultaneously reducing yield potential. Irrigated small plot experiments were therefore conducted in 2009 and 2011 to examine the effect of alternative N timing and plant populations on lodging and yield for two cultivars, under well-watered conditions.

Low sowing N treatments exhibited moderate to severe vegetative N stress, having soil plus fertiliser N at sowing of less than 80 kg ha^{-1} (sometimes as low as 15 kg N ha^{-1}) and the majority of fertiliser N applied in-season. These low sowing N treatments had significantly less lodging and were the highest yielding, exhibiting yield increases of up to 0.8 t ha^{-1} compared to high sowing N treatments. Increasing plant population above 100 plants m^{-2} increased lodging and decreased yield in high N treatments, but did not always increase lodging in low N treatments. Increased LAI, biomass and tiller count at the end of the vegetative growth phase were correlated with increased lodging in both cultivars, although the strength of the correlation varied with cultivar and season. Optimal N regime varied slightly between the cultivars, indicating that the optimisation of canopy management techniques for irrigated spring wheat systems would require further investigation of genotype × management interaction. It was therefore determined that canopy management techniques can be used to simultaneously increase yield and decrease lodging in irrigated spring wheat in the subtropics, but should be implemented differently to the techniques used in temperate regions of Australia, where recommended plant population and sowing N rates are higher than those identified in the present study.

While full irrigation of wheat in 2008 was forecast to be profitable (before the impact of lodging was apparent), irrigation water availability for irrigated wheat growing in the northern grains region is usually limited, and water rather than land is typically the limiting factor to production. Previous studies in other regions indicate that deficit (i.e. partial) irrigation of wheat is often considered to have greater economic water productivity (EWP) under such circumstances. Unfortunately, the cost/revenue functions traditionally used to evaluate alternative irrigation strategies are not applicable across multiple environments, and such studies have not accounted for the intrinsic value of water stored in the soil at the end of the cropping season.

The APSIM model was therefore used to determine whether growing larger areas of deficit irrigated wheat is more profitable than full irrigation of a smaller area in the northern grains region, when water rather than land is the limiting factor. The analyses accounted for the value of stored soil water across the entire farm by simulating rainfed crop production on unirrigated land, and/or by assigning an economic value to stored soil water remaining at the end of the season. Whole-farm profitability was assessed for alternative economic analyses where different values (inexpensive vs. expensive) were assumed for both irrigation water and stored soil water. Optimal irrigation strategies were those considered to be the most risk-efficient, being closest to a 1:2 ‘line of indifference’ that identifies the two unit increase in risk (measured as standard deviation) acceptable to farmers in return for a unit increase in profit.

The results of the simulation study demonstrated that irrigation strategies involving deficit irrigation of larger areas of wheat generally had greater levels of

absolute profitability, and were typically more risk-efficient than smaller areas of fully irrigated wheat. When precipitation or stored soil water at sowing was increased, the most risk-efficient strategies were those that spread the water across a larger area at a reduced frequency of irrigation. However in a low rainfall environment when water was expensive and soil water was given the same economic value as irrigation water, fully irrigated wheat in conjunction with fallow land was found to be the most profitable and risk-efficient option. The importance of evaluating farm-management strategies using EWP (i.e. incorporating gross margins) instead of crop water productivity (grain yield per unit of water use) was evident, as re-ranking of farm-management strategies occurred between these alternative methods of calculating whole-farm EWP. Accounting for the intrinsic value of stored soil water and precipitation was fundamental to understanding the benefit of deficit irrigation strategies in water limited situations, as the larger crop area sown in conjunction with deficit irrigation strategies accessed much larger absolute volumes of soil water and precipitation. Future evaluations of deficit irrigation strategies should account for such considerations.

The results of this study therefore support the hypothesis that lodging constrains irrigated wheat production in the northern grain production region of eastern Australia, and that agronomic techniques can be used to control lodging. The study also supports the second hypothesis that maximum whole-farm water productivity is achieved by partially irrigating a larger area of wheat when water availability is limited, except in low rainfall environments where irrigation water is expensive and soil water is assigned an economic value equivalent to the irrigation water.

Certification of dissertation

I certify that the ideas, experimental work, results, analyses, and conclusions reported in this dissertation are entirely my own effort, except where otherwise acknowledged. I also certify that the work is original and has not been previously submitted for any other award.

Signature of Candidate: _____________________ Date: __________

Signature of Supervisors:

Principal Supervisor: _____________________ Date: __________
(Professor Steven Raine)

Associate Supervisor: _____________________ Date: __________
(Professor Rod Smith)

External Supervisor: _____________________ Date: __________
(Dr Peter Carberry)

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Publications Arising

(Listed in Chronological Order)

Peake, A.S., Angus, J.F., 2009. Increasing yield of irrigated wheat in Queensland and Northern NSW. GRDC Northern Region Grains Research Updates, Goondiwindi, 3-4 March, 2009.

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*Peake, A.S., Hochman, Z., Dalgliesh, N.P., 2010. A rapid method for estimating the plant available water capacity of Vertosols. In: Dove, H., Culvenor, R.A. (Eds.), Food Security from Sustainable Agriculture - Proceedings of the 15th Australian Agronomy Conference, Lincoln, New Zealand, 15-18 November 2010.

Peake, A.S., Rebetzke, G., Chapman, S., Dreccer, F., McIntrye, L., Hundt, A., Bell, K., 2012. Agronomy for high yielding cereal environments: varieties, agronomic strategies and case studies, GRDC Northern Region Grains Research Updates, Goondiwindi, 6-7 March, 2012.

**Peake, A., Bell, K., Poole, N., Lawrence, J., 2012. Nitrogen stress during tillering decreases lodging risk and increases yield of irrigated bread-wheat (Triticum aestivum) in north-eastern Australia. In: Yunusa, I. (Ed.), Capturing Opportunities and Overcoming Obstacles in Australian Agronomy - Proceedings of the 16th Australian Agronomy Conference, Armidale, NSW, 14-18 October 2012.

Peake, A.S., Gardner, M., Poole, N., Bell, K., 2014a. Beyond 8 t/ha: varieties and agronomy for maximising irrigated wheat yields in the northern region. GRDC Northern Region Grains Research Updates, Goondiwindi, 4-5 March, 2014.

***Peake, A.S., Huth, N.I., Carberry, P.S., Raine, S.R., Smith, R.J., 2014b. Quantifying potential yield and lodging-related yield gaps for irrigated spring wheat in sub-tropical Australia. Field Crops Res. 158, 1-14.

*This conference paper is a slightly modified version of Appendix A.

**This conference paper formed the basis of Chapter 4.

***This journal paper is an abbreviated version of Chapter 3.

TABLE OF CONTENTS

List of Figures

List of Tables

Chapter 1 - Introduction

1.1. Background

Wheat is one of the world's most important agricultural crops, with annual global grain production of around 600-650 million tonnes (Rajaram and Braun, 2008), second only to maize in total global production when rice (the third most produced crop) is measured on a milled production basis (IGC, 2013). While Australia produced only around 3-4% of the world's wheat crop over the last 50 years, Australia plays a major role in supplying wheat to the global market, contributing 13% of the global wheat trade on average per annum in the same period.

Irrigation of commercial wheat in the northern grains production region of eastern Australia (also referred to as the 'northern grains region' (Figure 1.1)) has historically been relatively uncommon, as the greater profitability of irrigated cotton means wheat is generally grown on irrigation farms as a beneficial rainfed rotation crop (Hulugalle et al., 1999). However in 2008, record areas of irrigated spring wheat were sown in the northern grains region in response to high grain prices and good water availability. While the grain prices of 2008 may have been caused in part by short term speculative futures trading on the back of high oil prices (Banse et al., 2008), demand for food grain is predicted to increase over the next 20-50 years as the world's population expands (FAO, 2006). Demand-driven increases in grain prices are therefore likely to result in increased irrigated wheat production in the northern grains region.

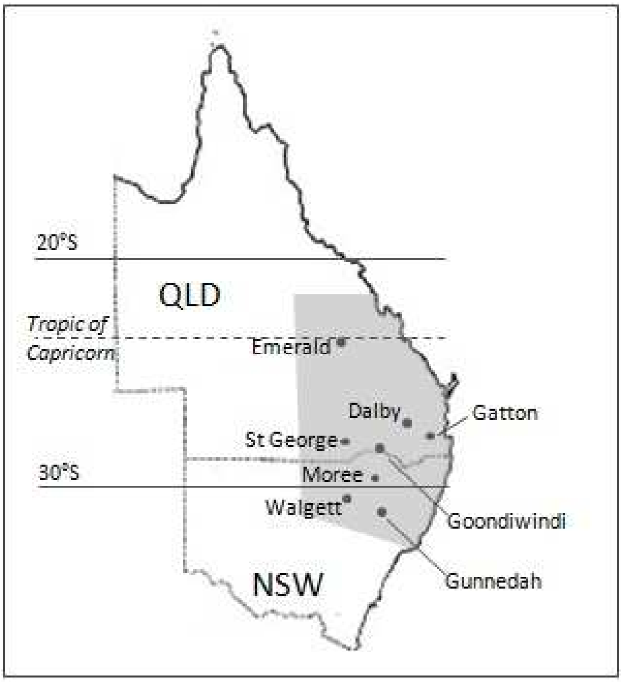


Figure 1.1. Map of the states of Queensland (QLD) and New South Wales (NSW), Australia, showing lines of latitude and the major towns near field monitoring and simulation experiment sites from this study. The shaded area represents the approximate boundaries of the northern grain production region of eastern Australia.

Maximising the rate of return per unit of irrigation water has for some time been the indicator used by irrigated growers in order to make short term management decisions. Various wheat studies around the world indicate that maximum water productivity (WP) for a given field can be obtained when achieving near-maximum yields (French and Schultz, 1984a; Musick et al., 1994; North, 2007b). Additionally, local irrigation industry analysts (John Stewart, Geoff Daniel, pers. comm.) suggest that irrigated wheat needs to be reliably produced at 6-7 t ha^{-1} or greater in order to be considered a regular profitable rotation crop on an irrigation enterprise. However, it is unclear as to whether these yield levels can be reliably achieved in the northern grains region as fully irrigated wheat has not been widely grown. It is also uncertain whether these yield levels represent the maximum yields possible in the system, and how much water is required by the crop to achieve them.

In contrast, maximum WP on a whole-farm level has generally been achieved through the use of deficit irrigation at lower yield levels of 4-5 t ha^{-1} (Zhang and Oweis, 1999; Tavakkoli and Oweis, 2004). Deficit irrigation maximises the marginal return per unit of irrigation water instead of the marginal return per unit of land area, by growing a crop over a larger area than could otherwise be irrigated if the crop water requirement was fully met. This practice may be highly relevant to irrigated wheat growers in the northern grains region, and would also reduce lodging risk through the reduction in yield potential of fields with decreased water input. While there is little information available on the water availability for irrigated wheat cropping at the end of the cotton season, crop consultants and growers in the region consider that the typical water availability status would involve no more than a single irrigation of approximately 1.3 ML ha^{-1} (applied using furrow irrigation) being available for wheat growing, per unit of irrigable farm area (Hamish Bligh, Rob Holmes, Phil Lockwood, pers. comm.).

Unfortunately, many irrigated wheat fields in the northern grains region in 2008 were affected by a disorder known as lodging, where plants fall over due to buckling of the stem or displacement of the surface root system. Lodging occurs primarily in fields with high potential yield, and is one of the main limitations to maximising yield in irrigated spring wheat production (Hobbs et al., 1998; Tripathi et al., 2005). In 2008 lodging was the suspected cause of low yields in fully irrigated crops that had been expected to yield 7-8 tonnes ha^{-1} but ultimately yielded 3-4 tonnes ha^{-1} (Paul Castor, pers. comm.). Lodging has been managed around the world using a combination of agronomic practices and genetically improved wheat cultivars. While germplasm development is a long term solution, improved agronomic practices could be adopted quickly in a farming system and be of more immediate benefit in the northern region if lodging mitigation techniques can be identified.

Little research has been conducted on the potential yield, water use requirement or water productivity of irrigated spring wheat in the northern grains region. Improved information would allow growers to (1) assess the size of lodging-related yield losses and evaluate the need for (and cost effectiveness) of lodging mitigation techniques, (2) compare the profitability of irrigated wheat against alternative crops, and (3) determine the optimal irrigation strategies for maximising economic return under water limiting conditions.

1.2. Objectives

In response to these issues, the overarching question to be addressed by this study is: *what are the agronomic practices required to achieve maximum water productivity in irrigated wheat, across the northern grains production region of eastern Australia?*

It is intended to answer this question by investigating two specific hypotheses:

1) *that 'lodging' constrains irrigated wheat yields in the northern grains region, and agronomic techniques can be utilised to control lodging.*

(2) *that when irrigation water availability is limited, maximum whole-farm crop water productivity for wheat is achieved by partially irrigating a larger crop area rather than fully irrigating a smaller area.*

These hypotheses are investigated in the context of spring-wheat irrigated production systems of the northern grains region, where water rather than land is generally the limiting factor to crop production. In this context the northern grains region refers to the major irrigated cropping areas in Queensland and northern New South Wales (NSW), with the towns of Emerald and Gunnedah representing the northern and southern extremities of field monitoring and simulation experiments (Figure 1.1).

Preliminary research led to the following specific research objectives being developed in order to test the hypotheses:

1. Evaluate and calibrate the APSIM (Agricultural Production Systems Simulator) farming systems model (Keating et al., 2003) to ensure its accuracy in predicting wheat yield potential and water use.
2. Determine the potential yield and lodging related yield gaps associated with irrigated wheat production systems.
3. Assess the ability of agronomic techniques to control lodging.
4. Determine the whole-farm crop water productivity of full and partial irrigation strategies for the typical water limited situation.

1.3. Structure of dissertation

Chapter two of this thesis presents the pertinent literature surveyed in establishing the scope of this study. An evaluation of the suitability of the APSIM model for simulating irrigated wheat production is discussed in Chapter three, which also assesses potential yield and lodging related yield gaps for commercial production fields during the 2008 season. A field investigation into the ability of agronomic techniques to reduce lodging in locally adapted wheat germplasm is reported in Chapter four. Chapter five contains the results of APSIM simulation experiments that examine the optimal irrigation scheduling methods for maximising whole-farm crop water productivity of irrigated wheat when irrigation water availability is limited. Chapter six contains a general discussion of the results and provides conclusions and recommendations for future research needs to support irrigated wheat growing in the subtropics, both in Australia and world-wide.

Chapter 2 - Literature review

2.1. Water productivity and ceiling yield terminology

Terminology in the areas of water productivity (WP) and ceiling yield varies between research studies, therefore it is necessary to briefly review such terminology before conducting a wider literature review. The definition for water productivity used herein is that suggested by Barker et al. (2003), who defined it as “the ratio of crop output to water either diverted or consumed, the ratio being expressed in either physical or monetary terms, or some combination of the two”. Additionally, the term ‘ceiling yield’ is used herein to collectively describe all descriptors of maximum yield, whether predicted or measured, in resource limited or non-limited conditions.

2.1.1. Water productivity indices

Water use efficiency (WUE) was originally defined as crop yield, per unit of water used to produce the yield (Viets, 1962). However it has since been defined in various ways due to the different spatial and temporal scales over which different research disciplines operate. Sinclair et al. (1984) pointed out that WUE indices should be defined and discussed with reference to their numerator (measures of productivity), denominator (measures of water use), and the time scale of the measurements, although it may also be appropriate to discuss the spatial scale at which measurements are taken (e.g. farm vs. field scale).

For the purposes of the present study, measures of water use efficiency productivity are grouped according to the reason they are used; (1) crop production indices, (2) irrigation efficiency indices, or (3) system evaluation indices. The term index (or indices) is considered more appropriate than the word ‘efficiency’ when the unit of numerator and denominator are not the same (BPA, 1999).

Crop production indices have generally been used to compare different crop management strategies, by examining the crop yield response to the water consumed by the crop (e.g. French and Schultz, 1984a; Musick et al., 1994; Lobell and Ortiz-Monasterio, 2006). They typically use crop biomass, grain yield or the value of the grain as the numerator, while the denominator tends to be either transpiration (water transpired by the crop) or evapotranspiration (the sum of water transpired and water lost through evaporation) (Sinclair et al., 1984). The terms ‘transpiration efficiency’ (TE) or crop water use efficiency (CWUE) have traditionally been used to discriminate between these indices (Angus and van Herwaarden, 2001). More recently, the term ‘crop water productivity’ (CWP) has begun to be used as a substitute term for CWUE (e.g. Zwart and Bastiaanssen, 2004).

Irrigation efficiency is a term used to describe volumetric comparisons between the water that leaves one component of the irrigation supply system, and the water that arrives at the next part of the system. Terms such as application efficiency, storage efficiency and distribution efficiency have been defined by the Australian irrigation industry to describe individual components of the irrigation storage and distribution system, so as to isolate where the greatest losses of irrigation water occur (BPA, 1999; Dalton et al., 2001). They are complementary to crop production indices, as they examine only the irrigation distribution component of the production system.

System efficiency indices are defined here as those that examine crop production indices and irrigation efficiencies simultaneously, so that interaction between the crop and irrigation supply system can be examined. The term ‘water productivity’ is sometimes used in irrigated crop studies as a system efficiency index where it measures the crop response (or economic return) on irrigation water inputs, and generally encompasses water lost to the system at the point of delivery as deep drainage or evaporation (e.g. Tolk and Howell, 2008).

2.1.2. Ceiling yield terminology

Many different terms have been used to describe ceiling yield in different contexts, and the predominant terms are defined as follows.

The term ‘yield potential’ was defined by Evans (1993) as ***“****the yield of a cultivar when grown in environments to which it is adapted, with nutrients and water non-limiting and with pests, diseases, weeds, lodging, and other stresses effectively controlled”*. Practically, this describes an observed yield of a particular cultivar under optimal management, but still leaves the cultivar subject to certain prevailing climatic conditions which can fluctuate from year to year (e.g. radiation and temperature).

‘Potential yield’ and ‘yield potential’ have sometimes been used interchangeably in the literature (Sinclair, 1993; Fischer and Edmeades, 2010). However Evans and Fischer (1999) suggested that ‘potential yield’ should be defined as *“the maximum yield that could be reached by a crop in given environments, as determined, for example, by simulation models with plausible physiological and agronomic assumptions.”*

Thus, according to Evans and Fischer (1999) ‘yield potential’ refers to a measured yield, while ‘potential yield’ refers to a predicted yield generated using known physiological relationships. However this definition does not specify whether the potential yield can be determined with any environmental resources (e.g. water) as limiting factors. Various authors have addressed this uncertainty by explicitly stating their assumptions, sometimes to the extent of adding a prefix e.g. “water-limited potential-yield” (Wolf and van Diepen, 1995; Wu et al., 2006; Hochman et al., 2009; van Ittersum et al., 2013). Other recent studies using the term ‘potential yield’ have used it in the same way without a prefix (e.g. Angus and van Herwaarden, 2001; Robertson and Kirkegaard, 2005; Lisson et al., 2007) and the term was used in a similar way in at least one study (French and Schultz, 1984a) that pre-dates the definition of Evans and Fischer (1999). Additionally, other studies have used the terms ‘attainable’ and ‘achievable’ to define variants of yield potential or potential yield (e.g. Robinson, 1995; Robertson et al., 2000; Hochman et al., 2009).

For the purposes of the present study, the definition of Fischer and Edmeades (2010) is adopted. They made no distinction between potential yield or yield potential, defining them as “*the yield of an adapted cultivar when grown with the best management and without natural hazards such as hail, frost, or lodging, and without water, nutrient, or biotic stress limitations (water stress being eliminated by full irrigation or ample rainfall).*” They also stated that potential yield (PY) “*is usually determined from carefully managed field experiments with the best cultivars, which in turn can be used to calibrate crop simulation models for PY prediction across time, space, and management options*”.

2.1.3. Summary

This study aims to investigate ways of increasing water productivity by determining (a) whether crop water productivity of irrigated wheat can be improved by using alternative agronomic management techniques to reduce the incidence of wheat lodging, and (b) whether system water productivity is greatest when wheat is deficit irrigated over a wider area. In order to examine the importance of reducing the incidence of lodging, it is also necessary to establish the water-limited potential yield of commercial fields from 2008 so that the yield loss associated with lodging can be determined.

2.2. Ceiling yield of irrigated wheat

2.2.1. Ceiling yield of wheat in the northern grains region.

Prior to 2008, fully irrigated wheat was rarely grown in the large irrigation districts of the northern grains region. In these irrigation districts, wheat has typically been grown as a rainfed rotation crop for breaking cotton disease cycles, hence little research has been conducted to specifically assess ceiling yield of irrigated wheat in the northern grains region.

Strong (1982, 1986) conducted research on the timing of N application in irrigated wheat on the Darling Downs using commercially available cultivars but only achieved maximum yields of 5.7 t ha^{-1} under N non-limiting conditions. In experiments conducted in at Gatton in 1995 and 1996, individual plots of Seri 82 were observed to yield 8.0 t ha^{-1} under irrigation (Peake, unpublished data), however this international cultivar has not been released commercially due to poor grain quality. The highest yielding commercial cultivar from the same experiments (Hartog) had a maximum mean yield of 6.4 t ha^{-1} at Gatton in 1996 (Peake et al., 2011). Ultimately the highest mean yields identified for the region in the literature were obtained by Meinke et al. (1997) and Keating et al. (2001) in experiments used to develop and test the wheat module within the APSIM farming systems model across a range of agronomic conditions. They recorded plot yields of between 7.2 and 7.6 t ha^{-1} for the cultivar Hartog, at Wellcamp and Gatton in south-east Queensland.

Local agricultural show records suggest that in commercial production fields across the region irrigated wheat yields are not much greater than the best rainfed yields, suggesting that ceiling yields have not been achieved. Results from the Springsure Show Society in central Queensland add weight to this hypothesis, with rainfed yields of 4.75 t ha^{-1} and 4.9 t ha^{-1} winning 1st prize in 2005 and 2007, and an irrigated yield of 5.35 t ha^{-1} winning the competition in 2008 (Ben Marshall, pers. comm.). The absence of irrigated wheat competitions at the significant irrigation districts around Narrabri, St George and Dirranbandi also indicate that high yielding wheat has not been of interest in these districts over a long period of time. However, Dirranbandi agronomist Greg Nichols (a local judge for cotton yield competitions) has observed wheat yields up to 6.25 t ha^{-1} in the district (Greg Nichols, pers. comm.).

2.2.2. Ceiling yield of spring wheat in southern Australian and international environments

Irrigated spring wheat has been grown more widely in southern parts of Australia where the alternative broad-acre irrigation crops are rice and maize, rather than cotton. Much research has been conducted by researchers in these areas to assist growers in achieving yields in excess of 8 t ha^{-1} (Stapper and Fischer, 1990a; Lacy and Giblin, 2006). The highest reported yield from these researchers is 8.9 t ha^{-1} oven dry (Stapper and Fischer, 1990b) which translates to approximately 10 t ha^{-1} when corrected to the standard wheat reporting moisture content of 12%. However the southern NSW and Victorian environments are quite different to those experienced throughout most of the northern grains region, having longer and cooler growing seasons that are more favourable to high yielding wheat production (because they experience more radiation per unit of thermal time accumulation during grainfilling).

A region of greater similarity to the northern grains region is Mexico, which is located at similar latitudes to south-east Queensland (albeit north of the equator) where substantial wheat research has been conducted by CIMMYT – the International Centre for Maize and Wheat Improvement. Yields of 8.5 t ha^{-1} have been achieved in farmer production fields at locations around CIMMYT, presumably harvested at or near 12% moisture, for a range of unreported cultivars (Ortiz-Monasterio, 2002). Experimental plot yields from the same area have been as high as 9.97 t ha^{-1} (Tripathi et al., 2005) although the use of support netting was necessary to prevent lodging in order to attain this yield. However the highest yields recorded in published literature for spring wheat come from China, in an unusually mild environment where Sinclair and Bai (1997) reported on a 14 t ha^{-1} crop from 1978, an exceptional season even by the region’s own standards. This research group reports that the same cultivar (Plateau 338) still holds the world record for spring wheat yield, which now stands at 1.013 t mu^{-1}, or 15.2 t ha^{-1} (Anonymous, 2015).

Having been generated using different cultivars and in different environments, these data have only limited relevance to this study. In the absence of comprehensive ceiling yield data for the target environment, potential yield estimates generated by crop simulation models represent a suitable alternative.

2.2.3. Determining potential yield through crop modelling

Ranging from static empirical models such as the photothermal quotient (Nix, 1976) to dynamic process models such as APSIM (Keating et al., 2003), models such as these and others (e.g. AFRCWHEAT2 (Porter, 1993), CERES-Wheat (Ritchie and Otter, 1985), DSSAT (Jones et al., 2003), and CROPSYST (Stöckle et al., 2003)) have been developed by researchers worldwide to address specific issues of local interest.

Crop simulation models have been widely used to examine the potential yield of irrigated spring wheat in sub-tropical regions around the world. Potential yield of irrigated wheat has been reported to be between 4 and 8 t ha^{-1} in India depending on location (e.g. Aggarwal et al., 1994; Hundal and Prabhjyot-Kaur, 1997; Arora et al., 2007), 7 to 8 t ha^{-1} in the Yacqui valley in Mexico (Bell and Fischer, 1994; Lobell and Ortiz-Monasterio, 2006), while in Zimbabwe yields of up to 10 t ha^{-1} were achieved while validating ZIMWHEAT, a modified version of CERES-Wheat (Macrobert and Savage, 1998).

APSIM is a robust farming systems model widely used in Australia (Robertson and Carberry, 2010) that has been validated in Australia and internationally in numerous studies (as cited by Keating et al. (2003) and Holzworth et al. (2014)). The advantage of a holistic, systems model such as APSIM is that it takes account of many factors in the farming system, in addition to the fundamental balance between temperature and radiation. Vapour pressure deficit, soil chemical and physical characteristics, the timing of fertiliser application, and light interception in different row and raised bed configurations are all factors that influence potential yield, which can be accounted for by the APSIM model. Nevertheless, there are still environmental factors that APSIM does not yet take into account, such as the effect of high temperature during critical growth periods such as flowering.

APSIM has accurately predicted grain yield of high-yielding rainfed and irrigated wheat plot trials in sub-tropical and temperate regions of Australia (Asseng et al., 1998; Chenu et al., 2011; Peake et al., 2011), as well as in India and Europe (Asseng et al., 2000; Balwinder-Singh et al., 2011). However APSIM has not previously been used to examine potential yield of commercial irrigated spring-wheat production systems in the northern grains region, and contains no functionality for the simulation of crop lodging. As with any simulation model, it should be tested for its suitability to new applications before being relied upon in a predictive sense.

2.3. Improving crop water productivity of irrigated wheat

2.3.1. Limitations to improving crop water productivity

Plant physiologists and breeders work to improve CWP by increasing TE (and thus ceiling yield) through genetic improvements to the efficiency with which the crop uses water (e.g. Condon et al., 2002; Richards et al., 2002). In contrast, crop agronomists focus on improving CWP by increasing grain yield through changes to the way the crop is managed. This generally occurs through improvements to the efficiency of rainfall capture by reducing runoff, evaporation and deep drainage (Bouman, 2007), or reducing yield loss due to pests, diseases, nutritional and other disorders such as lodging (Angus and van Herwaarden, 2001).

The most well-known Australian example of a study in wheat CWP was carried out by French and Schultz (1984a). In their study, a range of rainfed crops from South Australia were monitored for in-season water use. Water use was determined by adding rainfall measured between sowing and maturity to the change in soil water content for the same period, and it was assumed that drainage and runoff were negligible. Through the examination of their data and other data throughout Australia, they developed a boundary function (Figure 2.1) that defined the maximum yield possible from a wheat crop as:

$$\textit{Grain yield (kg ha}^{-1}\textit{) = (total season water use – soil evaporation) * 20}$$

where soil evaporation is defined as the average cropping season soil evaporation (in this case 110 mm) from the region of interest. Soil evaporation was estimated in their study from the plotted function and its intercept with the x-axis, and validated against experimentally determined soil evaporation from a number of studies in similar regions. Water use (apart from evaporation) was assumed to be used entirely by the plant through transpiration, and their constant of 20 kg ha^{-1} of grain production per mm of water represented transpiration efficiency (TE), almost identical to the maximum TE they extrapolated from the glasshouse transpiration studies of Passioura (1976).

This 20 kg ha^{-1} mm^{-1} constant is now used by agronomists and growers across Australia as a benchmark TE for wheat. When data points sit on the line of maximum TE, the crop is considered to have achieved the best yield possible given the water that was available to it during the growing season. However, it was clear from their study (Figure 2.1) that the majority of data points were some way from the line of maximum TE. Further experimentation identified nutrient deficiency, insect damage, water logging, sub-optimal sowing date and weed infestations as limiting factors that prevented crops from reaching the line of maximum TE (French and Schultz, 1984b), and nearly 30 years later commercial rainfed crops still struggle to achieve maximum CWP for similar reasons (Hochman et al., 2009).

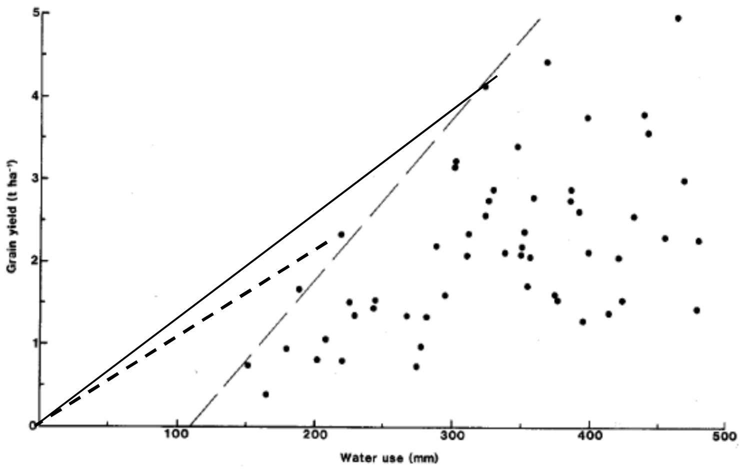


Figure 2.1. The original French and Schultz (1984a) scatter plot of grain yield vs. in-season water use, incorporating (— — —) the French and Schultz line for maximum transpiration efficiency (TE); (———) an overlaid function indicating the highest crop water productivity (CWP) of all the data points (12.7 kg ha^{-1} mm^{-1}); and (- - - -) the decreased CWP function (10.7 kg ha^{-1} mm^{-1}) for a lower yielding data point close to the maximum TE function.

The difference between the yield achieved by growers and potential yield of the crop is often referred to as the ‘yield gap’ (Lobell et al., 2009). The concept of the ‘yield gap’ is used worldwide to help promote genetic crop improvement programs, agronomic improvements to farming systems, and international aid efforts in agronomic and plant breeding research programs (Cassman, 1999).

All of the biotic and abiotic factors that contribute to the yield gap in rainfed wheat also contribute to the yield gap in irrigated wheat. However, the disorder known as lodging is much more of a limiting factor in irrigated wheat production, than in rainfed production systems.

2.3.2. Cause, effect and control of lodging in wheat

High yielding production regions around the world have frequently experienced yield losses due to the disorder known as lodging (e.g. Mulder, 1954; Stapper and Fischer, 1990a; Berry et al., 2004; Fischer, 2007). When lodging occurs, the wheat plants fall over either because (a) the stem collapses and folds at a weak point (usually near the base of the plant) or (b) the entire plant overbalances, with the weight of the plant partially levering the plant root system out of the soil, which has been saturated following rainfall or an irrigation event (Pinthus, 1973; Easson et al., 1993; Baker et al., 1998). The variability of such climatic and environmental factors also leads to variability in the incidence of lodging in fields or seasons that have similar agronomic characteristics, and has prompted the development of complex lodging risk models that allow the assessment of lodging risk in crops that have not yet lodged (Baker et al., 1998; Berry et al., 2003).

Yield losses of up to 80% have been recorded in severely lodged crops, partly due to the physiological disruptions that occur in a lodged crop (e.g. reduced radiation use efficiency caused by a less efficient canopy structure) and partly due to the inability of harvesting machinery to glean the lodged crop from the soil surface (Berry et al., 2004). Lodging can also reduce grain quality (Pinthus, 1973; Fischer and Stapper, 1987) which further decreases the economic return to the grower.

Some lodging prevention strategies involve the deliberate reduction of crop inputs in order to sacrifice some yield potential (Robins and Domingo, 1962; Pinthus, 1973; Hobbs et al., 1998) and avoid the greater losses in yield that can occur through lodging. However in many regions around the world lodging is successfully managed using a combination of altered agronomic practices and genetically improved wheat cultivars with greater resistance to lodging (Robins and Domingo, 1962, Pinthus, 1973; Hobbs et al., 1998). While developing lodging resistant cultivars is a long term task, new agronomic practices can be implemented quickly, and would be of more immediate benefit in the northern grains region.

Reduced light quantity and quality have been demonstrated to weaken stems and surface roots and increase lodging risk (Sparkes and King, 2007) suggesting that agronomic practices which increase crop vigour and canopy density during tillering also increase lodging risk. This result is supported by the numerous studies that have demonstrated reduced lodging associated with practices that reduce canopy size, such as reduced plant populations (Stapper and Fischer, 1990a; Easson et al., 1993; Webster and Jackson, 1993), delayed sowing dates (Berry et al., 2000; Spink et al., 2000 cited in Berry, 2004), and decreased nitrogen (N) availability during the vegetative growth phase (Mulder, 1954; Kheiralla et al., 1993; Crook and Ennos, 1995; Berry et al., 2000; Tripathi et al., 2003).

Application of plant growth regulators such as trinexapac-ethyl, chlormequat chloride and ethephon has also been demonstrated to reduce lodging risk (Herbert, 1982; Knapp et al., 1987; Crook and Ennos, 1995; Tripathi et al., 2003). These chemicals are considered to reduce lodging risk primarily by reducing crop height (and hence decreasing the length of the lever that is used to put pressure on the stem base or surface roots), as little credible evidence has been presented to support a consistent effect of plant growth regulators on stem or root characteristics likely to increase lodging resistance (Berry et al., 2004).

Additionally, altered soil conditions have also been demonstrated to reduce lodging risk. Reduced soil cultivation through direct drilling (Ellis et al., 1978 - cited in Berry et al., 2004) and rolling of the soil (Pinthus, 1973) are considered to increase soil bulk density and create a firmer platform to which roots can anchor (Berry et al., 2004). In irrigated wheat production, the use of raised beds has also been shown to reduce lodging (Fahong et al., 2004).

Unfortunately, these agronomic strategies are untested in conjunction with the cultivars, soil types and climatic conditions of the northern grains region. Additionally, as irrigated wheat has not been widely grown in the region, it is not clear whether lodging alone caused the 3-4 t ha^{-1} difference between anticipated and farmer-realised yield that was experienced in 2008, or whether another factor may have been responsible. It is therefore an objective of this study to determine the extent to which lodging reduced yield in 2008, and the ability of agronomic techniques to control lodging in the northern grains region.

2.3.3. Maximising crop water productivity for individual production fields

The French and Schultz (1984a) boundary function can be used to show that CWP for a single production field increases with increased water use as long as the crop responds to increased water input at maximum TE. This is visualised by the two overlaid lines in Figure 2.1 that intercept the origin and two data points with different CWP, both on or near the dashed line of maximum TE. The slope of the solid line represents CWP for the data point that had the highest CWP (12.7 kg ha^{-1} mm^{-1}) of all data points on the graph. The slope of the dotted line (10.7 kg ha^{-1} mm^{-1}) demonstrates the lower CWP achieved for another point close to the line of maximum TE.

Musick et al. (1994) collated a large CWP data set for both rainfed and irrigated winter wheat in the USA, and related it to absolute yield levels (Figure 2.2). In their study, maximum CWP from their line of best fit was achieved at the highest yields of 7-8 t ha^{-1}. However there is some uncertainty as to whether the maximum CWP actually occurred at such high yields. While the quadratic function achieved its highest level at 8 t ha^{-1}, the highest measured CWP from individual data points occurred at around 6 t ha^{-1} (Figure 2.2). Similar patterns of CWP were observed in a study from northern Syria by Zhang and Oweis (1999), who observed maximum CWP in bread wheat at yields of 7-8 t ha^{-1} (Figure 2.3a) with a less apparent plateau effect than Musick et al. (1994). Interestingly, they observed a much different relationship in Durum wheat (Figure 2.3b), where peak CWP was reached at 4-6 t ha^{-1}, and then decreased with increasing water application. In a study in southern Australia in the central Murray Valley, North (2007b) investigated CWP of irrigated wheat under centre-pivot and lateral-move (CPLM) irrigation systems and found that maximum CWP occurred from 5 t ha^{-1} up to the maximum yield of 7 t ha^{-1}. Steiner et al. (1985) achieved similar results on irrigated wheat using data sets from both NSW and South Australia, with maximum CWP occurring in the highest yielding treatment which yielded 7.8 t ha^{-1}.

The literature therefore indicates that strategies to maximise CWP of irrigated wheat on an individual field basis vary between production regions, often using full-irrigation but sometimes using less than the crop's full irrigation water requirement. However the profitability of irrigation enterprises is dependent on maximising CWP of the entire farm, rather than for individual fields.

2.3.4. Maximising water productivity on a whole-farm basis

One disadvantage of using CWP to evaluate irrigation strategies is that it does not account for the losses in irrigation storage, distribution or application, which make up a large proportion of irrigation losses (Dalton et al., 2001). Additionally, CWP does not reflect the profitability of different irrigation strategies, an important water productivity measure for commercial irrigation enterprises. In comparing alternative irrigation strategies it is therefore important to use system water productivity indices

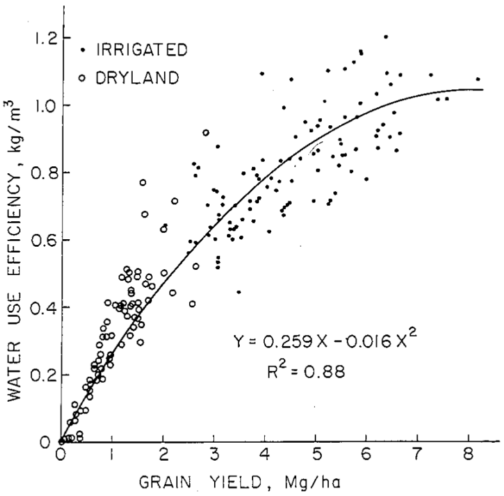


Figure 2.2. The relationship between water use efficiency and grain yield for winter wheat from Musick et al. (1994).

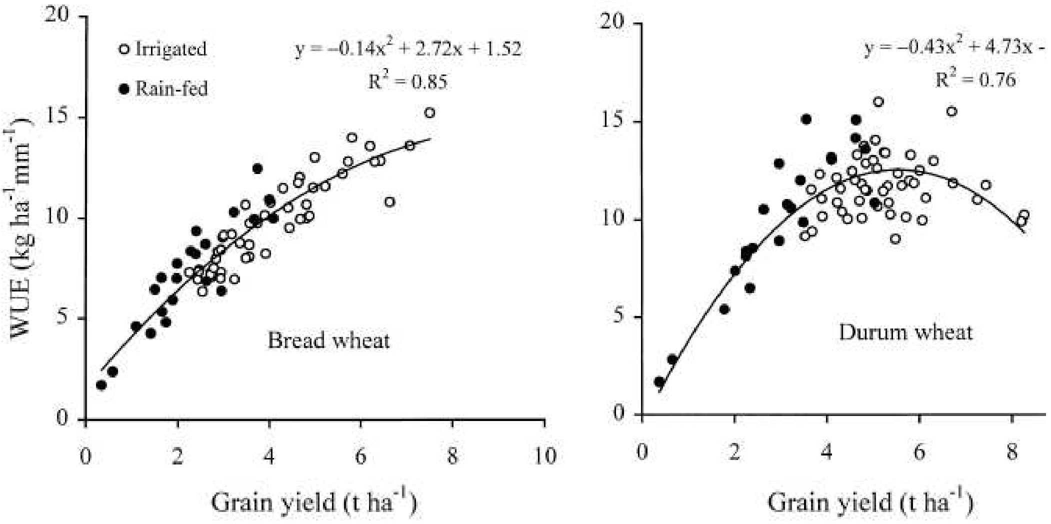


Figure 2.3. The relationship between water use efficiency and grain yield for (a) bread wheat and (b) durum wheat from Zhang and Oweis (1999).

which assess the effectiveness of crop and irrigation management strategies as a whole, in conjunction with a measure of economic return.

Many studies of system water productivity from around the world have used crop production functions to determine the most profitable level of irrigation input (e.g. English, 1990; Zhang and Oweis, 1999; North, 2007b). By first determining the average relationship between yield and total water use, appropriate revenue and production cost functions can then be generated based on local price and cost data (e.g. Figure 2.4).

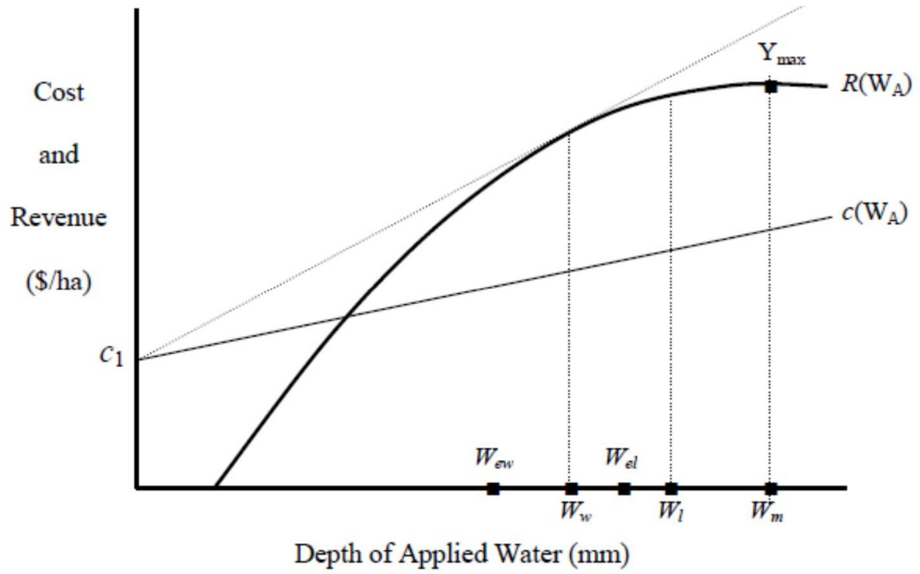


Figure 2.4. Cost and revenue functions ($c(W_A)$ and $R(W_A)$) showing the amount of applied water required to achieve maximum yield (W_m) and maximum profit per hectare when land (W_l) and water (W_w) are limiting. The figure also shows the depth (or amount of equivalent rainfall) of applied water at which the net whole-farm profit is equal to that at W_m for the land (W_{el}) and water (W_{ew}) limiting situations. From North (2007a) as adapted from English and Rajah (1996).

Such production functions define the critical points where irrigation strategies are most profitable when either land or water is the limiting factor. In Figure 2.4, the marginal return per unit of water is greatest at W_w, where the revenue function ($R(W_A)$) has maximum return per unit of additional water input. The marginal return per unit of land is greatest at W_l, where the difference between $R(W_A)$ and $c(W_A)$ is greatest. However when land is limited, maximum whole-farm profit is obtained by applying the amount of water at W_{el}, where the difference (in $ ha^{-1}) between $R(W_A)$ and $c(W_A)$ is the same as found at W_m but total water use is lower. When water is limited, maximum whole-farm profitability is found at a point W_{ew} which has been arbitrarily placed in this figure, but may be different to W_w if the decrease in net profit from reduced irrigation per unit area can be more than offset by irrigating a greater area.

Many permutations of this production function framework have been published and these have been summarised well by North (2007a). Their common purpose is to determine the maximum system WP of irrigated production systems, and thus promote the benefits of ‘deficit irrigation’. Deficit irrigation is defined herein as the deliberate under-irrigation of the crop such that it receives less water than the amount required to achieve maximum evapotranspiration (English, 1990; Fereres and Soriano, 2007). In Figure 2.4, deficit irrigation would be used to apply limited water per unit land area, such that the water application is equal to We_l or We_w. These represent the depth of applied water at which profitability is maximised when either land or irrigation water is the limiting factor, on a whole-farm basis.

Zhang and Oweis (1999) conducted an extensive economic analysis that generated crop and cost production functions (based on English, 1990) for land and water limited situations, for different average rainfall zones in Syria. They found that maximum system WP was achieved by using partial irrigation to achieve yields of 4-5 t ha^{-1}, in water limited situations, whereas maximum CWP for individual fields had been achieved at higher yield levels. At high yield levels, their crops exhibited a typical declining marginal yield response to additional irrigation water. Limited water supply and a high cost of water application meant it was more profitable to grow a larger area of partially irrigated wheat to achieve moderate yield levels.

In Australia, a similar study was carried out by North (2007b) on overhead irrigated wheat in the central Murray Valley in southern NSW, using the same analytical framework as English and Raja (1996). However in their study, system WP was maximised at the same yield levels (6-7 t ha^{-1}) at which CWP was maximised for individual fields (North, 2007b).

While crop/cost production functions are useful for visualising the advantages of deficit irrigation, they have a number of disadvantages. Firstly, production functions vary between environments (Zhang, 2003), thus field data and production cost data must be collected in multiple locations in order to generate functions for each environment of interest. Additionally, functions are based on a long term average yield response curve, and the recommendations may not apply in a particular season if rainfall or other climatic variables are markedly different from the median (North 2007a). Pereira et al. (2002) also pointed out that the success of ‘deficit’ and supplemental irrigation is dependent on in-crop rainfall volume as well as timing, and that they are not very successful strategies in drought years in their environments (Syria/Tunisia). Their findings may be applicable to the northern region where winter rainfall is often low.

Additionally, crop/cost functions are less beneficial for evaluating large scale furrow irrigated farms, where control over irrigation water is imprecise, and water delivery occurs in large volumes. When the amount of water to be applied is a choice between 140 mm of irrigation or none, it is difficult to manipulate the farming system to the optimum point on the production function.

Lobell and Ortiz-Monasterio (2006) favoured an alternative approach when optimising system WP for farmers in the Yaqui valley, Mexico. They used a validated crop model (CERES-Wheat) to conduct virtual experiments on varying irrigation strategies, and applied the yield outputs to a simple economic model. A peculiarity of their study, was that the economic analysis did not have a variable irrigation water cost among the different irrigation strategies, as the cost of water in their farming system was not considered a significant cost to the production system, despite irrigation water becoming increasingly limited in their region. Additionally, the fixed cost of production was so high among their farmers that a minimum yield of 5 t ha^{-1} was required to ‘break even’. Ultimately, their results showed that the most profitable irrigation strategy depended on the amount of stored soil water at sowing. When stored soil water was low to moderate at planting, the full irrigation strategy was most profitable, with partial irrigation strategies becoming more profitable when stored soil water at sowing was high.

Evaluation of these studies demonstrates a number of points pertinent to the current investigation:

- Both crop and economic production functions vary between environments, and need to be developed on a case by case basis for different regions.
- The appropriate level of irrigation to maximise profit in a given season depends on in-season rainfall and soil water at sowing, both of which are highly variable in the northern grains region.

- None of these studies investigated the opportunity/cost of land left idle when irrigation water is limited, and did not account for the profitability of any area planted to rainfed wheat. The absence of this analysis gives a false economy to the partially irrigated treatments in their analyses which cover a greater land area (and hence receive a greater absolute volume of in-crop rainfall) than the fully irrigated treatments.
- Additionally, no allowance was made in these studies for in–season storage losses, which is one of the primary factors influencing whole-farm WP in the northern grains region (Cameron et al., 1997; Dalton et al., 2001). Whole-farm WP may be enhanced by irrigation strategies that apply irrigation water across a larger land area early in the growing season, if storage losses are greater than soil evaporation losses for the irrigated area.

Lobell and Ortiz-Monasterio (2006) found that the modelling approach was beneficial for optimising system WP, and allowed the user to examine irrigation management regimes for multiple environments, soil types and climatic conditions. In a review of irrigation management techniques in water scarce environments, Pereira et al. (2002) stated: *"More research approaches are required to relate yield responses with gross margin or revenue responses to water deficits. The development of decision support tools integrating irrigation simulation models, namely for extrapolating field trials data, economic evaluation and decision tools should be useful to base the appropriate irrigation management decisions for water scarcity conditions"*. Additionally, the crop modelling approach can be used to demonstrate the level of risk associated with different strategies, by using historical weather data to generate probability distributions of production and profitability (e.g. Hammer et al., 1996; Hochman et al., 2009).

2.4. Conclusions

The lack of attention given to fully irrigated wheat production has meant that little research has been conducted on the potential productivity of irrigated wheat growing in the northern grains region. The prevalence of lodging in the 2008 season suggests that lodging may be a major constraint to WP in the northern region, however the extent to which it limited yield in 2008 is unknown, and agronomic control methods for lodging are untested in irrigated wheat production systems of the northern grains region. Additionally, research from other irrigated wheat production systems around the world have given variable recommendations as to the most profitable strategy for irrigating wheat.

Therefore as discussed in chapter 1, this dissertation aims to address these issues through:

(1) determination of the potential yield, water use requirements and lodging related yield gaps associated with irrigated wheat production systems in the northern grains region,
(2) an investigation into the ability of agronomic techniques to control lodging in locally adapted germplasm relevant to the northern grains region, and
(3) determination of the whole-farm crop water productivity of full and partial irrigation strategies for the typical limited-water availability situation found in the northern grains region.

Chapter 3 - Quantifying potential yield and lodging related yield-gaps for irrigated spring wheat in the northern grains production region of eastern Australia

3.1. Introduction

In 2008, irrigated growers in the northern grains production region of eastern Australia sowed record areas of irrigated wheat in response to high grain prices and good water availability. The decision to sow irrigated wheat followed a wet summer in which a flood event filled water storages after the cotton planting window had closed. The high wheat price gave the prospect of earlier cash flow than waiting for the next cotton crop after two years of drought (and little or no crop production). Thus the decision to sow wheat was straightforward for many irrigated growers. These irrigated enterprises no longer viewed themselves as cotton growers, but rather, commodity growers needing to make the greatest return on the available irrigation water.

While farm managers sought to make the greatest economic return on the available irrigation water, widespread lodging in commercial fields contributed to low yields. Unfortunately, there has been little research on the potential yield or water use requirement of irrigated spring wheat in the region. Such information would allow growers to assess the risk of lodging-related yield losses and compare the profitability of irrigated wheat against alternate crops. Prior to the 2008 season the highest recorded on-farm irrigated wheat yields in the region were between 5 and 6 t ha^{-1}; no better than the highest rainfed yield in favourable seasons.

Researchers worldwide understand the benefits of simulation modelling over the traditional field experimentation approach for investigating many agronomic questions. For example, Lobell and Ortiz-Monasterio (2006) found that the modelling approach was beneficial for optimising irrigated farming system water productivity, and allowed the user to examine irrigation management regimes for multiple environments, soil types and climatic conditions. Additionally, the crop modelling approach can be used to demonstrate the level of risk associated with different strategies, by using historical weather data to generate probability distributions of production and profitability (e.g. Hammer et al., 1996; Hochman et al., 2009). However, generating meaningful recommendations from simulation experiments depends on appropriate parameterisation of the simulation model, which should be demonstrated through accurate simulation of validation data obtained from field experiments (Passioura, 1996; Sinclair and Seligman, 2000).

Crop simulation models have been widely used to examine the potential yield of irrigated spring wheat in sub-tropical regions. Amir and Sinclair (1991) and Andarzian et al. (2008) validated simple mechanistic models for assessing potential yields in Israel and Iran, at grain yields up 8 t ha^{-1}. More complex models (CERES-Wheat, DSSAT, WTGROWS) have been used throughout India to show that potential yield varies between 4 and 8 t ha^{-1} depending on location (Aggarwal and Kalra, 1994; Aggarwal et al., 1994; Hundal and Prabhjyot-Kaur, 1997; Arora et al., 2007; Timsina et al., 2008). In Mexico, potential yields in the Yaqui Valley have been assessed at 7 to 8 t ha^{-1} using CERES-Wheat (Bell and Fischer, 1994; Lobell and Ortiz-Monasterio, 2006), while in Zimbabwe yields of up to 10 t ha^{-1} were achieved while validating ZIMWHEAT, a modified version of CERES-Wheat (MacRobert and Savage, 1998).

In Australia, the most widely used crop model is the farming systems simulator APSIM (Keating et al., 2003; Carberry et al., 2009; Holzworth et al., 2014). APSIM has accurately predicted grain yield of high-yielding rainfed and irrigated wheat plot trials in sub-tropical and temperate regions of Australia (Asseng et al., 1998; Chenu et al., 2011; Peake et al., 2011) as well as in India and Europe (Balwinder Singh et al., 2011; Asseng et al., 2000). However it has not previously been used to investigate potential yield of broad-acre spring-wheat production systems in the subtropics, and contains no functionality for the simulation of crop lodging.

A common aspect of the potential-yield studies above was that validation data were obtained from crops where water and nitrogen (N) were considered non-limiting. Interestingly, lodging was not recorded as being present in any of the experiments or commercial fields from which the data were sourced, despite the regular occurrence of lodging in experiments and high-yielding commercial fields used to determine potential yield in spring and winter wheat (e.g. Stapper and Fischer, 1990b; Berry et al., 2004; Tripathi et al., 2004, 2005).

Lodging can reduce yield due to physiological disruptions (i.e. reduced radiation use efficiency and decreased photosynthesis caused by a less efficient canopy structure) and the difficulty of harvesting badly-lodged crops (Berry et al., 2004). Lodging has the potential to cause significant economic losses in mechanized, high-input farming systems such as those of the northern grains region, where the achievement of grain quality benchmarks is necessary to maximise economic returns. This is particularly so because large amounts of N fertiliser are required at high yield levels to achieve the highest Australian grain protein classification of 13%, and high soil N levels increase the risk of lodging (e.g. Mulder, 1954; Berry et al., 2000). However no assessment has been made of yield gaps associated with lodging or other constraints in this production system.

Therefore, the objective of this study was to determine (1) potential yield and water use and (2) lodging related yield gaps, in the lodging-susceptible, high-input irrigated farming systems of the northern grains region. A significant emphasis of the study involved validation of the APSIM model for use in achieving both objectives. However, the widespread incidence of lodging in the monitored commercial fields during the study period instigated the establishment of a second objective for this study: to identify agronomic management practices that may have contributed to lodging.

3.2. Materials and methods

3.2.1. Overview

Given the intensive use of the APSIM model in rainfed wheat production areas of Australia, the approach taken in this study was to (a) determine if the APSIM model could successfully simulate irrigated wheat production by assessing its ability to simulate commercial irrigated wheat production fields and field experiments, (b) use APSIM to determine the potential yield and water use requirement of irrigated wheat production, and (c) determine the magnitude of lodging related yield gaps by comparing APSIM predicted yield to farmer-realised yield.

3.2.2. Field measurements

Thirteen commercial wheat fields were monitored for biomass development and grain yield production at a range of locations across the northern grains region in 2008 to reflect the localities in which large areas of irrigated wheat had been sown, broadly representing the districts of the Darling Downs, Border Rivers and Maranoa-Balonne.

In 2009, three commercial fields were monitored near Emerald (in central Queensland), along with two field experiments at Gatton (south-east Queensland), in part to assess the APSIM model in a wider range of environments, but also due to the absence of irrigated wheat crops in the same districts as 2008. The experiments at Gatton (discussed in detail in Chapter 4) consisted of multiple agronomic treatments (plant population and bed configuration) investigated in factorial combination with two cultivars and two N application strategies. Two plant populations from each experiment were used as monitored treatments in the present study. Crop inputs were recorded for each field to allow simulation of the field with APSIM. All the cultivars monitored are protected by Plant Breeders Rights legislation within Australia.

Commercial fields were soil-sampled soon after sowing to determine the soil water and N content of the soil to a depth of 180 cm. Sowing soil samples were analysed for gravimetric soil water content, nitrate-N concentration, soil organic carbon and pH. Four or five cores from an area approximately 0.5 hectares (100 m × 50 m) in each field were collected, and split into depth layers (0-15 cm, 15-30 cm, 30-60 cm and in further 30 cm increments to 180 cm). Depth layer samples from each core were combined with samples from the same depth layer from other cores in the same field. The seven depth layer samples from each field were then split into two samples, one for soil mineral N analysis and one for soil water analysis. Samples for N analysis were dried at 40°C and the nitrate-N content of the samples was determined by using a 1:5 soil/water extraction, method 7B1 (water soluble nitrate) from Rayment and Higginson (1992). Ammonium-N was not measured as it is typically small in vertosol soil types in relation to nitrate-N, and is difficult to measure accurately when samples cannot be kept cool between sampling and analysis (Neal Dalgliesh, pers. comm.). The 1:5 soil/water extraction was also used to determine pH, while organic carbon assays were obtained using the Walkley and Black method (methods 4A1 and 8B1 respectively from Rayment and Higginson (1992)). Soil water samples used in determining gravimetric moisture content were weighed in the field, then dried at 105°C for a minimum of 48 hours. Dry weight was subsequently determined only when sample weights showed no weight decrease over a period of 6 hours.

For each crop, biomass samples and phenology (growth stage) observations were taken periodically at all sites, at approximately DC31, DC39, DC65 and maturity as defined by Zadoks et al. (1974). Phenology was assessed weekly when the crops neared anthesis (DC65). Three biomass cuts of 0.5 m^2 were taken from each site within the section of the field that had been soil sampled. The cuts were collected from representative, healthy sections of the crop, avoiding localised field conditions such as missing rows or waterlogged depressions. Lodged sections of the fields were also avoided where possible when taking biomass cuts as the primary objective was to assess the potential yield of the field, and the extent to which lodging would affect grain yield was unknown. Biomass cuts were dried at 80°C for a minimum of 48 hours, and were not removed until sample weights showed no decrease over a period of 6 hours. The distance between field sites meant that it was difficult to keep biomass samples cool while being transported, and it is possible that measured biomass may have been reduced as a result of respiration during the time elapsed between sampling and drying.

Lodging severity for the commercial fields is defined as follows: ‘Mild’ lodging occurred more than three weeks after anthesis, with average stem angles less than 30 degrees from vertical; ‘Moderate’ lodging occurred within two weeks of anthesis, and stem angle from vertical had worsened to more than 30 degrees within three weeks after anthesis; ‘Severe’ lodging began at or prior to flag leaf emergence, with average stem angle worsening to more than 60 degrees from vertical prior to anthesis before straightening in a phototropic response

At three of the fields, volumetric soil water content was measured using a neutron moisture meter (NMM). The NMM data were calibrated to gravimetric soil water content using a minimum of 8 soil cores taken over the range of moisture contents experienced through the season. NMM readings were taken using a CPN 503 DR Hydroprobe (CPN International, Martinez, USA) with a 16 second count. Calibration equations were developed for the NMM using soil samples taken during access tube installation, and throughout the season at a range of moisture contents by installing access tubes in nearby crop and taking readings, along with gravimetric soil samples. The first NMM readings were taken during access tube installation at sowing, then two weeks after sowing, and thereafter at regular intervals until physiological maturity was reached.

Farmer-realised yield for each field was collected by the grower or harvest contractor and hence sampled lodged areas of the field. Grain yield was recorded as measured by a calibrated yield monitor, adjusted to 12.5% moisture, for the section of the field that was monitored.

3.2.3. APSIM validation simulations

APSIM 7.4 (Holzworth et al., 2014) was parameterised to simulate each crop. The nearest SILO database (Jeffrey et al., 2001) climate files were used for each site, augmented by farmer measured rainfall where the SILO location was more than 5 km from the property. Irrigation dates and volumes were estimated by the farmer as the amount of water delivered to the field (i.e. after farm distribution losses). APSIM irrigation efficiencies of 85% and 100% were applied for the simulation of furrow and CPLM (Centre-Pivot Lateral-Move) irrigated fields, respectively.

The APSIM 2-stage evaporation constants ‘u’ and ‘cona’ were set to 4 and 2.5 respectively for the period 1st April to 31st October, and then to 6 and 4 respectively after November 1st, according to the standard parameterisation for northern region soils in the APSOIL database (Dalgliesh et al., 2006). Soil water content was set equal to the measured soil water data on the date of sowing, and reset to equal the measured data on the dates of measurement. In the cases where soil sampling occurred 4-6 weeks after sowing, sowing soil water content was estimated by reverse extrapolation using APSIM.

Soil types were classified into their appropriate APSOIL ‘Typical Vertosol’ class as described by Peake et al. (2010) (Appendix A). All soil cores obtained through the season were used to assist with soil classification. Field soil parameterisation was modified slightly from the APSOIL Typical Vertosol parameters to match in-season soil moisture measurements when they were outside the upper and lower bounds of soil water content of the chosen soil type.

While a range of wheat cultivars are available for selection within APSIM, few have been specifically studied and parameterised for all regions in which they are grown. Hence it was important to determine that phenology was adequately simulated, given the importance of flowering date in determining grain yield (e.g. Ortiz-Monasterio et al., 1994). Where the date of anthesis for a cultivar was simulated to be more than 5 days different to observed (or the cultivar was not available in the APSIM cultivar set) an alternative cultivar was chosen that more closely simulated the observed anthesis phenology data for the monitored field.

Furrow irrigated fields were observed to have a different canopy structure to overhead irrigated fields, due to unplanted ‘furrow gaps’ (Figure 3.1). On top of the 1m beds there were generally 4 rows of wheat spaced 13 cm apart to make a 40 cm section of wheat on top of the beds separated by 60 cm furrow gaps, while 2m beds generally had 7-10 rows of wheat sown in a 140 cm wide section separated by 60 cm furrow gaps. An adjustment was made to APSIM to allow simulation of these crops, by using the APSIM ‘skip_row_factor’ function originally developed to reduce light interception in ultra-wide row sorghum crops (Whish et al., 2005). The proportion of lost light interception was calculated based on field observations of crop height and duration of incomplete light interception for a north-south configured irrigated field (Appendix B). The APSIM ‘skip_row_factor’ function was calibrated at values of 0.3 and 0.68 to simulate the expected reduction in light interception of 10 and 20% for 2 metre and 1 metre bed fields, respectively. As a result the crops were therefore simulated to have decreased crop growth and grain yield due to the ‘furrow gaps’. It should be noted that this parameterisation simulates the maximum yield loss likely in north-south aligned configurations, and may overstate the effect in east-east configured beds due to the low position of the sun in the northern sky during spring.

Figure 3.1. A late planted, quick maturing cultivar (Kennedy) sown on 1m beds with north-south furrows at St George, showing a ‘furrow gap’ not intercepting midday light, one week prior to anthesis.

3.2.4. Simulation of potential yield and water use

Long term APSIM simulations were conducted to determine the potential yield and water use requirements of irrigated wheat. Simulations were conducted at sites to represent the major irrigated cropping areas in Queensland and Northern NSW, selected as Emerald, Dalby, St George, Goondiwindi, Walgett and Gunnedah (Figure 1.1). Simulations were conducted using SILO (Jeffrey et al., 2001) climate files for each location, between 1960 and 2012. Typical Vertosol soil types from the APSOIL database (Dalgliesh et al., 2006) were chosen to represent the typical plant available water holding capacity of soils at each location: 269 mm at Gunnedah and Dalby (Typical Vertosol #2), and 213 mm at the remaining locations (Typical Vertosol #6).

Soil moisture, nitrate-N and organic matter were reset each year at sowing, and simulations were conducted under N non-limiting conditions, by having 280 kg ha^{-1} of soil mineral N available at sowing, and an additional 150 kg ha^{-1} of N added as fertiliser within two months of sowing. The cultivar used for all simulations except Emerald was Hartog, chosen because of its appropriate phenological representation of the commercial cultivar Kennedy which was grown successfully without lodging in many fields in the 2008 season. The cultivar Lang was used for the simulations at Emerald, in order to correct for the difference between observed phenology and the APSIM-predicted phenology for Hartog in central Queensland. The sowing date was selected to represent a typical sowing date for quick maturing cultivars planted early in the sowing window, as recommended by local agronomists at each location, being the 23rd May (Emerald), 1st June (Goondiwindi, St George, Walgett) or the 8th June (Dalby, Gunnedah).

Three irrigation system layouts were simulated for each location; centre-pivot and lateral-move (CPLM), and one metre (1m) and two metre (2m) bed furrow irrigation. CPLM simulations were conducted using the default APSIM 7.4 wheat model parameters. Simulations to represent the potential yield of 1 metre and 2 metre bed furrow irrigation fields additionally used the 'skip_row_factor' function discussed previously. Sowing soil moisture was set to equal 75% of the plant available water capacity (PAWC). Irrigation scheduling was simulated to match best industry practice, with a soil water deficit of 40 mm and 70 mm (over 1.2 m in depth) triggering irrigation events for overhead irrigation systems and furrow irrigated fields, respectively. These irrigation schedules were close to water non-limiting but still produced mild water stress during hot weather, so that the yield and water use requirements represented an attainable target for well grown commercial fields, rather than a perfectly grown crop.

An additional simulation was conducted for the CPLM system at each location. This simulation used modified APSIM-Wheat parameters to simulate the potential yield of cv. Kennedy by assuming a maximum kernel weight of 45 mg (dry weight) compared to the APSIM default of 41mg, as 45mg grains were observed in well-grown Kennedy crops in 2009.

3.3. Results

3.3.1. Field observations

3.3.1.1. Seasonal conditions

In 2008, the region experienced higher than average temperatures in the first 50 days of the growing season (Figure 3.2a) followed by a very cool period for the next 30 days, then warmer than average temperatures for most of the remainder of the growing season. Rainfall through the growing season was close to the long term average (data not shown), with a large rain event just prior to harvest in many of the monitored fields. Solar radiation fluctuated throughout the season but was generally below average due to frequent cloudy weather and rain events (Figure 3.3a). Lodging was evident in many of the fields by the middle of grainfilling, but worsened after the rain event.

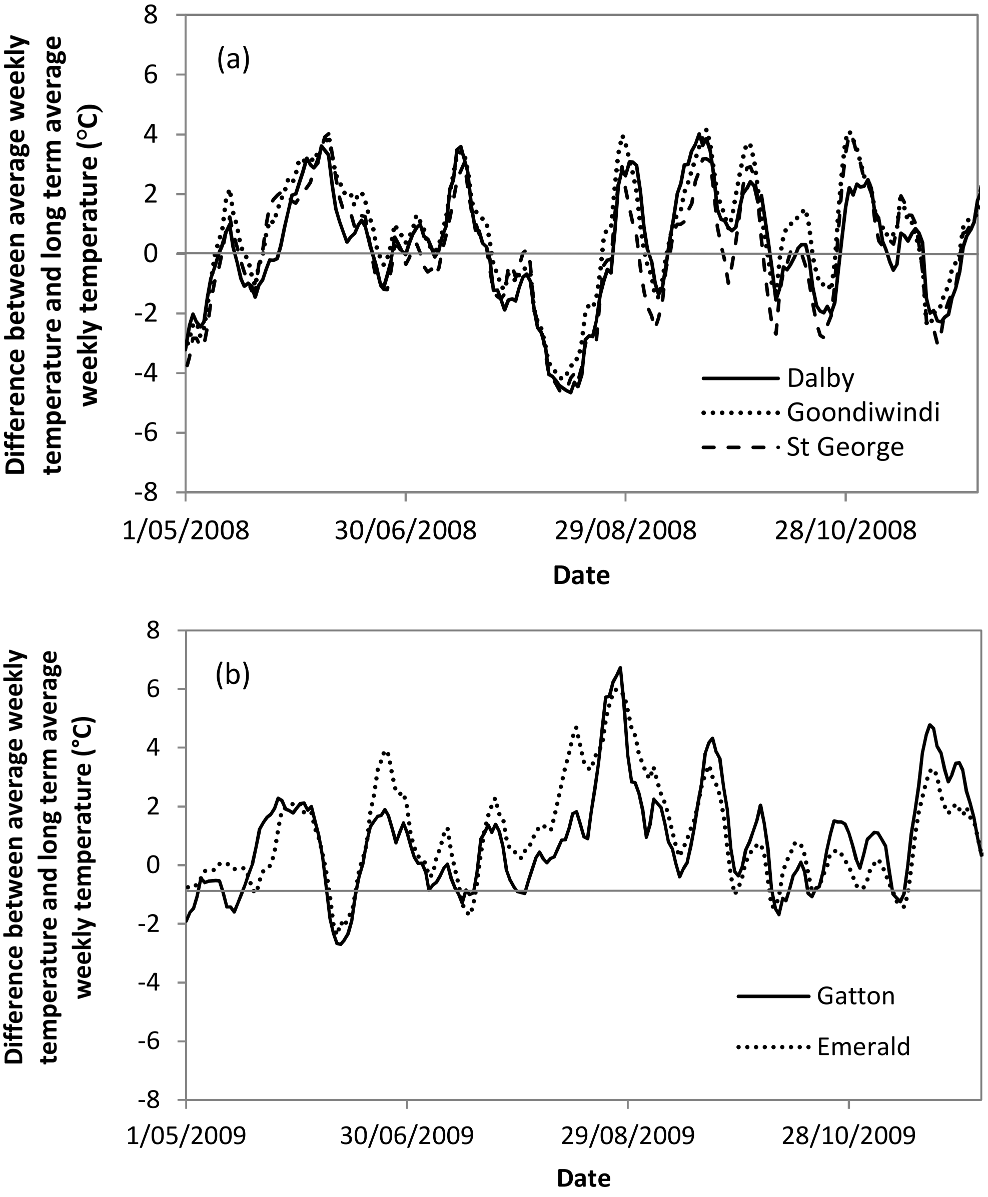


Figure 3.2. The difference between average weekly temperature and long term average weekly temperature for (a) Dalby, Goondiwindi and St George in 2008, and (b) Emerald and Gatton in 2009.

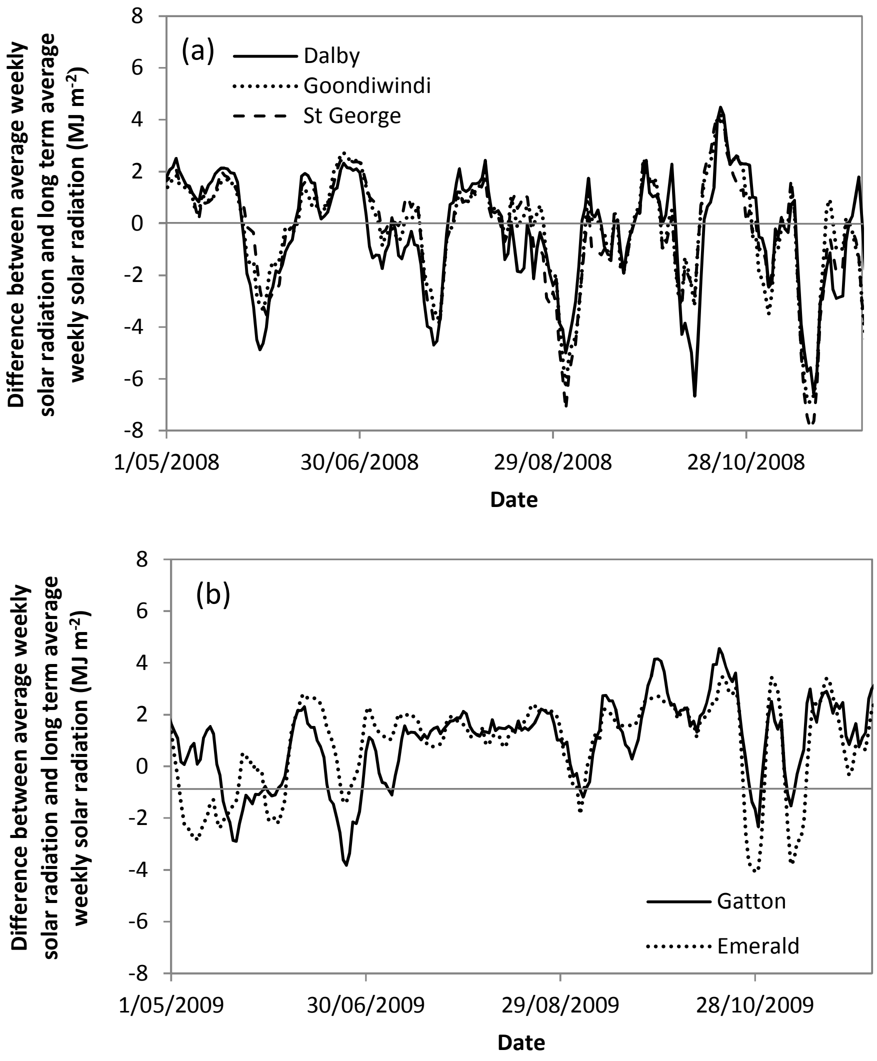


Figure 3.3. The difference between average weekly solar radiation and long term average weekly temperature for (a) Dalby, Goondiwindi and St George in 2008, and (b) Emerald and Gatton in 2009.

In 2009, temperature at Gatton and Emerald was above average for most of the first 120 days of the growing season (Figure 3.2b), after which temperatures were close to the long term average for the remainder of the growing season. Growing season rainfall was very low in Emerald, and slightly below the long term average at Gatton (data not shown). Solar radiation fluctuated throughout the season but was generally above average due to infrequent cloudy weather and rain events (Figure 3.3b).

3.3.1.2. Agronomic characteristics of monitored fields

A summary of the major agronomic management differences between the fields that were monitored is included in Table 3.1(a-c), along with comments as to the performance of the crop. Raised beds were generally used in fields normally reserved for cotton production as discussed in section 3.2.3

Table 3.1a. Location, agronomic details and crop performance at 18 monitored fields from 2008 (fields 1-13), and 2009 (fields 14-18)

Field	Location	Irrigation Type	Bed Configuration	Sowing Date	Cultivar	Grower Harvested Yield	Crop Lodging Severity[#] and General Comments
1a 1b	Brookstead (S27.76° E151.44°)	Lateral Move	Not Applicable	12/6/08	EGA Gregory Kennedy	5.9 t ha^{-1} 7.0 t ha^{-1}	No Lodging. Water stressed during late-grain filling. Irrigator was moved to another field after flowering.
2	Dalby (S27.18° E151.26°)	Furrow	2m beds, no furrow gap*	13/6/08	Kennedy	4.5 t ha^{-1}	No Lodging. N-stressed for long periods. In-crop N application was delayed.
3	Dalby	Furrow	3m beds, no furrow gap*	13/6/08	Ventura	5.75 t ha^{-1}	No Lodging. Yellow spot (leaf disease) limited yield.
4	Goondiwindi (S28.55° E150.32°)	Centre Pivot	Not Applicable	29/5/08	Ventura	5.0 t ha^{-1}	Moderate lodging. Water stressed during late grain filling. Lodging began at anthesis, after which the grower decided to stop irrigating.
5	Goondiwindi	Furrow	2m beds	29/5/08	Ventura	4.0 t ha^{-1}	Moderate lodging. Poor germination, excellent recovery, weather damage experienced prior to harvest.
6	St George (S28.04° E148.58°)	Furrow	1m beds	5/5/08	EGA Gregory	4.8 t ha^{-1}	Moderate lodging
7	St George	Furrow	1m beds	20/6/08	Kennedy	5.2 t ha^{-1}	No lodging, late sown.
8	St George	Furrow	2m beds	10/5/08	Strzelecki	3.3 t ha^{-1}	Severe lodging - began at DC32.
9	Dirranbandi (S28.58° E148.23°)	Furrow	2m beds	17/5/08	Baxter	4.0 t ha^{-1}	Severe lodging – began at DC39.
10	Dirranbandi	Furrow	2m beds	3/6/08	Ventura	4.2 t ha^{-1}	Moderate lodging.
11	St George	Furrow	1m beds	26/5/08	Ventura	3.2 t ha^{-1}	Moderate lodging, hail damage.
12	St George	Furrow	1m beds	12/5/08	EGA Gregory	3.8 t ha^{-1}	Moderate lodging, weather damage.
13	Moree (S29.46° E149.85°)	Furrow	2m beds	10/5/08	EGA Gregory	5.75 t ha^{-1}	Mild lodging.
14	Comet (S23.61° E148.55°)	Furrow	2m beds	20/5/09	Kennedy	6.4 t ha^{-1}	Mild lodging. Canopy managed. Mild N stress observed at DC31 prior to in-crop N application.
15	Rolleston (S24.46° E148.62°)	Furrow	1m beds	28/5/09	Kennedy	6.2 t ha^{-1}	No lodging. Canopy managed. Severe N stress observed at DC31 prior to in-crop N application.
16	Rolleston	Lateral move	Not Applicable	20/5/09	Kennedy	7.3 t ha^{-1}	Moderate lodging.
17a[A] 17b[A]	Gatton (low sowing N) (S27.54° E152.33°)	Hand-shift sprinklers	Simulated 2m beds, (not raised)	13/5/09 5/6/09	EGA Gregory Kennedy	5.6 t ha^{-1} 7.4 t ha^{-1}	No lodging in Kennedy; moderate lodging in Gregory. Canopy managed. Severe N stress observed at DC31 prior to N application.
18a[A] 18b[A]	Gatton (high sowing N)	Hand-shift sprinklers	Simulated 2m beds, (not raised)	13/5/09 5/6/09	EGA Gregory Kennedy	5.0 t ha^{-1} 6.1 t ha^{-1}	Moderate (Kennedy) and severe lodging (Gregory).

* Furrows were 40cm wide and not considered to have limited yield due to closure of the crop canopy over the furrow [#] Lodging severity defined as follows: ‘Mild’ lodging: occurred more than three weeks after anthesis, average stem angles were less than 30 degrees from vertical; ’Moderate’ lodging occurred within two weeks of anthesis, and stem angle from vertical had worsened to more than 30 degrees within three weeks after anthesis; ‘Severe’ lodging began at or prior to flag leaf emergence, with average stem angle worsening to more than 60 degrees from vertical prior to anthesis before straightening in a phototropic response. [A] Two separate plant populations were sown and used for model validation for each cultivar in each of these fields.

Table 3.1b. Location, field alignment, simulated evapotranspiration, soil type, PAWC at sowing and irrigation schedule for monitored fields from 2008 (fields 1-13), and 2009 (fields 14-18)

Field Number	Location	Bed alignment (degrees)[A]	Simulated evapo-transpiration (mm)	Soil Type [B] and PAWC (mm)	Plant Available Water at sowing (mm)	Growing Season Rainfall (mm)[C]	Irrigation Schedule: Date and volume (mm equivalent rainfall)
1a 1b	Brookstead	NA	492 483	TV5 (226)	185	100	15th June (28 mm), 21st Aug (50 mm), 19th Sep (90 mm)
2	Dalby	NA	375	TV5 (226)	253	170	3rd Sept (100 mm), 25th Sep (100 mm)
3	Dalby	NA	510	TV1 (289)	193	171	6th Sept (150 mm), 2nd Oct (120 mm)
4	Goondiwindi	NA	359	TV7 (204)	116	173	10 irrigation events of 10-20 mm between 25th June and 20th Sep (135 mm in total)
5	Goondiwindi	5	454	TV8 (192)	139	244	31st May (100 mm), 27th August (100 mm), 27th Sep (100 mm)
6	St George	85	411	TV8 (192)	164	212	14th Aug (100 mm), 27th Sep (100 mm)
7	St George	5	379	TV10 (166)	209	161	17th July (100 mm), 28-Aug (100 mm),
8	St George	80	494	TV9 (180)	217	212	10th July (60 mm), 28th Aug (90 mm), 25th Sep (100 mm)
9	Dirranbandi	30	432	TV7 (204)	197	183	16th July (100 mm), 27th Aug (100 mm), 27th Sep (100 mm)
10	Dirranbandi	30	378	TV10 (166)	135	132	28th June (100 mm), 20th Aug (100 mm), 8th Oct (100 mm)
11	St George	20	403	TV10 (166)	155	197	11th Aug (100 mm), 26th Sep (100 mm)
12	St George	20	468	TV9 (180)	196	212	17th July (100 mm), 28th Aug (100 mm), 26th Sep (100 mm)
13	Moree	85	450	TV9 (180)	211	182	25th Aug (100 mm), 1st Oct (100 mm)
14	Comet	25	460	TV4 (248)	232	15	11th July (125 mm), 4th Aug (100 mm), 18th Aug (100 mm), 4th Sep (100 mm)
15	Rolleston	45	475	TV8 (192)	211	38	19th July (125 mm), 15th Aug (100 mm), 29th Aug (100 mm), 15th Sep (100 mm)
16	Rolleston	NA	546	TV8 (192)	228	40	15 irrigation events of between 9 and 50 mm, from 19th June to 30th September (494 mm in total)
17a 17b	Gatton (low sowing N)	5	532 499	TV4 (248)	172 174	101	EGA Gregory 11 irrigations of 15-40 mm between 11th Jun 6th Oct (310 mm in total) Kennedy 11 irrigations of 15-40 mm between 11th Jun 6th Oct (310 mm in total)
18a 18b	Gatton (high sowing N)	5	550 507	TV4 (248)	172 174	101	EGA Gregory 11 irrigations of 15-40 mm between 11th Jun 6th Oct (310 mm in total) Kennedy 11 irrigations of 15-40 mm between 11th Jun 6th Oct (310 mm in total)

[A] = degrees from north-south alignment, [B] = TV is an abbreviation for Typical Vertosol, [C] = calculated between the date of soil sampling and physiological maturity

Table 3.1c. Location, soil mineral N and fertiliser N applications for monitored fields from 2008 (fields 1-13), and 2009 (fields 14-18)

Field number	Location	Soil mineral N at sowing (kg N ha^{-1})			In-crop N applied: date of application and (kg N ha^{-1})	Total N (sowing N + in-crop N application)
		(0-90 cm)	(90-180 cm)	Total (0-180 cm)		
1a 1b	Brookstead	252	181	**433**	None applied	433
2	Dalby	110	0	**110**	3rd Sep (75 kg ha^{-1})	185
3	Dalby	308	165	**473**	None applied	473
4	Goondiwindi	350	38	**388**	None applied	388
5	Goondiwindi	167	55	**222**	13th Aug (23 kg ha^{-1})	245
6	St George	321	152	**474**	14th Aug (60 kg ha^{-1})	534
7	St George	529	126	**655**	None applied	655
8	St George	496	238	**734**	None applied	734
9	Dirranbandi	344	158	**502**	None applied	502
10	Dirranbandi	269	78	**347**	None applied	347
11	St George	330	251	**580**	None applied	580
12	St George	496	246	**742**	None applied	742
13	Moree	182	191	**373**	18th Aug (37 kg ha^{-1}), 15th Oct (37 kg ha^{-1})	447
14	Comet	58	94	**152**	10th July (140 kg ha^{-1}), 3rd Aug (30 kg ha^{-1})	322
15	Rolleston	40	13	**53**	18th July (100 kg ha^{-1}), 14th Aug (100 kg ha^{-1})	253
16	Rolleston	158	240	**398**	30th June (33 kg ha^{-1}), 25th July (33 kg ha^{-1}), 4th Aug (42 kg ha^{-1}), 10th Aug (20 kg ha^{-1})	526
17a 17b	Gatton (low sowing N)	41	19	**60**	EGA Gregory: 21st July (190 kg ha^{-1}), 18th Aug (50 kg ha^{-1}) Kennedy: 10th Aug (190 kg ha^{-1}), 10th Sep (50 kg ha^{-1})	300
18a 18b	Gatton (high sowing N)	94	31	**125**	EGA Gregory: 21st July (125 kg ha^{-1}), 18th Aug (50 kg ha^{-1}) Kennedy: 10th Aug (125 kg ha^{-1}), 10th Sep (50 kg ha^{-1})	300

In 2008, many of the wheat crops were sown on fields that had high levels of soil N (Table 3.1c), as fertiliser N had been applied with the intention of sowing a cotton crop the previous summer. However the cotton was ultimately not sown due to insufficient water availability at sowing time. In 2009, crops were generally sown on fields with lower levels of soil N (Table 3.1c) in an effort to reduce their lodging risk as part of a technique known as canopy management. This technique is used internationally to improve crop yield through access to N later in the season, while also decreasing lodging risk (Sylvester-Bradley et al., 2000). Moderate to severe N stress was observed (as leaf yellowing) in most of these crops prior to the application of N during late tillering and early stem elongation.

3.3.1.3. Crop yield

In 2008, fields that experienced no lodging yielded between 4.5 and 7.0 t ha^{-1}. All but one of the non-lodged fields were assessed as being disease, N or water-limited (Table 3.1a). Grain yield in moderately to severely-lodged fields was low, ranging from 3.2 to 5.0 t ha^{-1} (Table 3.1a). The worst lodging was observed in fields of the long-season cultivars Strzelecki and Baxter.

Grain yield in 2009 was generally higher, with yields ranging from 5.0 to 7.4 t ha^{-1}. The lowest yields were produced by the long-season cultivar EGA Gregory, which lodged under both high-N and canopy-managed N regimes at Gatton (Table 3.1a).

3.3.2. Validation of the APSIM model

3.3.2.1. Simulation of phenology (2008 and 2009)

APSIM simulated crop development of most crops to reach growth stages close to anthesis to within 5 days of the observed date (Figure 3.4a). The exceptions were two crops of cv. Ventura in 2008, and three Kennedy crops in Central Queensland (CQ) in 2009. In these crops APSIM simulations using the default cultivar settings reached growth stages substantially faster than observed in the field, and initial simulations of season yield potential were markedly lower (by up to 2 t ha^{-1} in the most extreme case) when the initial phenology parameters were used. For these crops, an alternative APSIM cultivar was selected to represent them in the APSIM validation simulations, such that the simulated growth-stage fell within 5 days of the observed growth-stage (Figure 3.4b).

3.3.2.2. Simulation of biomass, grain yield and yield components from 2008 crops

APSIM tended to over-predict total biomass in the 2008 monitored crops (Figure 3.5a), and there was a near-significant difference between the regression slopes for the lodged and non-lodged crops (p=0.063), with the non-lodged crop biomass yields over-predicted at maturity more than the lodged crops. Grouped linear regression explained 91% of the variation across all fields, and the RMSD was 2.3 t ha^{-1}, 29% of the mean observed biomass.

Farmer-realised grain yield across the 13 fields from 2008 was not well predicted by APSIM (Figure 3.5b). Many of the fields experienced moderate to severe lodging (Table 3.1a), which began between mid stem-elongation and mid grainfilling. Lodging in mildly lodged fields began either in late grainfilling, or during a severe

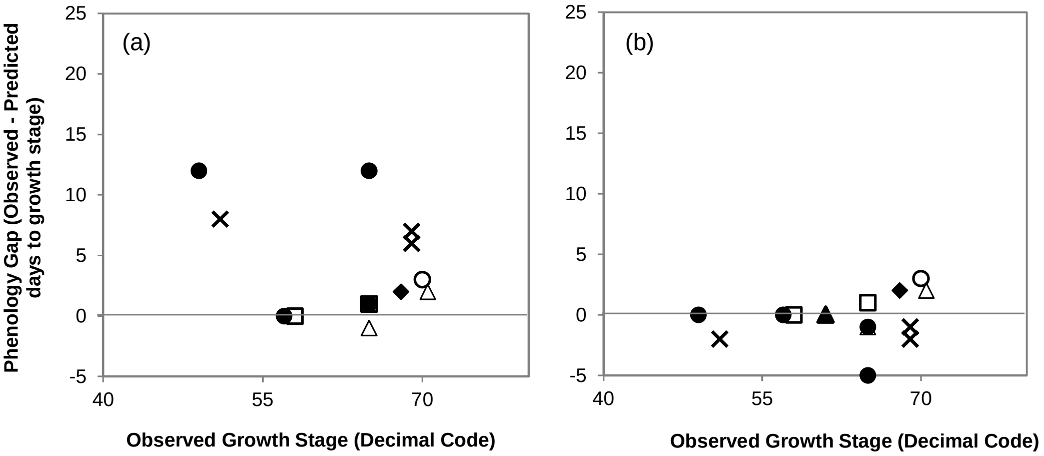


Figure 3.4. Phenology gap (difference in days between observed and simulated time to reach a growth stage) vs. the observed near-anthesis growth stage of the crop for the 2008 and 2009 commercially monitored fields, (a) prior to and (b) after the reconfiguration of cultivar phenology parameters. Cultivar key: ○ = Baxter, ● = Ventura, × = CQ Kennedy, □ = Kennedy, ◆ = Strzelecki, △ = EGA Gregory).

weather event at maturity. The weather event (150-200 mm of rainfall across three days) occurred before most of the fields could be harvested.

While some of the data points fell close to the 1:1 line (Figure 3.5b), approximately half of the fields yielded <75% of the APSIM predicted yield, due to lodging and weather damage losses. The worst lodging was observed in fields of the long-season cultivars Strzelecki and Baxter. Field 4 yielded slighty more than the APSIM predicted yield, which may have been caused by incorrect simulation of crop water input as the farmer was uncertain of irrigation volumes applied later in the

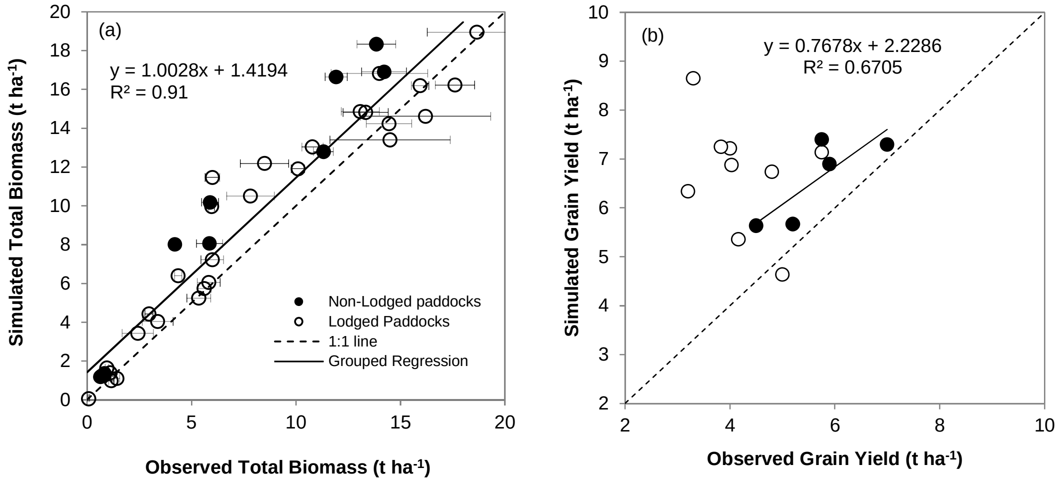


Figure 3.5. Simulated vs. observed (a) above-ground biomass for each sampling date throughout the season and (b) farmer-measured grain yield for the (○) lodged and (●) non-lodged crops monitored in 2008. Horizontal bars in (a) represent the standard error of observed biomass.

season when the irrigator was being used almost constantly. The average yield gap (simulated – observed grain yield) of the lodged fields was 2.5 t ha^{-1} (with a standard error of 0.55 t ha^{-1}) when Field 4 was excluded from the analysis.

APSIM did however predict the yield of the non-lodged plots well, with 67% of the variation accounted for by linear regression, and a RMSD of 1.0 t ha^{-1}, 18% of the mean grain yield. The average yield gap (simulated – observed grain yield) of the non-lodged fields was 0.9 t ha^{-1} (with a standard error of 0.24 t ha^{-1}) however two of the non-lodged crops had yields more than 20% below the APSIM predicted yield. In one (Field 3) a severe infestation of yellow spot (*Pyrenophora triticirepentis*) limited yield. In the other (Field 2) soil N at sowing may have been over-estimated due to difficulties obtaining a representative soil sample, as anhydrous ammonia had been applied in bands shortly before soil sampling.

Grain number was better predicted by APSIM (Figure 3.6a), with grouped regression explaining 60% of the variation once an outlier (Field 9) was excluded from the regression analysis. Kernel weight was less well predicted (Figure 3.6b), with most of the fields simulating the APSIM threshold kernel weight (dry) of 0.041g when the observed average kernel weight was between 0.025 and 0.038 grams. The poor prediction of these yield components for Field 9 was probably caused by the severe lodging observed in this field.

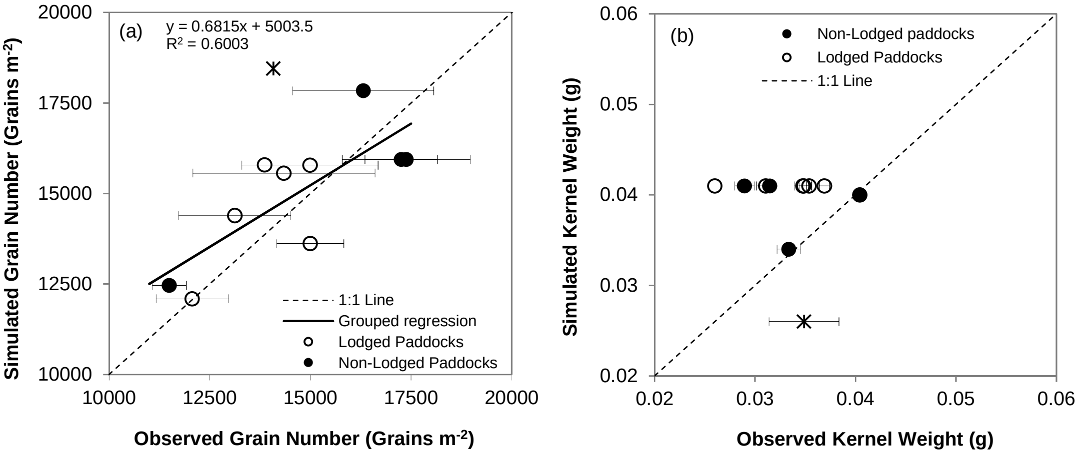


Figure 3.6. Simulated vs. observed (a) grain number and (b) kernel dry weight for the (○) lodged and (●) non-lodged monitored fields in 2008. Linear regression in (a) excluded the outlier Field 9 which also lodged (✱).

3.3.2.3. Simulation of biomass, grain yield and yield components from 2009 crops

In contrast to the 2008 season, APSIM generally under-predicted total biomass in the 2009 monitored crops (Figure 3.7a). The grouped regression of all crops explained 86% of the variation between observed and simulated biomass, with an RMSD of 2.3 t ha^{-1}, 27% of the mean biomass (Figure 3.7a). The Kennedy crops from central Queensland (CQ) simulated very closely to observed data. However, biomass production in the Kennedy and Gregory crops in the low N field at Gatton was under-predicted by up to 50% in some comparisons, and simulation of grain

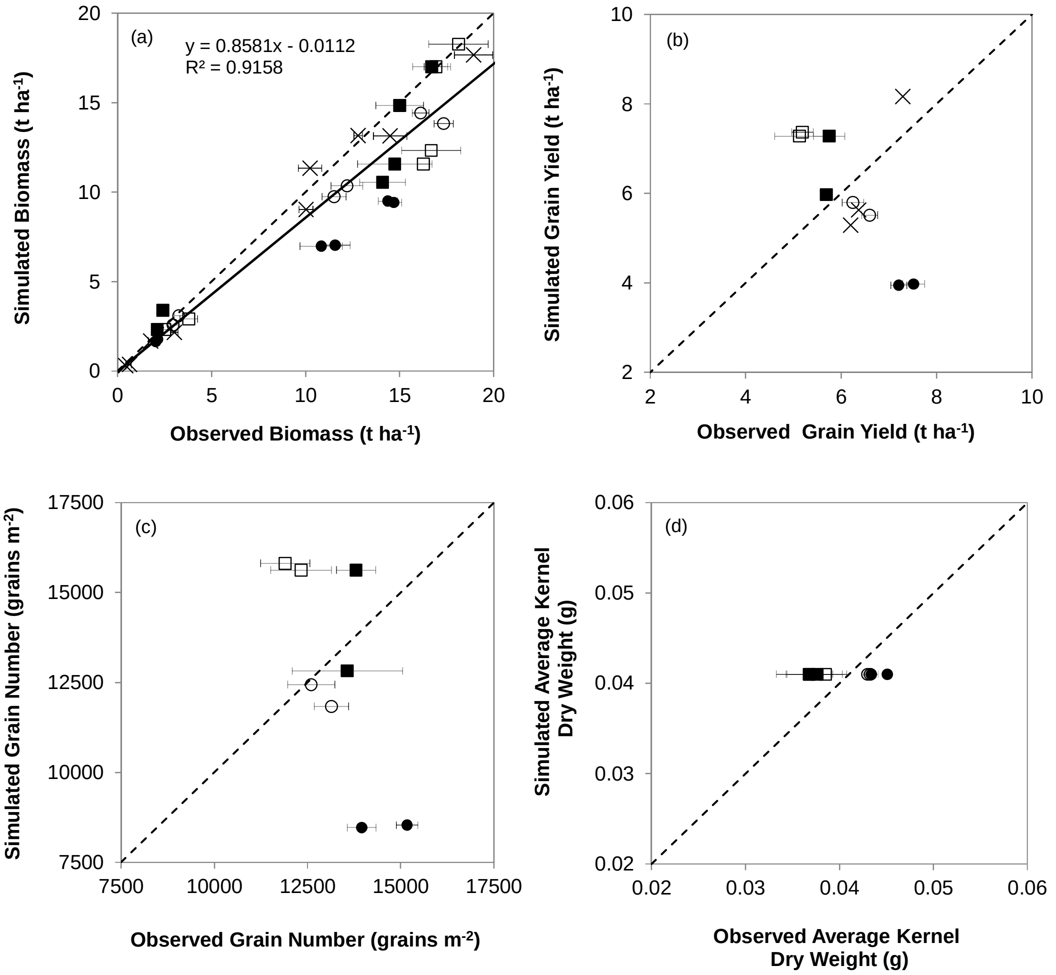


Figure 3.7. Simulated vs. observed (a) above-ground biomass for each sampling date throughout the season, (b) grain yield, (c) grain number and (d) average kernel dry weight for the 2009 crops: (○) Gatton high N Kennedy, (●) Gatton low N Kennedy, (□) Gatton high N Gregory, (■) Gatton low N Gregory, and (×) Kennedy grown in central Queensland. The dashed line (- - - -) represents the 1:1 line, the solid line (——) in (a) represents the grouped linear regression for all data. Duplicate points at Gatton are derived from two plant populations within the same experiment.

yield across the range of CQ and Gatton crops did not accurately predict observed grain yield (Figure 3.7b).

Grain number and kernel weight from the Gatton 2009 crops were not accurately simulated across the range of crops (Figure 3.7c,d), with grain number being over-predicted for the three of the Gregory crops (which all lodged) and substantially under-predicted for the Kennedy crops in the low N, canopy managed field. Kernel weight was simulated to be at the maximum APSIM default value of 0.041 g for all Gatton crops. Yield component data from the CQ crops were not collected.

All except one of the APSIM simulations from 2009 suggested that yield-limiting N-stress occurred during the growing season, while negligible water stress was recorded. Visible observations of N stress symptoms (leaf yellowing) were also recorded during tillering and early stem elongation in two of the CQ Kennedy crops, and the Kennedy and Gregory grown in the low N field at Gatton. In these crops, N stress was observed to rapidly decline (as rapid greening of the canopy) in response to in-crop N application, while the APSIM simulations suggested that N stress remained in the crop for two weeks longer than observed in the field (data not shown).

The 2009 simulations were re-run under N non-limiting conditions by adding additional soil mineral N to the APSIM soil file to ensure that no N stress occurred during the simulation. Prediction of biomass (Figure 3.8a) improved in N non-limiting simulations, with linear regression accounting for 89% of the variation, and RMSD of 1.8 t ha^{-1} (18% of the mean observed biomass). The prediction of both yield and grain number improved (Figure 3.8b,c) but were still poorly correlated with the observed data. Interestingly the grain yield of Kennedy in the low N field was still under-predicted by 1.5 t ha^{-1}, a surprising result given the severe N stress observed in this field prior to in-crop N application at DC31. Due to the APSIM cap on maximum kernel dry weight, no change in the prediction of average kernel dry weight was observed (Figure 3.8d) in N non-limiting simulations. Maximum observed kernel weight of 45.5 mg was observed for Kennedy in this field, 10% greater than the default APSIM value of 41 mg. Additionally, observed grain number for Kennedy in this field was 20% higher than simulated grain number (Figure 3.8c).

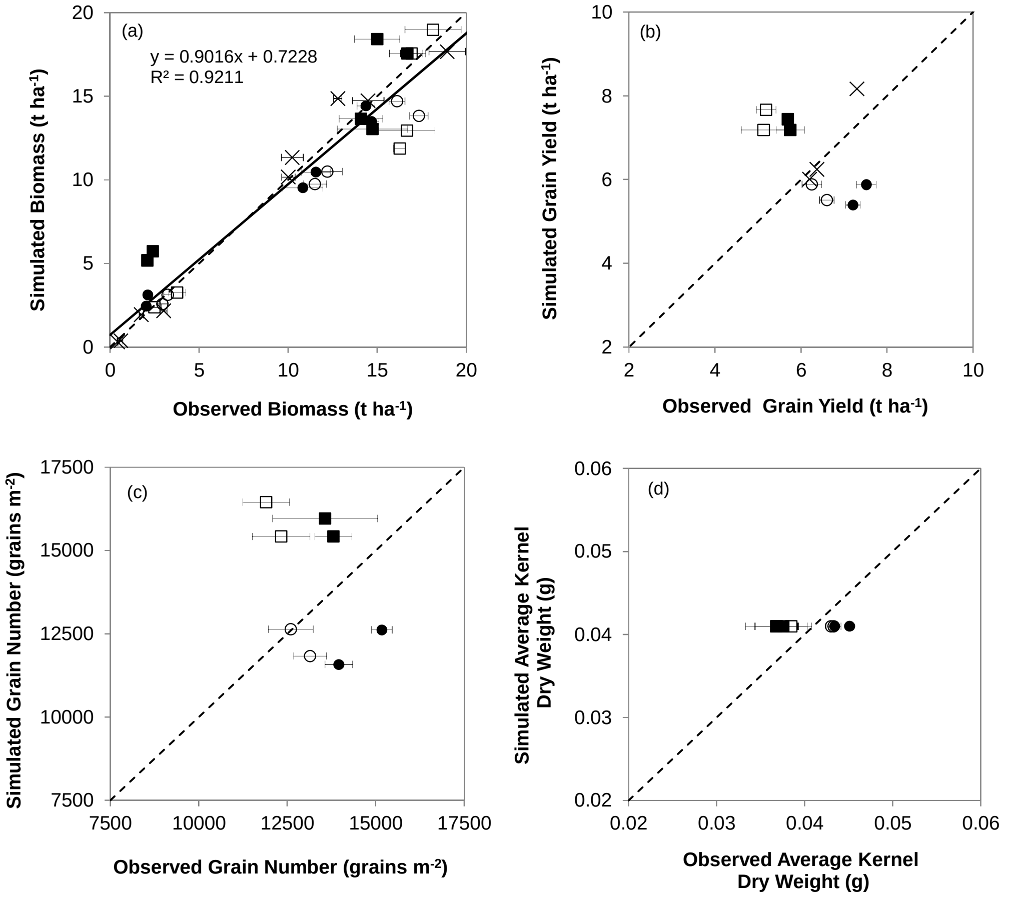


Figure 3.8. Simulated vs. observed (a) above-ground biomass for each sampling date throughout the season, (b) grain yield and (c) grain number and (d) average kernel dry weight, for N non-limiting simulations of the 2009 crops: (○) Gatton high N Kennedy, (●) Gatton low N Kennedy, (□) Gatton high N Gregory, (■) Gatton low N Gregory, and (×) Kennedy crops grown in central Queensland. The dashed line (- - - -) represents the 1:1 line, the solid line (——) in (a) represents the grouped linear regression for all data.

3.3.2.4. Summary of APSIM validation for the cultivar Kennedy in 2008 and 2009 assuming no N limitation to crop growth

In N non-limiting simulations across both 2008 and 2009, APSIM predicted the yield of Kennedy with approximately 10% error or less (Figure 3.9a), with an RMSD of 1.0 t ha^{-1}, 16% of the mean observed grain yield. The most extreme outliers were at Field 3 where prolonged N stress was experienced and not fully relieved, and at Field 17 where severe vegetative N stress was observed prior to in-crop N application. The accuracy of the simulations was further improved by increasing maximum kernel weight to 45 mg in the simulations for Fields 17a and 18a where larger kernel weights were observed (Figure 3.9b), decreasing the RMSD to 0.73 t ha^{-1} (11% of the mean observed grain yield), within the range of normalised RMSD's reported against mean observed data for other models used in other spring wheat potential yield validation studies (Timsina and Humphreys, 2006).

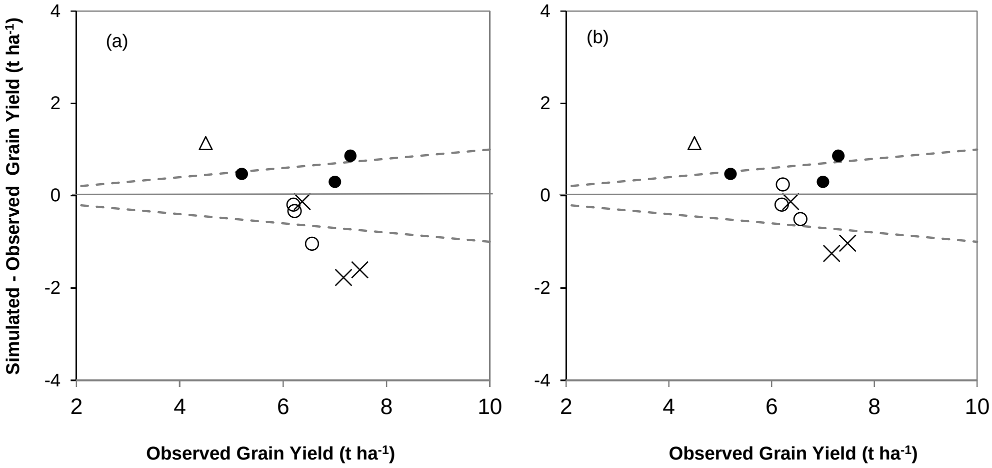


Figure 3.9. Simulated - observed grain yield vs. observed grain yield when using N non-limited simulations for all Kennedy crops monitored in 2008 and 2009, when (a) maximum kernel weight of 0.041 g was used for all crops, and (b) maximum kernel weight of 0.045 g was used for crops where observed kernel weight was greater than 0.041 g. (×) canopy managed crops experiencing severe early N stress, (O) canopy managed crops experiencing moderate early N stress, (●) non-canopy managed crops with high soil mineral N levels at sowing, and (△) crops experiencing prolonged N stress through to maturity. The area within the dashed lines includes crops where simulated yield varied from observed yield by less than 10%.

3.3.2.5. APSIM prediction of crop water use in 2008

Detailed soil water monitoring occurred in three Fields (1a, 3, 5). At Field 1a and 3, APSIM tracked the use of total profile extractable soil water well (Figure 3.10a,b). However at Field 4, after simulating observed water use closely during the first half of the season, simulated water use diverged from the measured soil water contents from 100-150 days after sowing. The farmer at this location was uncertain about the exact amount of water applied later in the season, and it is possible the values used in the simulation were lower than the actual volume of water applied to the crop.

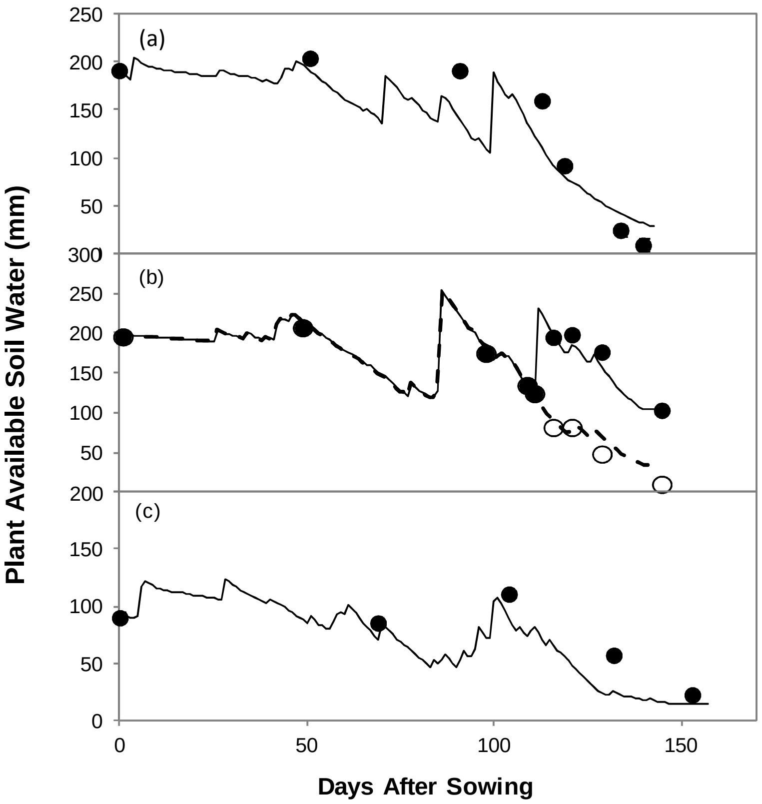


Figure 3.10. Observed (●) and simulated (continuous lines) profile extractable soil water for (a) Field 1a, (b) Field 3, and (c) Field 4. The dashed line (- - -) and open circle (○) in (b) represent simulated and observed soil water from a section of the field which received one less irrigation, but from which no yield estimate was obtained.

3.3.3. Assessment of agronomic management factors potentially contributing to lodging in the 2008 crops.

The average yield gap between simulated and observed grain yield for the monitored fields in 2008, was 0.9 t ha^{-1} in the non-lodged fields, and 2.5t ha^{-1} in lodged fields. Yield gaps generally increased with increased severity of lodging (Figure 3.11a), and soil mineral N at sowing (Figure 3.11b). Of the 13 fields monitored in 2008, 11 had more than 300 kg ha^{-1} of soil N at sowing (measured to 180 cm depth) with more than 200 kg ha^{-1} of N in the top 90 cm (Table 3.1c). Five fields had more than 500 units N to 180 cm depth, yet the N requirement to produce above ground biomass in a wheat crop with 8 t ha^{-1} grain yield is approximately 250 kg ha^{-1} N (Ortiz-Monasterio, 2002). One field (Field 7) had more than 500 kg ha^{-1} of soil mineral N available at sowing but did not lodge, probably because it was sown late and was unable to develop the biomass and yield potential required to create the physical crop conditions necessary for lodging to occur.

Fertile tiller number per unit area was assessed at harvest, and plotted against yield gap (Figure 3.12). When fertile tiller number was calculated on a whole-field area basis, no significant relationship was observed between yield gap and fertile tiller number per unit area (Figure 3.12a). However when calculating the fertile tiller number on a bed area basis (omitting the unsown furrow gap from the calculation of ground area), a significant linear relationship was observed between fertile tiller number and yield gap (Figure 3.12b).

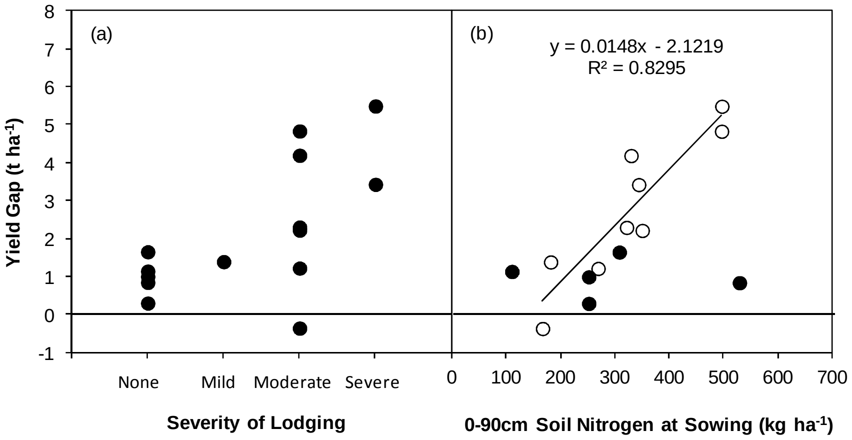


Figure 3.11. Yield gap (simulated - observed grain yield) vs. (a) visual lodging severity ratings for all 2008 monitored fields, and (b) 0-90cm soil mineral N at sowing for (○) lodged and (●) non-lodged fields, including a linear regression (solid line) for the relationship between yield gap and soil mineral N for the lodged fields.

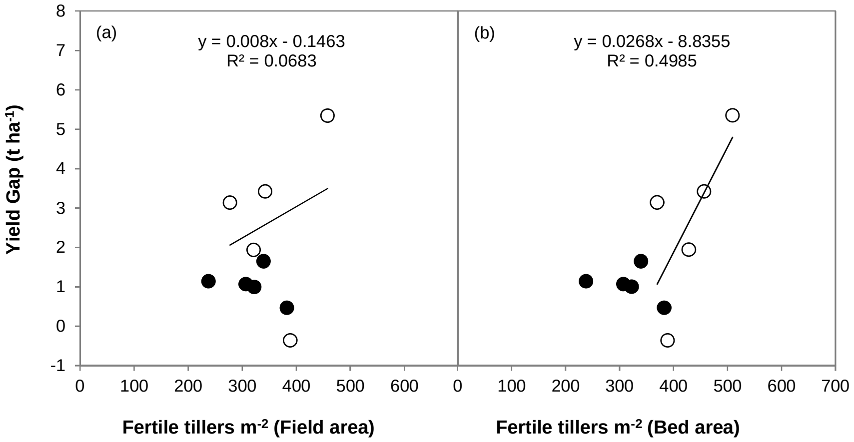


Figure 3.12. Relationship between yield gap (simulated - observed grain yield) and fertile tillers number, when calculating fertile tiller number on (a) the whole field basis, and (b) the bed area basis (i.e. excluding unsown areas in furrows) for (○) lodged fields, (●) non-lodged fields and including a linear regression (solid line) for the relationship between yield gap and fertile tillers for the lodged fields.

3.3.4. APSIM simulated potential yield and water use for irrigated wheat in the northern grains region

CPLM irrigation was found to produce 10-12% and 20-22% higher average yield compared to the furrow irrigated 2m and 1m beds, depending on location (Figure 3.13). The use of higher maximum kernel weight for Kennedy in the CPLM

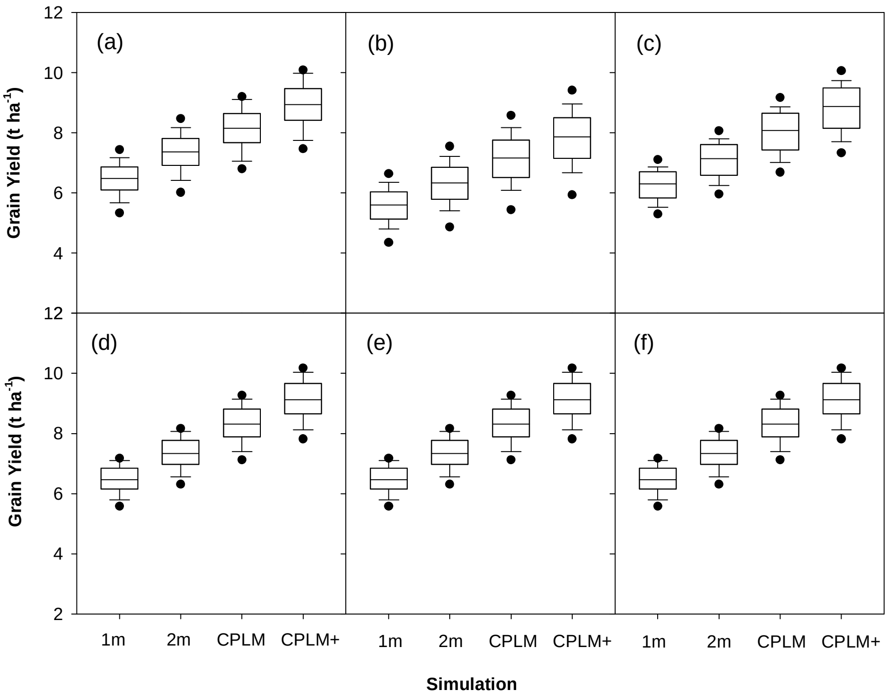


Figure 3.13. Boxplots for potential yield from 110 year simulations of cv. Kennedy under best industry practice irrigation at (a) Dalby, (b) Emerald (c) Goondiwindi, (d) Gunnedah (e) St George and (f) Walgett. Simulation analyses were for '1m' bed furrow irrigation, '2m' bed furrow irrigation, CPLM (Centre Pivot-Lateral Move) irrigation systems, and CPLM+ (CPLM systems with higher potential kernel weight). Boxed areas indicate the upper and lower quartiles, whiskers represent the upper and lower deciles, and the area bounded by circles represents 90% of all years. Median year is represented by the solid line within the interquartile range box.

simulations increased yield by an additional 10% at each location. The highest long term average yield for the CPLM simulations using the adjusted maximum kernel weight of 0.045 g was simulated at Gunnedah (9.1 t ha^{-1}), while the lowest average yield was observed at Emerald (7.8 t ha^{-1}). The range for 95% of simulated outcomes (i.e. ± 2 standard deviations from the mean) across the 110 year simulation was 2.4, 2.8 and 3.2 t ha^{-1} for the 1m, 2m and CPLM analyses on average across the six environments.

Evapotranspiration water use was also affected by irrigation method (Figure 3.14). The CPLM irrigation had 6-11% and 13-18% higher mean evapotranspiration across locations compared to the furrow irrigated 2m and 1m beds. Using the higher maximum kernel weight for Kennedy in the CPLM simulations had no effect on simulated evapotranspiration compared to the simulations using the standard kernel weight. In this case, the crops continued to transpire at the same rate regardless of whether the simulation had filled the crop 'sink' to capacity. Mean evapotranspiration from the CPLM simulations ranged from 530mm at Gunnedah to 495mm at Emerald. The range for 95% of simulated outcomes (i.e. ± 2 standard deviations from the mean) for evapotranspiration was 148, 172 and 198 mm for the 1m, 2m and CPLM analyses respectively, on average across the six environments.

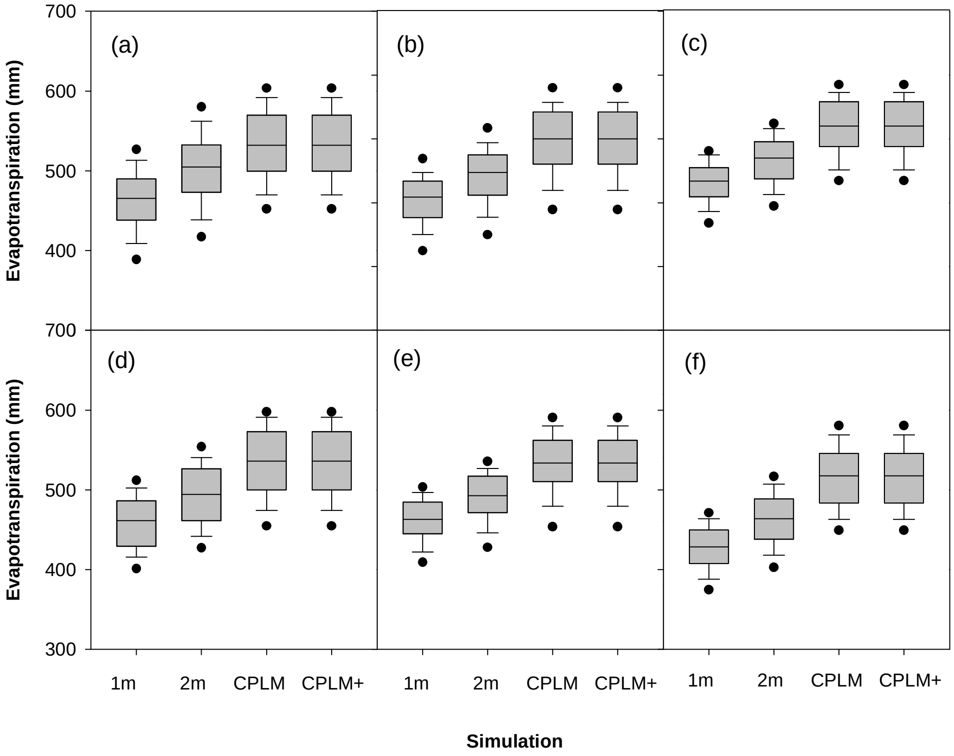


Figure 3.14. Boxplots of evapotranspiration water use from potential yield simulations for cv. Kennedy under best industry practice irrigation at (a) Dalby, (b) Emerald (c) Goondiwindi, (d) Gunnedah (e) St George and (f) Walgett. Simulation analyses were for '1m' bed furrow irrigation, '2m' bed furrow irrigation, CPLM (Centre Pivot-Lateral Move) irrigation systems, and CPLM+ (CPLM systems with higher potential kernel weight). Boxed areas indicate the upper and lower quartiles, whiskers represent the upper and lower deciles, and the area bounded by circles represents 90% of all years. Median year is represented by the solid line within the interquartile range box.

3.4. Discussion

3.4.1. APSIM validation

3.4.1.1. Phenology

One of the critical tasks in simulating crops is ensuring that crop phenological development is simulated correctly. This is necessary because the length of the crop's growing season and the timing of flowering in relation to in-season water and N stress can drastically alter the final yield of a crop (e.g. Stapper and Fischer, 1990a; Ortiz-Monasterio et al., 1994). However, the large number of wheat cultivars available to Australian growers means that some cultivars used by growers in the course of this study have not been subjected to rigorous phenological investigation. Their phenological parameters are derived from limited datasets that do not represent the diverse range of production environments used for commercial wheat production in Australia. Thus in this study, APSIM generally simulated flowering date well in cultivars that had been calibrated against larger datasets of regionally representative phenology data, such as the widely grown cultivars EGA Gregory and Kennedy. The cultivar that was modelled with the most difficulty was Ventura, a lesser known cultivar sourced from southern Australia in 2008 for its reputed good performance under irrigated conditions (Paul Castor, pers. comm.).

3.4.1.2. Prediction of biomass & grain yield in lodged fields in 2008

In the 2008 season when residual soil N at sowing was generally high, observed biomass was predicted well by APSIM during the early growth stages. However later in the season, APSIM-simulated biomass was generally greater than measured biomass, a similar pattern to other APSIM evaluations in the same region (Wang et al., 2003; Chenu et al., 2011). These differences between observed and predicted biomass were probably due in part to the biotic and abiotic stresses (e.g. lodging, disease and nutritional limitations) experienced by field crops that are not simulated by models such as APSIM. Over-prediction of biomass may also have been due to the difficulty of drying green biomass samples in an oven soon after sampling at remote locations. Testing indicated that green biomass samples (as opposed to samples taken at crop maturity) could lose up to 15% of their dry weight when not placed into a drying oven on the day of collection even if they were refrigerated during the interval between collection and drying (data not shown). It is also possible that some of the differences in this study were caused by varietal differences in phenological development and biomass partitioning, given that biomass accumulation parameters for Australian wheat cultivars within APSIM have predominantly derived from the cultivar Hartog, which was released in the 1980’s. Newer, higher yielding cultivars such as Kennedy may produce less vegetative biomass and higher harvest index under high yielding conditions.

Across the full range of commercial cultivars tested in 2008, farmer-realised grain yield was not predicted accurately in lodged fields, but was noticeably better predicted in non-lodged fields. This contrasted with the prediction of biomass which was similarly accurate in both lodged and non-lodged fields. This contrast was potentially caused by the specific sampling of unlodged areas where possible in the collection of biomass cuts (section 3.2.2.), whereas farmer-realised grain yield was measured across the entire crop area. However it may also have been caused by inability of commercial harvesting machinery to completely glean the lodged crop due to the low placement of wheat heads. Additionally, shattering (grain falling on the ground) and/or sprouting of the grain may have been more prevalent in lodged fields, and were likely to have worsened between the collection of maturity biomass cuts and the subsequent commercial harvest.

3.4.1.3. Prediction of biomass & grain yield in canopy managed fields in 2009

Irrigated wheat fields monitored in the 2009 season were generally sown to quick maturing cultivars, and grown using the canopy management technique of in-crop N application. This followed a concerted education campaign on agronomic techniques available for reducing lodging risk (e.g. Peake and Angus, 2009) that was conducted between the 2008 and 2009 seasons. Ultimately, lodging in 2009 was not as severe in canopy managed fields. Most of these fields experienced visible N stress during tillering, followed by a rapid relieving of the stress after application of N (and irrigation to incorporate the fertiliser) during early stem-elongation.

Based on its tendency to under-predict the 2009 biomass and grain yield data, it is suggested that the APSIM wheat module under-estimates the ability of spring wheat cultivars to recover from N stress, although more detailed testing is required to confirm the underlying reasons behind this observation. Specifically, this trend was observed under conditions where N fertiliser was applied during the cropping season to alleviate severe N stress, and then incorporated under ideal (irrigated) conditions for rapid N uptake. Additionally, it is important to note that the influence of seasonal conditions was confounded with the different growing techniques used between the two seasons of field monitoring. Further testing in replicated field trials is required to confirm that the canopy management technique of in-crop N application does reduce lodging in Australian wheat cultivars.

3.4.1.4. Prediction of ceiling yield

The APSIM model parameters for wheat biomass and yield development were primarily constructed from the wheat cultivar Hartog in experiments conducted in the mid 1990's. While Hartog is no longer widely grown in the region, the cultivar Kennedy is closely related to Hartog and achieved the highest yields recorded during the field monitoring, with four yields of 7 t ha^{-1} or greater. Yields of Hartog have been closely simulated by APSIM in high yielding rainfed experiments in the region (Chenu et al., 2011; Peake et al., 2011), and APSIM was also able to predict the yield of most Kennedy crops from this study with 10% error or less, if the simulations assumed no N stress within the canopy managed fields. Hence the model was considered suitable for estimating the yield potential of Kennedy in the region, assuming it is grown under optimal conditions and that lodging is avoided.

While it is readily apparent that the standard APSIM parameterisation under-predicted grain yield in the highest yielding fields, the basis for this trend is unclear. It is possible that potential yield of the cultivar Kennedy may be higher than the cultivar Hartog, which was used in APSIM parameterisation experiments in the early 1990's. However it is also possible that the canopy-management technique of in-crop N application may have been the primary cause of the increased grain yield.

The observed maximum kernel weight for Kennedy at Gatton means it is appropriate to use this larger value (0.045 g) when conducting simulations on the yield potential of irrigated wheat in the northern grains region. However, the yield of two treatments in Field 17b (at Gatton in 2009) were still under-predicted by more than 1 t ha^{-1}, even once maximum kernel weight in the simulations was increased by 10% to match the observed data. Observed grain number was also 20% higher than simulated for these crops.

Despite this trend it was decided not to simultaneously re-parameterise grain number determination routines in APSIM. This decision was taken due to the preliminary nature of the 'skip-row-factor' parameterisation developed for this study, which directly impacts upon grain number determination. Inaccuracy in the calibration of 'skip-row-factor' and its application to the low N fields at Gatton could have been related to over-estimation of grain number. Therefore further experimentation is recommended to determine whether in-crop N application or genetic improvements in modern cultivars increase potential yield through both increased grain number as well as average kernel weight.

3.4.2. Potential yield and water use for irrigated wheat under different agronomic management regimes in the northern grains region

The simulations conducted to determine potential yield indicated that long-term average potential yields for the cultivar Kennedy are 8 t ha^{-1} or greater for CPLM irrigation systems at Dalby, Goondiwindi and Gunnedah, when using the standard APSIM parameterisation. When the maximum kernel weight of Kennedy was increased to the 45 mg (dry weight) ceiling observed in the field experiments in this study, the average potential yield of Kennedy under CPLM irrigation increased by approximately 10%, rising above 8 t ha^{-1} for St George and Walgett, and reaching 9.1 t ha^{-1} at Gunnedah. In contrast to the yield simulations, water use was unchanged in the simulations that used a higher maximum kernel weight parameter because the duration of grain filling and green leaf area was unchanged.

These yields are higher than the previous highest published yields identified for the region of 7.2-7.6 t ha^{-1} (Meinke et al., 1997; Keating et al., 2001) and higher than farmer-realised yields previously obtained in the region in irrigated production fields. However, within the duration of the field monitoring described herein and shortly following its completion, 8 t ha^{-1} grain yield has since been achieved in at least three commercial fields of irrigated bread wheat in the northern grains region (Peake et al., 2012; Hamish Bligh, pers. comm.; Greg Rummery, pers. comm.). Additionally, five commercial cultivars have been recorded as yielding over 9 t ha^{-1} in subsequent field trials not reported herein, the highest yield of 9.94 t ha^{-1} being recorded for the cultivar Trojan at Spring Ridge (near Gunnedah) in 2014 (Peake and Gardner, unpublished data).

However it is also important to note that season-to-season variability meant that there was a simulated range in grain yield of approximately 3 t ha^{-1} across 95% (two standard deviations) of the historical climate record. Thus, yields 1.5 t ha^{-1} lower than the long term average could occur under CPLM systems in some years even though water and N may not be limiting. The simulated evapotranspiration requirements to achieve potential yield also varied between location and season, with average evapotranspiration water use varying between 490 and 530 mm depending on location for the CPLM system simulations.

The potential yield simulations indicated that 1m and 2m bed irrigation systems would have a lower potential yield (in the order of 22% and 11%) than CPLM systems. However, these estimates rely on calculated differences in light interception that require further field validation, to determine whether crops grown on raised beds on an east-west configuration are able to partially compensate for the decreased light interception observed in ‘furrow gaps’ (Appendix B).

3.4.3. Causes and impacts of lodging on irrigated wheat production in the northern grains region in 2008.

3.4.3.1. Mechanisms and causes of lodging

Berry et al. (2004) broadly summarised lodging yield reduction effects as being due to the reduction of grain number or size through physiological effects (such as reduced ability to produce assimilate due to disrupted canopy structure and decrease light interception), or the inability of harvesting equipment to physically capture the grain from prostrate plants. It is likely that at least some of the fields in this study experienced ‘physiological’ yield loss from lodging, particularly those fields which lodged at or prior to anthesis, the most sensitive growth stage to lodging related yield loss (Pinthus,1973). Physical capture of the grain could also have been disrupted in some fields through grain sprouting, potentially increased by lodging due to decreased airflow within the lodged canopy. Shattering (grains falling out of the florets prior to harvest) may also have been accentuated by lodging during harvest, as wheat heads substantially askew from vertical alignment are probably more prone to drop grains in front of the header front during the harvesting process. An additional cost to the industry in 2008 was absorbed by harvest contractors (which are heavily used by Australian wheat growers), who charged a minimal increase in harvesting fees for lodged crops even though badly lodged fields sometimes took twice as long to harvest.

Lodging has previously been associated with increased shading caused by the development of a thick crop canopy (Sparkes and King, 2007). Previous studies (e.g. Easson et al., 1993; Stapper and Fischer, 1990a; Berry et al., 2004) have demonstrated increased lodging susceptibility of agronomic strategies such as high seeding rates, decreased row spacing and increased residual soil mineral N at sowing, each of which increase biomass production during tillering. The agronomic and climate data from this study supported these findings, with increased tiller density and higher soil N reserves correlated with the greater yield gaps observed in lodged fields.

3.4.3.2. The effect of agronomic management on lodging in 2008

The cost of lodging in 2008 has previously been conservatively estimated at $20 million AUD (Peake and Angus, 2009). In this study, the calculated average loss due to lodging was 1.6 t ha^{-1} (the difference in yield gap between lodged and non-lodged fields). Discussions with commercial agronomists across the region suggest that the area of lodged wheat in 2008 was at least 60-70,000 ha. During the 2008 season the wheat price fluctuated wildly, and rose to over $400 per tonne for the highest quality classification. Therefore the cost of lodging to growers may have been in excess of $30-$40 million if the lodged crop could potentially have been accepted into the highest quality grade, even after accounting for increased harvesting costs due to lodging.

The longer-season cultivar Gregory experienced moderate to severe lodging even when grown using canopy management techniques in the 2009 Gatton trial, which suggests that Gregory is more prone to lodging than the quick maturing cultivar Kennedy. Maximum yield of Gregory in these fields was 5.6 t ha^{-1}, nearly 2 t ha^{-1} below the best yielding Kennedy treatments, yet simulations of both N limited and N non-limiting conditions suggested Gregory should yield 1.5-2.0 t ha^{-1} more than Kennedy in these fields. This trend emphasises the importance of evaluating the accuracy of simulation models for new applications.

The long-season cultivar Strzelecki has been used in APSIM simulations to suggest that yields of 10 t ha^{-1} may be possible in the region with the use of long-season cultivars (Peake and Angus, 2009). However the one commercial field of Strzelecki monitored in 2008 yielded just 3.3 t ha^{-1} due to lodging and associated harvest losses, 5.5 t ha^{-1} below the simulated grain yield for this field. As the long-season cultivar Baxter also experienced severe lodging in 2008, irrigated growers in the northern region have been advised to grow quick maturing cultivars until testing of commercial cultivars has been conducted to determine whether high yielding long-season cultivars with acceptable levels of lodging resistance can be identified (Peake et al., 2012). If such cultivars exist, they may ultimately possess greater yield potential than the quick maturing cultivar Kennedy.

3.5. Conclusions

The results of this study show that the potential yield of irrigated spring wheat in the northern region is currently between 8 and 9 t ha^{-1}, and requires approximately 490–530 mm of evapotranspiration. On average across lodged fields in 2008, lodging was associated with a 1.6 t ha^{-1} reduction in farmer-realised yield, although there was a 5.5 t ha^{-1} difference between APSIM predicted yield and farmer-realised yield in the worst lodged field. Lodging was probably exacerbated in many fields by high levels of soil N at sowing and the use of lodging-susceptible cultivars.

The study also demonstrated some limitations of the APSIM model in simulating high yielding wheat production under irrigation, and the rate of recovery of crops from N stress when experiencing rapid changes in soil N availability. However it has also demonstrated the value of using simulation models for yield gap analysis. While APSIM was unable to predict yield in fields affected by lodging, APSIM predictions of yield were strongly correlated with the observed yield of non-lodged fields in the 2008 season. This enabled use of the model to estimate the cost of lodging by calculating potential yield ‘benchmark’ estimates in the yield gap analysis, and allowed the identification of agronomic characteristics in fields that are likely to have contributed to the widespread lodging experienced in 2008.

Further study is necessary to determine whether potential yield in the region could be higher than reported in the present study, through the use of in-crop N application or longer season cultivars. Such a study would first need to identify lodging resistant longer season cultivars, or be conducted using mechanical aids such as lodging nets to prevent lodging from influencing experimental results. Further investigation is also required to determine whether agronomic techniques such as in-crop N application can effectively reduce lodging risk without reducing yield potential in the northern grains region.

Chapter 4 – An investigation into the ability of agronomic methods to reduce lodging in irrigated spring wheat in the northern grains production region of eastern Australia

4.1. Introduction

Research into high yielding wheat production suggests that maximum crop water productivity for an individual field is obtained when achieving near-maximum yields (French and Schultz, 1984a; Musick et al., 1994). However, achieving high wheat yields in both irrigated and rainfed environments has been limited by the disorder known as lodging (Stapper and Fischer, 1990b; Berry et al., 2004; Peake et al., 2014b), defined as the ‘permanent displacement of plant shoots from an upright position’ (Pinthus, 1973). Additionally, deficit irrigated crops can also be at risk of lodging in favourable seasons with high potential yield.

Yield losses of up to 80% have been recorded in severely lodged crops, partly due to the physiological disruptions that occur in a lodged crop (e.g. reduced radiation use efficiency caused by a less efficient canopy structure), and partly because harvesting machinery cannot completely glean the lodged crop from the soil surface (Berry et al., 2004). Lodging can also reduce grain quality (Pinthus, 1973; Fischer and Stapper, 1987) which further decreases economic returns.

Lodging can be managed using agronomic practices and/or the use of genetically improved, semi-dwarf wheat cultivars with greater resistance to lodging (Reitz and Salmon, 1968; Pinthus, 1973). While plant genetic improvement is a long term task, improved agronomic practices can be implemented quickly. This is pertinent to the irrigation districts of subtropical Australia, where high grain prices have recently stimulated a rapid expansion in irrigated wheat production, and yields are constrained by lodging (Chapter 3) (Peake et al., 2014b).

Reduced light quantity and quality have been demonstrated to weaken stems and surface roots and increase lodging risk (Sparkes and King, 2007) suggesting that agronomic practices which increase crop vigour and canopy density also increase lodging risk. This supports numerous studies in spring and winter wheat that have demonstrated lodging reduction through practices that reduce canopy size, such as reduced plant populations (Stapper and Fischer, 1990a; Easson et al., 1993; Webster and Jackson, 1993), later sowing dates (Berry et al., 2000; Spink et al., 2000 cited in Berry, 2004), and the application of plant growth regulators (Herbert, 1982; Knapp et al., 1987; Crook and Ennos, 1995; Tripathi et al., 2003). These practices are known as ‘canopy management’ techniques and are used in rainfed winter wheat production to improve yields through reduced biomass production, improved access to nutrients later in the season and decreased lodging risk (Sylvester-Bradley et al., 1997; Sylvester-Bradley et al., 2000).

Decreasing nitrogen (N) availability during the vegetative growth phase is another canopy management technique that has been widely demonstrated to reduce lodging (Mulder, 1954; Kheiralla et al., 1993; Crook and Ennos, 1995; Berry et al., 2000; Tripathi et al., 2003). However, a feature of these and other studies was that total season N availability varied between treatments. Lodging reductions in these studies may have been achieved by lowering the yield potential of low lodging treatments, and it remains unclear whether in-crop N application can reduce lodging risk without reducing yield potential. A range of studies (e.g. Widdowson et al., 1961; Bremner, 1969; Islam et al., 2002) have attempted to address this uncertainty with experiments that varied sowing N application before applying complementary in-crop N rates to ensure total season N was the same for all treatments. Unfortunately due to lack of lodging or other experimental limitations in these studies, they were unable to conclusively demonstrate that in-crop N application reduces lodging while maintaining maximum yield potential.

Bremner (1969) showed that in-crop application of N reduced lodging in rainfed winter wheat compared to treatments with the same amount of N applied at sowing, without reducing yield. However their yield levels (4-5 t ha^{-1}) suggested that yield was limited due to water or nutrient limitation(s), and their results were not tested statistically. Widdowson et al. (1961) conducted similar experimentation, comparing autumn and spring applications of the same N rate. They observed increased yield in most (but not all) years, and also observed consistent lodging reductions associated with in-crop N application. However their yield levels of 4-5 t ha^{-1} suggest that their experiments may also have been water or N limited, and may not be applicable to modern spring wheat germplasm capable of yielding 8 t ha^{-1}.

Islam et al. (2002) conducted an investigation of split N timings at different application rates and found a yield advantage associated with in-crop N application at yield levels of 4-5 t ha^{-1}, but observed no lodging in any of the treatments. Hobbs et al. (1998) presented data from an unknown location that indicated in-crop N application reduced lodging of irrigated spring wheat in a subtropical environment, but data were not presented to show whether in-crop N application yielded similarly to sowing N treatments. Crop monitoring reported in Chapter 3 observed less lodging and smaller yield gaps in canopy-managed fields, however the use of canopy management techniques was confounded with location and season. In the most applicable study identified, Fischer (1993) investigated split N applications in high yielding (up to 7.5 t ha^{-1}) irrigated spring wheat on low fertility soils and found that delaying N application to DC31 (Zadoks et al., 1974) did not reduce yield, however they did not observe lodging in their experiment. Additionally, their experiment was conducted in a temperate environment with a longer growing season than found in subtropical environments.

While previous research suggests that in-crop N application could be used to reduce lodging risk of irrigated wheat in the subtropics, it remains unclear whether it can effectively reduce lodging without reducing yield potential when used in combination with the cultivars and climatic conditions of the northern grains region. In particular, the short duration between initiation and flag leaf emergence in subtropical regions (sometimes as little as 4-5 weeks) may hinder the ability of a wheat crop to recover from an early N deficit and/or low plant populations and achieve maximum yield. Therefore the objective of this study was to determine whether the canopy management techniques of in-crop N application and low plant populations reduce lodging risk without decreasing the yield potential of irrigated spring wheat in subtropical Australia.

4.2. Methods

4.2.1. Experimental design

Experiments were conducted at the Gatton CSIRO research station (S27.54° E152.33°) in 2009 and 2011. Experiments aimed to compare lodging susceptibility and yield of alternative N timing strategies in combination with different plant populations. Nitrogen timing × plant population treatments were tested in combination with two cultivars; EGA Gregory (a long-season cultivar hereafter referred to as Gregory), and Kennedy (a quick maturing cultivar), both of which are white-grained semi-dwarf bread-wheats (*Triticum aestivum*).

All experiments were fully irrigated, using hand-shift sprinklers. The standard plot configuration for all experiments simulated two-metre wide beds using blocks of seven rows (23.3 cm apart) sown over 1.4 m and separated by 60 cm wide wheel-track gaps, sown on flat ground with no raised beds. An alternative plot/row configuration was also sown in the 2009 experiments, with the objective of investigating the yield potential and lodging susceptibility of one metre wide beds in comparison to the standard two metre wide plots. These contained two sets of three rows of wheat separated by a 60 cm gap, thus representing paired one metre wide beds which covered the same area as a standard two-metre bed plot. All plots were sown as seven metre long plots, with plot-ends trimmed to create five metre long plots on the day of harvest.

In 2009 four adjacent experiments were conducted in the same field, with each experiment conducted using a single cultivar. The experiments were sown on different dates; 13th May (Gregory) and 5th June (Kennedy) in order to optimise yield potential for the phenology of each cultivar. Two of the experiments (one containing each cultivar) were conducted on a section of the field with low residual soil N that had been prepared by growing and harvesting biomass from a forage sorghum crop. These two experiments had the majority of their N requirement applied ‘in-crop’, at late GS32 and GS39 (as defined in the modified decimal code of Tottman (1987)). The other two experiments (one for each cultivar) were conducted on an adjacent section of the same field which had been fallowed and contained the majority of the season N requirement as residual soil N, present at sowing. Field history of the two areas was identical prior to the forage crop, and soil testing revealed no nutrient deficiencies (other than N) in either section of the field. The aim of the N application strategies was to create differential N levels during tillering (the vegetative growth phase), after which non-limiting amounts of N would be applied. N application regimes and residual soil N levels for the experiments are presented in Table 4.1.

N regime was varied minimally within each 2009 experiment due to concerns that highly variable N rates could influence neighbouring plots. Each experiment consisted of a 2 × 3 factorial, consisting of the two bed configurations (one metre or two metre), and three agronomic management regimes: 100 and 200 viable seeds m^{-2} sown without additional N, and 200 viable seeds m^{-2} sown with an additional 50 kg ha^{-1} N applied at sowing. The aim of the seed rates was to establish contrasting plant

Table 4.1. Residual soil N and in-crop N regimes for the 2009 and 2011 experiments.

	Gatton 2009				Gatton 2011		
	Low Sowing N	Low Sowing N +50	High Sowing N	High Sowing N +50	Low Sowing N	Medium Sowing N	High Sowing N
	kg ha^{-1} N				kg ha^{-1} N		
Sowing soil N (to 180 cm)	60	60	125	125	15	15	15
Fertiliser N (sowing)		50		50	0	50	150
Fertiliser N (GS31-32)*	190	140	125	75	200	150	50
Fertiliser N (flag leaf)	50	50	50	50	50	50	50
Total soil + fertiliser N	**300**	**300**	**300**	**300**	**265**	**265**	**265**

*Top-dressing occurred at GS32 in 2009, and GS31 in 2011.

populations of approximately 100 plants m^{-2} (the standard plant population used in rainfed wheat production in the northern grains region) and 200 plants m^{-2} (the maximum recommended plant population for irrigated wheat growing in southern Australia (Lacy and Giblin, 2006)). The additional N was applied to applicable treatments as urea spread by hand after sowing (but prior to emergence), and incorporated with an irrigation of 20 mm. Plots with fertiliser N applied at sowing had less N applied later in the season (Table 4.1). When sowing the experiment, a single bed configuration was used exclusively in each planting run, thus creating a split plot design. Each treatment was replicated three times except for the treatments where 200 viable seeds m^{-2} were sown with the additional 50 kg ha^{-1} N, which were only replicated twice due to space limitations in the irrigated area.

Observations in 2009 indicated that low N plots had not accessed N from adjacent high N plots during the vegetative growth phase. Therefore in 2011, all N treatments were included within the same experiment. A forage sorghum crop was grown and baled in the summer of 2010/2011 to decrease the residual soil N for the experimental area.

The 2011 experiments used only the standard two metre wide plots as described for the 2009 experiments. The factorial design included two cultivars, three N regimes and two seeding rates (100 and 200 viable seeds m^{-2}), across three replicates. The cultivars were sown in separate ‘split-plots’ within each replicate on 13th May (Gregory) and the 3rd of June (Kennedy) in an attempt to optimise yield potential for the phenology of each cultivar, while allowing statistical comparison between the two cultivars. Rain between the two sowing dates meant that as also occurred in 2009, the difference between sowing dates was longer than intended. The three N regimes (Table 4.1) had varying rates of N applied at sowing, GS31 and flag leaf emergence. The second application (GS31) was carried out at a noticeably earlier growth stage than in 2009, because N stress in the low N treatments was more severe due to the lower soil residual N compared to 2009.

4.2.2. Field measurements

Soil samples were taken on the day of sowing to determine the soil water and N content of the soil to a depth of 180 cm. Sowing soil samples were analysed for gravimetric soil water content, nitrate-N concentration, soil organic carbon and pH. Four or five cores were collected from the experimental area in each year, and split into depth layers (0-15 cm, 15-30 cm, 30-60 cm and in further 30 cm increments to 180 cm). Depth layer samples from all cores were combined to give a single sample for each depth layer. The seven depth layer samples from each experiment were then split into two samples, one for soil N and one for soil water. Samples for N analysis were dried at 40 °C and the nitrate-N content of the samples was determined by using a 1:5 soil/water extraction, method 7B1 (water soluble nitrate) from Rayment and Higginson (1992). The 1:5 soil/water extraction was also used to determine pH, while organic carbon assays were obtained using the Walkley and Black method (methods 4A1 and 8B1 respectively from Rayment and Higginson (1992)). Soil water samples used in determining gravimetric moisture content were weighed in the field and then dried at 105°C for a minimum of 48 hours. Dry weight was subsequently determined only when sample weights showed no weight decrease over a period of 6 hours.

Biomass samples were taken from $0.5m^2$ sections of the plot comprising a 25 cm section across the entire 2 m plot width, which thus included a proportionate area of the simulated ‘furrow gap’. Samples were collected at GS31, anthesis and maturity, dried at 80°C for a minimum of 48 hours, and were not removed until sample weights showed no further decrease over a period of 6 hours. Anthesis samples were taken on the average date of 50% anthesis for all plots within a given experiment in 2009, and on the day of 50% anthesis for individual plots in 2011. Fertile tiller number was determined from a subsample of each biomass cut at GS31, anthesis and maturity. Leaf area (measured using a LICOR LI-3100 leaf area meter) was measured at GS31 and anthesis and used to calculate leaf-area-index. Phenology ratings were taken using the decimal code system described by Tottman (1987), which offers a more precise definition of growth stages around floral initiation than the decimal code of Zadoks et al. (1974), which is still commonly used by Australian researchers and agronomists. Growth stage (‘GS’) notation has been used herein when the system of Tottman (1987) has been used to describe crop growth stage, whereas the Decimal Code (‘DC’) notation was used when referring to growth stages in accordance with the system proposed by Zadoks et al. (1974).

Grain was harvested from the plots using mechanized small plot headers. Plot yields were adjusted linearly to account for the area removed in collecting biomass samples. Grain yield is reported at 12% moisture, calculated by weighing subsamples of grain from each plot on the day of harvest, then drying samples in the same way as the biomass samples. Biomass and kernel weight data were obtained from subsamples of the machine harvested grain, and are presented on a dry weight basis. Grain and biomass yield were calculated for the entire two-metre plot width, which included a portion of unsown wheel track situated within the harvested area.

4.2.3. Lodging ratings and statistical analysis

Regular lodging ratings were used to calculate ‘average lodging during grainfilling’ which is referred to in the results and discussion as ‘grainfill lodging’. Lodging was rated on the first day possible after each potential lodging event (rainfall or irrigation), and every 4 to 5 days between lodging events. Ratings for a given day were similar to those used by Mulder (1954) and Stapper and Fischer (1990a), consisting of the average stem angle from vertical for the whole plot. This was used to calculate average lodging during grainfill by multiplying each daily score by the number of days before the next score was taken, and then averaging these over the number of days between anthesis and harvest. This method quantifies the likelihood that lodging may have caused physiological disruption to the crop. In contrast, a lodging score taken at harvest may be wholly due to a single late lodging event immediately prior to harvest, and thus would not reflect on the development of lodging through the season.

Experiments were analysed using linear mixed models with the REML (restricted maximum likelihood) procedure in Genstat (version 14). In 2009 the four experiments were analysed together in a multi-environment analysis (with a split-plot design within each of the four experiments (considered fixed effects) due to the one metre vs. two metre bed comparison), to determine if agronomic treatments interacted with cultivar or residual soil N level in the four different experiments. The statistical analysis examined the factorial design of the three seed rate × N combinations, across the two bed configurations, both of which were also designated as fixed effects. Square root transformation was necessary prior to analysis of average lodging during grainfilling, and the results reported have been back-transformed. The treatment structure was also partitioned in the 2011 analyses to investigate the factorial combination of seed rate × N-regime × cultivar (each of which were designated as fixed effects). In all analyses the level of significance was set at 5% unless stated otherwise. The least significant difference (LSD) procedure was used to compare levels of an effect if the F-test was significant.

4.3. Results

4.3.1. Field observations

4.3.1.1. Seasonal conditions

In 2009, temperatures were slightly above average between sowing and anthesis, after which temperatures were close to the long term average for the remainder of the growing season (Table 4.2). In 2011, temperatures were slightly below average during tillering, and were approximately equal to the long term average for the remainder of the growing season (Table 4.2).

Table 4.2. Average daily temperature and irrigation volumes for the experimental period in 2009 and 2011.

	May	June	July	August	September	October	Total
Average Daily Temperature (°C)							
2009	17.0	14.4	13.1	16.8	18.7	20.7	
2011	16.0	13.6	12.9	14.8	16.8	19.5	
Long Term Average	16.9	14.2	13.2	14.4	17.3	20.4	
Irrigation + Rainfall (mm)							
2009	129	56	96	74	145	50	550
2011	85	33	130	122	132	147	649

Each experiment had more than 150 mm of stored soil water at sowing, and in-season rainfall and irrigation combined was at least 500mm for each experiment (Table 4.2). This ensured that more than 650 mm of water was available for growing season evapotranspiration when taking rainfall, stored soil water and irrigation into account.

4.3.1.2. Agronomic characteristics of monitored fields

The low N regimes induced visible N stress in both years. In 2009, the low N plots were moderately yellowed by GS32 and had a distinctly different canopy structure (shorter and more upright leaves) than the high N plots. In 2011, the low N plots showed extreme yellowing and stunting by late tillering and the decision was taken to apply in-crop N at an earlier growth stage (GS31). Lodging was severe in 2009, with lodging in many plots beginning prior to anthesis following an irrigation event. Lodging was less severe in 2011, not beginning in any treatment until after anthesis.

4.3.2. Analysis of management regimes × bed types across experiments in 2009

An analysis of the management × bed type factorial design was conducted across the four 2009 experiments to determine if the effect of the agronomic treatments was consistent across cultivars and/or soil residual N. Little interaction was observed between the management regimes and experiments for most of the observed traits (Table 4.3), hence the effect of agronomic management was generally stable across the two cultivars and both residual N levels.

4.3.2.1. Established plant population

Final plant population varied between experiments in 2009, with the two experiments of cv. Kennedy averaging 65% establishment (the number of emerged seedlings per 100 viable seeds sown), while the Gregory experiments averaged only 40% establishment. Final plant populations were therefore much lower than intended (Table 4.3, 4.4), with high/low populations on average across experiments of approximately 73/37 plants m^{-2} for Gregory, and 117/68 plants m^{-2} for Kennedy. The addition of 50 kg ha^{-1} N at sowing did not significantly affect establishment in any of the experiments (Table 4.4). Established plant populations were not significantly different ($p>0.05$) between bed configurations (Table 4.3).

4.3.2.2. Anthesis date

Although an attempt was made to sow the two cultivars on separate days in order to synchronise anthesis, rain between the sowing dates delayed sowing of the quicker maturing cultivar (Kennedy). Anthesis date was not rated for each individual plot due to the difficulty of assessing anthesis on all tillers in heavily lodged plots. However, approximate anthesis date was 7 days different between the cultivars, with Gregory treatments reaching 50% anthesis on approximately the 3rd of September, and Kennedy reaching 50% anthesis on approximately the 10th of September.

4.3.2.3. Grainfill lodging and grain yield

Significant differences were observed between experiments for grainfill lodging and grain yield, with grain yield highest in the least lodged experiments (Figure 4.1). The experiments sown on soil with greater N available at sowing yielded less and lodged to a greater degree than the duplicate experiments, where N was primarily applied in-crop. The grain yield increase obtained by applying N in-crop was 0.85 t ha^{-1} in Kennedy, and 0.54 t ha^{-1} in Gregory (Table 4.3).

Within-experiment management regimes did not interact with experiment (Table 4.3) for lodging or grain yield, therefore the agronomic treatments in the factorial design had a similar effect across all four experiments. The addition of 50 kg ha^{-1} of N at sowing to the high seeding rate caused a significant increase in grainfill lodging across all four experiments, accompanied by a near-significant ($p=0.055$) decrease in yield of 0.3 t ha^{-1} (Table 4.3), compared to treatments where the additional N was applied in-season (at GS32). The higher seed rate did not have significantly different grain yield or lodging to the low seeding rate, although grainfill lodging was numerically greater in the high seed rate treatment.

Table 4.3. REML F probabilities and main effect means from the analysis of management × bed type × experiment at Gatton in 2009.

	Growth Stage 32				Anthesis			Maturity					
	Plant population (plants m^{-2})	Tiller count (tillers m^{-2})	Biomass (t ha^{-1})$^{\#}$	LAI (cm^{2} cm^{-2})	Fertile tiller count (tillers m^{-2})	Biomass (t ha^{-1})$^{\#}$	LAI (cm^{2} cm^{-2})	Average grainfill lodging (%)	Grain yield (t ha^{-1})$^{++}$	Biomass (t ha^{-1})$^{\#}$	Harvest index (%)	Grain number (grains m^{-2} /1000)	Average kernel weight (mg)$^{\#}$
REML F probabilities													
Exp.	<0.001	0.002	0.006	<0.001	<0.001	<0.001	0.016	<0.001	<0.001	0.003	<0.001	0.003	<0.001
Man.	<0.001	<0.001	<0.001	<0.001	0.008	0.167	0.209	<0.001	0.055	0.234	0.127	0.009	0.536
Bed	0.041	0.003	<0.001	0.007	<0.001	0.059	0.131	<0.001	<0.001	<0.001	0.192	0.004	0.29
Exp. × Man.	0.132	0.094	0.138	0.036	0.078	0.241	0.621	0.723	0.148	0.034	0.509	0.121	0.88
Exp. × Bed	0.939	0.654	0.964	0.688	0.979	0.781	0.43	0.057	0.439	0.448	0.629	0.467	0.564
Man. × Bed	0.385	0.856	0.148	0.53	0.253	0.768	0.245	0.342	0.251	0.048	0.282	0.224	0.927
Exp. × Man. × Bed	0.772	0.241	0.174	0.183	0.135	0.515	0.413	0.325	0.944	0.78	0.744	0.59	0.666
Experiment means													
Gregory - High sowing N	69.0 b	727 a	3.0 a	5.1*	637 a	16.8 a	6.47 a	71.4 a	4.94 d	17.4*	0.25 c	11.7 c	37.5 c
Gregory - Low sowing N	53.9 c	512 b	2.2 b	2.8*	528 b	15.2 a	5.99 a	40.2 b	5.48 c	16.9*	0.30 c	12.8 b	38.6 c
Kennedy - High sowing N	100.7 a	712 a	2.9 a	5.5*	481 b	11.6 b	5.87 a	25.5 c	6.02 b	15.0*	0.35 b	12.7 bc	42.3 b
Kennedy - Low sowing N	100.7 a	548 b	2.4 b	3.7*	356 c	10.2 c	4.48 b	3.2 d	6.87 a	14.4*	0.42 a	13.9 a	44.2 a
Management means													
High SR +50N	94.4 a	740 a	3.0 a	5.2*	509 ab	13.9 a	5.84 a	39.5 a	5.64 b	16.7*	0.30 a	12.8 a	40.5 a
High SR + zeroN	96.2 a	623 b	2.7 b	4.3*	521 a	13.5 a	5.53 a	27.1 b	5.91 ab	15.2*	0.35 a	13.0 a	40.9 a
Low SR + zeroN	52.7 b	511 c	2.2 c	3.4*	471 b	12.8 a	5.73 a	22.5 b	5.93 a	15.8*	0.34 a	12.5 a	40.6 a
Bed type means													
Two metre beds	83.9 a	692 a	2.9 a	4.7 a	537 a	13.8 a	5.82 a	34.4 a	6.01 a	16.5*	0.33 a	13.1 a	41.0 a
One metre beds	78.2 a	558 b	2.3 b	3.9 b	463 b	13.1 a	5.59 a	24.6 b	5.65 b	15.3*	0.33 a	12.4 b	40.3 a

Shaded cells indicate F probabilities that are significant ($p<0.05$). Means with different suffix-letters are significantly different from other means within the same main effect group. Main effect groups with a suffix asterisk(*) were not tested for significant differences due to the presence of higher order interactions. Abbreviations: Exp., experiment; Man., management; Bed, bed type; SR, seed rate; LAI, leaf area index. $^{\#}$Reported on a dry weight basis. $^{++}$Reported at 12% moisture.

Table 4.4. Established plant populations for the three management treatments within each of the four experiments in 2009. Treatments with different suffix letters within each column are significantly different (*p*<0.05)

	Established Plant Population (plants m^{-2})			
Management*	Gregory High sowing N	Gregory Low sowing N	Kennedy High sowing N	Kennedy Low sowing N
High + 50	83.7 a	62.3 a	113.3 a	125.3 a
High + 0	82.8 a	65.3 a	113.8 a	115.8 a
Low + 0	40.5 b	34.2 b	75 b	61 b

*(sowing rate + applied N (kg ha^{-1}) at sowing)

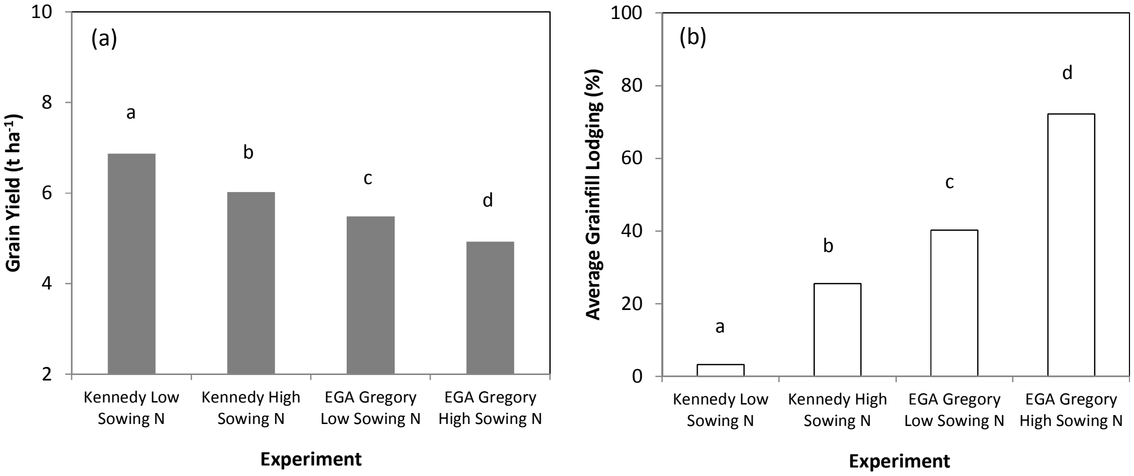


Figure 4.1. (a) Average grain yield and (b) average grainfill lodging for the four 2009 experiments. All means for grain yield and lodging are significantly different (p<0.05).

Bed type also had a significant effect on lodging across all experiments, with two metre beds significantly more susceptible to lodging than one metre beds. However the two metre beds still had a significantly greater grain yield of 0.35 t ha^{-1} more than the one metre beds on average across experiments (Table 4.3), probably due to the greater ground area sown in the wider bed configuration.

It should be noted that the grain yield data in Table 4.3 is not directly comparable to the data presented for these treatments in the previous chapter (Table 3.1a) as it does not present the three-way interaction data required to make the direct comparison (whereas the data presented in Table 3.1 was the measured data for the equivalent three-way interaction).

4.3.2.4. Anthesis and maturity biomass and yield components

At anthesis, biomass, tiller count and LAI all exhibited similar trends to grainfill lodging, although the main effects of these traits were not always significant in the REML analysis (Table 4.3). Across experiments, anthesis biomass, tiller count and LAI were highest in the Gregory experiment with high sowing N, and lowest in the Kennedy low sowing N experiment. Across management regimes, maximum levels of these traits tended to occur in the high seeding rate + 50 kg ha^{-1} N treatment, and their lowest values were recorded in the low seeding rate treatment. Unsurprisingly, these traits were also greater in the two-metre bed configuration than the one-metre bed configuration when measured at anthesis.

At maturity, significant experiment × management and management × bed-type interaction was observed for biomass (Table 4.3). The experiment x management interaction was observed partly as different patterns of biomass response to management between the two Kennedy experiments (Figure 4.2a), where biomass tended to decrease as the lodging susceptibility of the management regime increased in the high sowing N experiment, whereas the opposite trend was observed for Kennedy in the low sowing N experiment. It may also have been due to decreased biomass in the Gregory 'High 0' treatment in the low sowing N experiment which was ultimately not significantly different to the same treatment in the high sowing N experiment (Figure 4.2b). The management × bed-type interaction was observed as slightly greater differences between the bed types in the 'Low 0' and 'High 0' treatments compared to the 'High 50' treatments (Figure 4.3), possibly indicating that the additional 50 kg ha^{-1} of N at sowing increased the ability of 1m beds to tiller into the furrow gap and create more biomass.

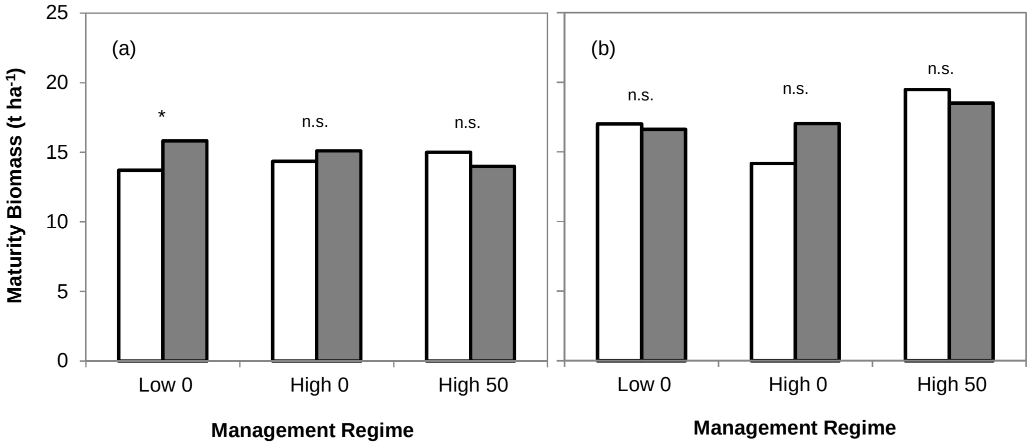


Figure 4.2. Management regime × experiment interaction patterns for maturity biomass in (a) Kennedy and (b) Gregory, for the low sowing N (white bars) and high sowing N (grey bars) experiments. 'Low 0' = low seeding rate with zero additional sowing N, 'High 0' = high seeding rate with zero additional sowing N, 'High 50' = high seeding rate with an additional 50 kg ha^{-1} N applied at sowing. Paired data marked with 'n.s.' are not significantly different ($p>0.05$), paired data marked with an asterisk (*) are significantly different ($p<0.05$).

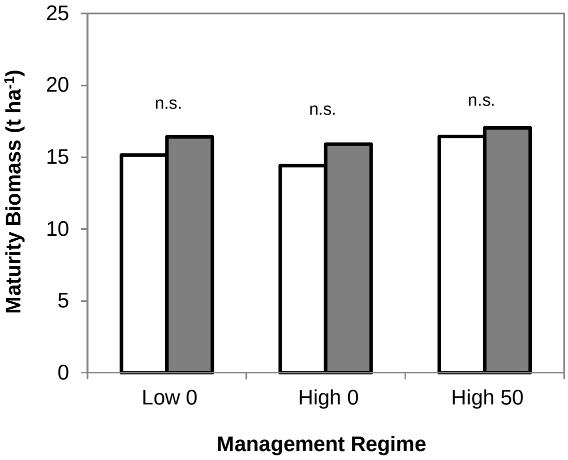


Figure 4.3. Management regime × bed type interaction patterns for maturity biomass, showing 1m beds (white bars) and 2m beds (grey bars). 'Low 0' = low seeding rate with zero additional sowing N, 'High 0' = high seeding rate with zero additional sowing N, 'High 50' = high seeding rate with an additional 50 kg ha^{-1} N applied at sowing. Paired data marked with 'n.s.' are not significantly different ($p>0.05$).

Harvest index was significantly different between experiments, with the highest harvest index of 0.42 recorded in the least lodged (Kennedy – low sowing N) experiment (Table 4.3). Harvest index was not significantly different between management regimes or bed types. Grain yield differences between experiments were explained by increases in both grain number and average kernel weight, but no significant differences were observed for either yield component among management regimes (Table 4.3). The increased yield of two metre beds compared to one-metre beds was logically explained by a significant increase in grain number and non-significant increase in average kernel weight (Table 4.3).

4.3.2.5. Vegetative growth traits and their relationship to lodging

Management and bed type had a significant ($p<0.05$) effect on biomass, tiller count and LAI at the end of the vegetative growth phase. On average across the four experiments, higher seed rate and the addition of 50 kg ha^{-1} N at sowing significantly increased biomass production, tiller count and LAI at GS32 (Table 4.3). Unsurprisingly, the same traits were also significantly greater in the two-metre beds compared to the one metre beds. Significant interaction was observed between experiment and management regimes for LAI due to slightly different rates of LAI increase across management regimes between the two cultivars (Figure 4.4).

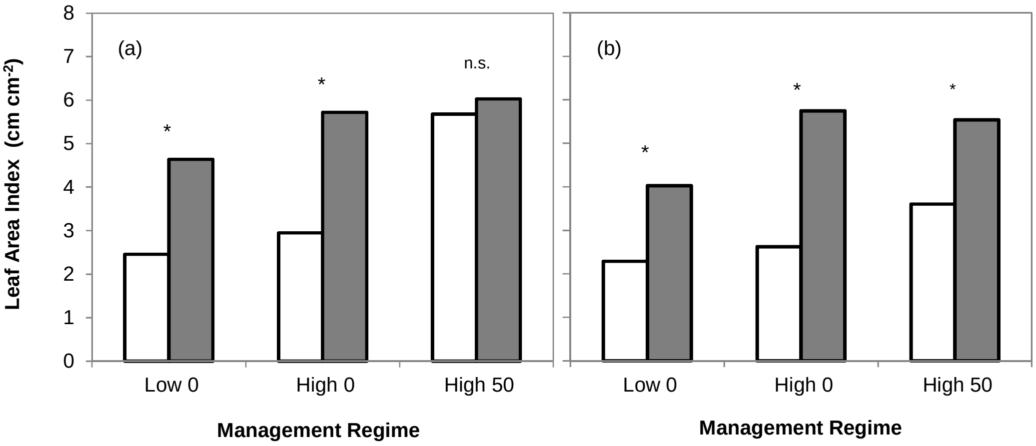


Figure 4.4. Management regime × experiment interaction patterns for Leaf Area Index at late GS32 for (a) Kennedy and (b) Gregory, for the low sowing N (white bars) and high sowing N (grey bars) experiments in 2009. 'Low 0' = low seeding rate with zero additional sowing N, 'High 0' = high seeding rate with zero additional sowing N, 'High 50' = high seeding rate with an additional 50 kg ha^{-1} N applied at sowing. Paired data marked with 'n.s.' are not significantly different ($p>0.05$), paired data marked with an asterisk (*) are significantly different ($p<0.05$).

There was a strong correlation between grainfill lodging and biomass, LAI and tiller number when measured at GS32 (Figure 4.5). These relationships were initially examined on average across all four experiments (Figure 4.5a-c) due to the absence of significant higher order interactions for most of these traits (Table 4.3), and then examined separately for each cultivar (Figure 4.5d-f).

On average across all experiments, there was a strong linear relationship between grainfill lodging and tiller count, biomass and LAI (Figure 4.5a-c). Similar levels of correlation were observed for the same comparisons when examined separately between the Gregory and Kennedy experiments (Figure 4.5d-f). However the x-axis intercept was significantly different ($p<0.05$) for each cultivar, indicating that Gregory was more susceptible to lodging than Kennedy when grown using the same agronomic management regimes. Progression of lodging over time in 2009 reflected the average grainfill lodging score for all of the main effect comparisons (Figure 4.6), as no re-ranking was observed among the main effect comparisons between observation dates.

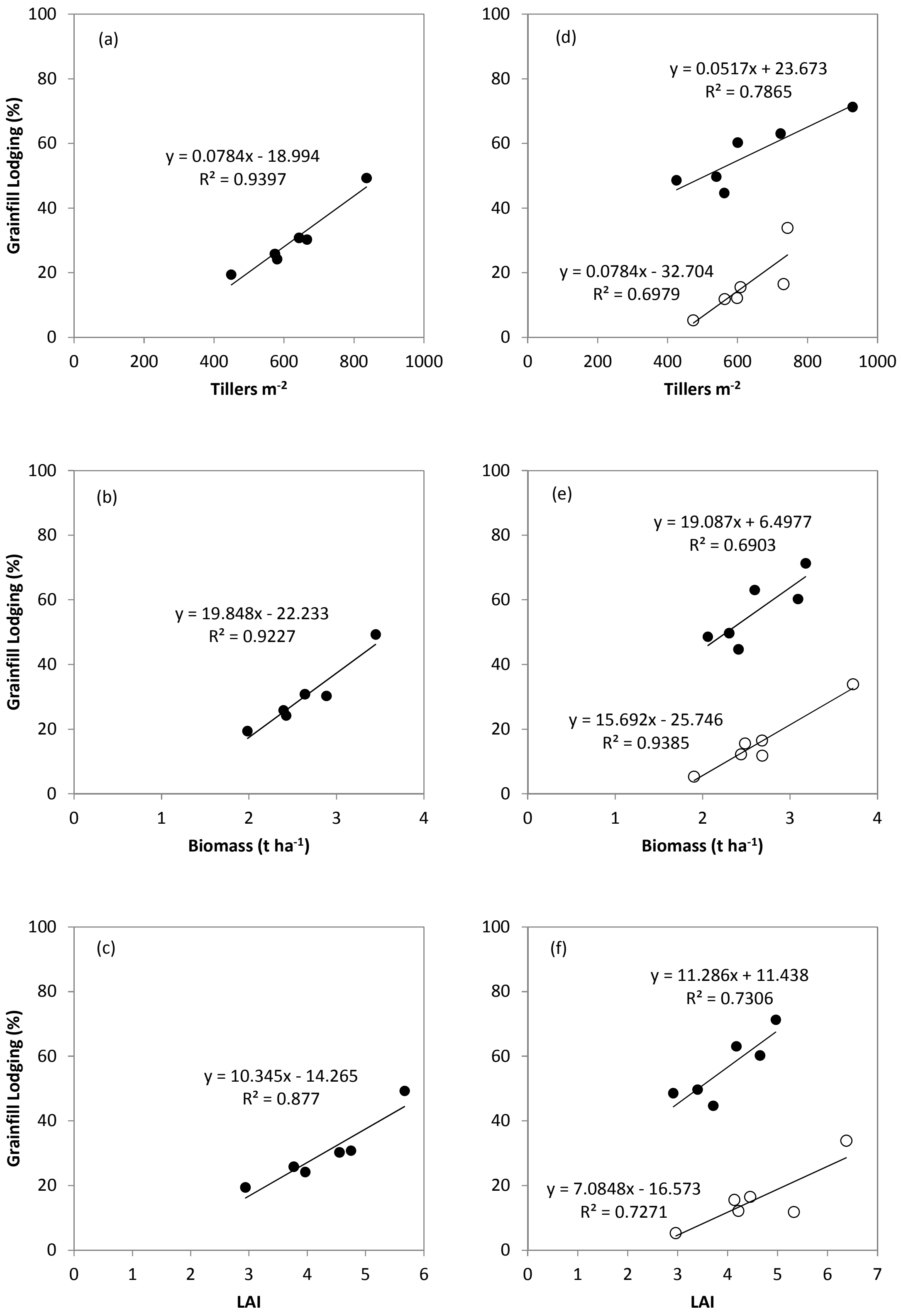


Figure 4.5. Grainfill lodging vs. (a,d) tiller count (b,e) biomass and (c,f) LAI measured at GS32 for the six management × bed type treatments, averaged across (a,b,c) all 2009 Gatton experiments, and (d,e,f) presented separately for the (○) Kennedy and (●) Gregory experiments.

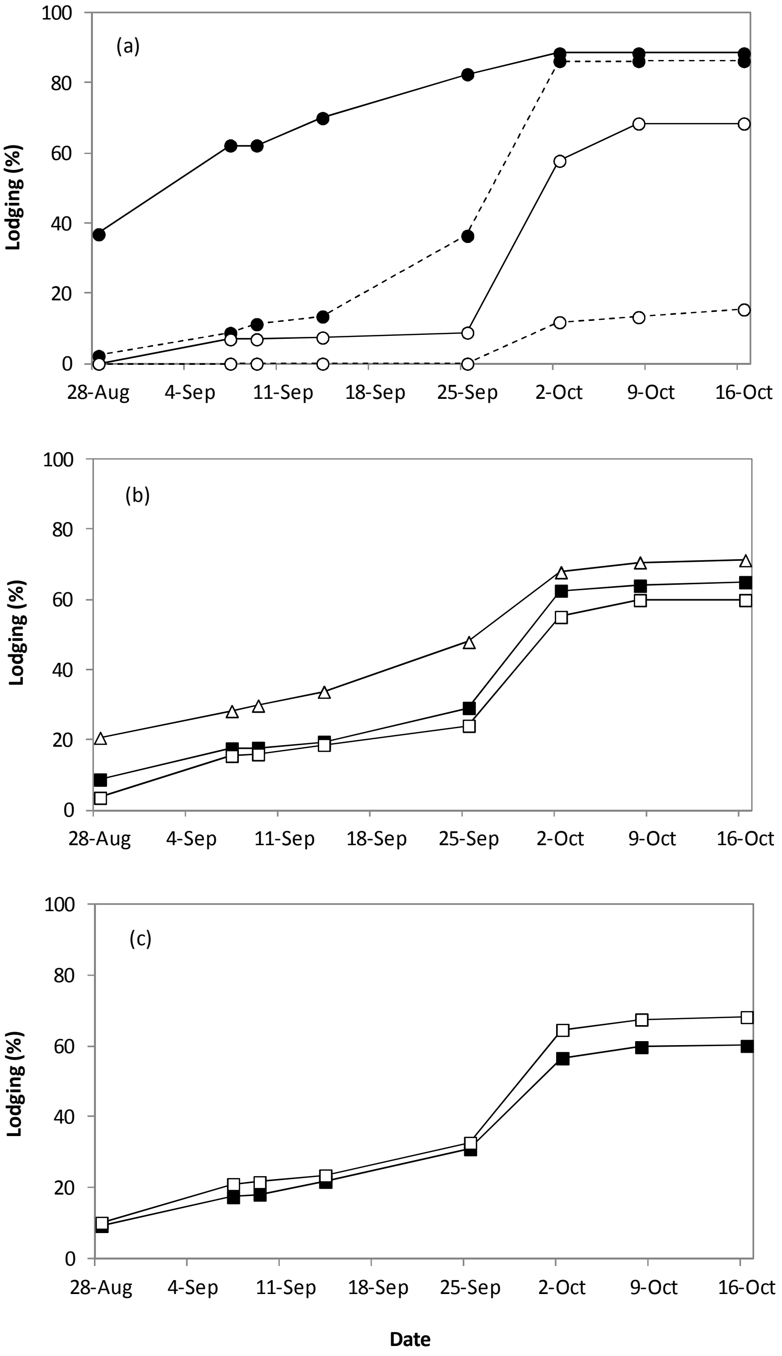


Figure 4.6. Progression of lodging at Gatton in 2009 for the main effect of (a) experiments with (- - - -) low residual soil N, (——) high residual soil N, (○) Kennedy and (●) Gregory, (b) management regimes with (■) high seed rate, no additional sowing N (□) low seed rate, no additional sowing N (△) high seed rate with an additional 50 kg ha^{-1} N at sowing, and (c) bed types (□) two metre beds (■) one metre beds.

4.3.3. Analysis of cultivar × N rate × seed rate at Gatton in 2011

An analysis of the cultivar × N rate × seed rate factorial design was conducted for the 2011 experiment to determine whether the effect of sowing N rate and seed rate were consistent across cultivars. Significant ($p<0.05$) cultivar × N rate and cultivar × seed rate interaction was observed for most agronomic traits measured at GS31 (Table 4.5), but these interactions were rarely significant for the same traits when assessed at anthesis and maturity (Table 4.6). The effect of sowing N rate and seed rate was therefore variable between cultivars during the vegetative growth phase, but was more stable when measured at or after anthesis. However, cultivar × N rate interaction was significant ($p<0.05$) for grainfill lodging and was approaching significance ($p=0.066$) for grain yield, thus the effect of N rate was considered variable between cultivars for these traits.

4.3.3.1. Established plant population

Establishment was greater in Gregory (87%) than Kennedy (63%) on average across all treatments in 2011, and significant ($p<0.05$) two-way interactions were observed for plant population between cultivar and both N rate and seed rate (Table 4.5). Final plant population of Kennedy was lower in low sowing N treatments, but no change was observed for Gregory between N treatments, suggesting that the germination of Kennedy may have been slightly affected by low soil N status. The interaction between cultivar and seed rate was observed in the slightly larger difference in establishment between Gregory (85%) and Kennedy (60%) at the high seed rate, compared to the difference between the two cultivars at the low seed rate (92 and 70%). This trend was potentially due to difficulties in counting emerged plants in the high seed rate plots of Gregory which began producing tillers before counts were taken, thus making it difficult to distinguish between separate plants and tillers emerging below the soil surface from the same plant.

4.3.3.2. Anthesis date

Untimely rain disrupted the intended gap between cultivar sowing dates that was intended to synchronise anthesis between the two cultivars. Consequently, anthesis was 11 days later in Kennedy on average across N rates and seed rates (Table 4.6). Significant ($p<0.05$) cultivar × N rate interaction was observed as a substantially delayed anthesis date in the low sowing N rate of Gregory in comparison to the higher sowing N rates, a trend not observed to the same extent in Kennedy (Figure 4.7a). Seed rate did not have a significant effect on anthesis date (Table 4.6).

Table 4.5. REML F probabilities and main effect and significant higher order interaction means for traits measured at GS31, from the analysis of cultivar × N rate × seed rate at Gatton in 2011.

	Growth Stage 31			
	Plant population (plants m^{-2})	Tiller count (tillers m^{-2})	Biomass (t ha^{-1})	LAI (cm^2 cm^{-2})
REML F probabilities				
Cv.	<0.001	<.001	<.001	<.001
N. rate	0.892	<.001	<.001	<.001
S. rate	<0.001	0.095	0.029	0.057
Cv. × N. rate	0.024	0.891	<.001	0.018
Cv. × S. rate	<0.001	0.008	0.02	0.055
N rate. × S. Rate	0.44	0.937	0.078	0.133
Cv. × N rate. × S. Rate	0.759	0.512	0.332	0.829
Cultivar means				
Gregory	131.4*	590*	1.7*	2.95*
Kennedy	95.0*	350*	1.4*	1.83*
Nitrogen rate means				
High	114.0*	605 a	2.3*	3.89*
Medium	113.0*	451 b	1.5*	2.38*
Low	112.6*	349 c	0.8*	1.19*
Seed rate means				
High	144.8*	494*	1.6*	2.54*
Low	81.6*	432*	1.4*	2.18*
Cultivar × N rate means				
Gregory high sowing N	124.6 a	741 a	2.75 a	5.05 a
Gregory medium sowing N	131.5 a	591 b	1.61 c	3.09 b
Gregory low sowing N	138.1 a	457 c	0.74 e	1.31 cd
Kennedy high sowing N	103.4 b	482 a	1.91 b	2.89 b
Kennedy medium sowing N	94.4 bc	329 b	1.33 d	1.76 c
Kennedy low sowing N	87.1 c	256 c	0.84 e	1.07 d
Cultivar × seed rate means				
Gregory high S rate	170.1 a	687 a	1.89 a	1.84 a
Gregory low S rate	92.7 c	501 b	1.51 b	1.6 b
Kennedy high S rate	119.4 b	332 c	1.35 b	1.35 c
Kennedy low S rate	70.5 d	368 c	1.37 b	1.35 c

Shaded cells indicate F probabilities that are significant ($p<0.05$). Means with different suffix-letters are significantly different from other means within the same main effect group. Main effect groups with a suffix asterisk(*) were not tested for significant differences due to the presence of higher order interactions. Abbreviations: Cv., cultivar; S rate, seed rate; LAI, leaf area index

Table 4.6. REML F probabilities and main effect means for traits measured at anthesis or maturity, from the analysis of cultivar × N rate × seed rate at Gatton in 2011.

	Anthesis Traits				Maturity Traits						
	Fertile tiller count (tillers m^{-2})	Biomass (t ha^{-1})*	LAI (cm^{2} cm^{-2})	Date of Anthesis (Day of year)	Average Grainfill Lodging (%)	Grain Yield (t ha^{-1})$^{++}$	Biomass (t ha^{-1})*	Harvest Index (%)	Grain Number (grains m^{-2} /1000)	Average Kernel weight (mg)*	Height (cm)
REML F probabilities											
Cv.	0.005	0.766	0.197	<0.001	<0.001	<0.001	0.258	<0.001	0.700	0.000	<0.001
N. rate	0.115	0.022	0.005	<0.001	<0.001	0.012	0.041	0.949	0.216	0.021	<0.001
S. rate	0.701	0.832	0.047	0.098	0.006	0.002	0.076	0.747	0.204	0.054	0.012
Cv. × N. rate	0.167	0.756	0.154	<0.001	0.015	0.066	0.908	0.971	0.832	0.028	0.051
Cv. × S. rate	0.617	0.718	0.9	0.474	0.219	0.372	0.245	0.588	0.409	0.344	0.408
N rate. × S. Rate	0.745	0.866	0.938	0.229	0.099	0.237	0.167	0.544	0.724	0.393	0.400
Cv. × N rate. × S. Rate	0.595	0.461	0.64	0.609	0.779	0.126	0.325	0.808	0.630	0.138	0.367
Cultivar means											
Gregory	383 a	8.16 a	4.64 a	241.3*	23.8*	5.63 b	15.1 a	0.34 b	13.8 a	36.1*	102.4 a
Kennedy	327 b	8.05 a	4.38 a	252.9*	9.8*	6.85 a	14.5 a	0.42 a	13.7 a	44.9*	98.6 b
Nitrogen rate means											
High	380 a	8.80 a	5.52 a	244.6*	21.7*	6.11 b	14.6 ab	0.37 a	13.3 a	41.1*	104.6 a
Medium	330 a	7.99 ab	4.26 b	245.3*	14.9*	6.44 a	15.6 a	0.39 a	14.0 a	41.3*	103.4 a
Low	356 a	7.52 b	4.15 b	251.4*	13.9*	6.17 ab	14.1 b	0.38 a	14.0 a	39.2*	93.4 b
Seed Rate means											
High	359 a	8.06 a	4.31 a	247.7 a	18.1 a	6.05 b	15.2 a	0.39 a	13.6 a	39.9 a	98.9 b
Low	351 a	8.14 a	4.98 a	246.5 a	12.7 b	6.43 a	14.3 a	0.37 a	14.0 a	41.2 a	102 a

Shaded cells indicate F probabilities that are significant ($p<0.05$). Means with different suffix-letters are significantly different from other means within the same main effect group. Main effect groups with a suffix asterisk(*) were not tested for significant differences due to the presence of higher order interactions. Abbreviations: Exp., experiment; Man. management; Bed, bed type; SR, seed rate; LAI, leaf area index. $^{\#}$Reported on a dry weight basis. $^{++}$Reported at 12% moisture.

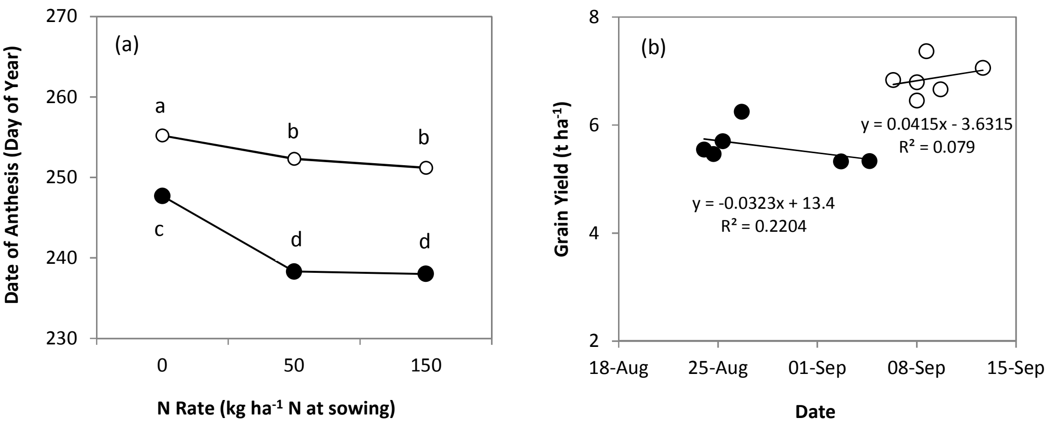


Figure 4.7. (a) Date of anthesis for N rate × cultivar means, and (b) grain yield vs. anthesis date for N rate × seed rate means for (○) Kennedy and (●) Gregory, at Gatton in 2011.

Anthesis date was not strongly correlated with grain yield among N rate × seed rate means within cultivars (Figure 4.7b). The Gregory treatments were lower yielding in general than the Kennedy treatments, but this was unlikely to be due to frost as no frost events were recorded during the three weeks prior to anthesis in Gregory, and no frost damage was observed in any treatment. A slight negative correlation was observed between anthesis date and grain yield in Gregory, probably due to the extreme N stress of the low sowing N treatments, which reached anthesis later due to late developing tillers initiated after the application of N at GS31.

4.3.3.3. Grainfill lodging and grain yield

The only significant higher order interaction for either grain yield or grainfill lodging in 2011 was the cultivar × N rate interaction, which was significant ($p<0.05$) for grainfill lodging, and approaching significance ($p=0.066$) for grain yield (Table 4.6). The low and medium sowing N treatments in Kennedy were not significantly different to each other for either yield or grainfill lodging (Figure 4.8a). However the medium sowing N treatment did have significantly less lodging and greater yield compared to the high sowing N treatment (Figure 4.8a).

In the Gregory treatments, no significant differences were observed among N regimes for grainfill lodging (Figure 4.8b), but grain yield was significantly lower ($p<0.05$) in the low sowing N treatment than the medium sowing N treatment, which in turn was numerically higher but not significantly greater ($p>0.05$) than the high sowing N treatment.

The main effect of seed rate was significant ($p<0.05$) for both yield and grainfill lodging in 2011, with grainfill lodging of 18.1% and 12.7% for the high and low seed rates on average across cultivars and N rates. The lower seed rate also produced significantly higher yields (6.4 vs. 6.0 t ha^{-1}) than the higher seed rate on average across all N rates and both cultivars.

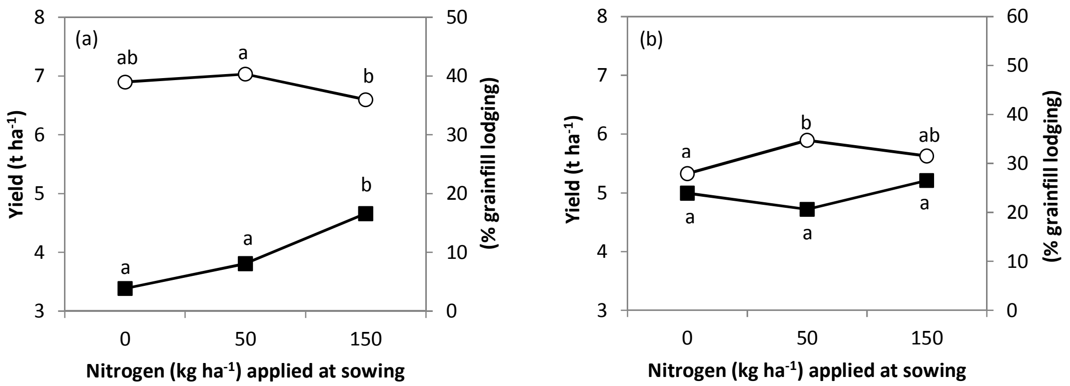


Figure 4.8. Yield (○) and average grainfill lodging (■) across 3 N regimes for (a) Kennedy and (b) Gregory in 2011. Means on the same response curve with different superscript letters are significantly different ($p<0.05$).

4.3.3.4. Anthesis and maturity biomass and yield components

At anthesis, biomass, tiller count and LAI had similar numerical trends to grainfill lodging but the main effects of these traits were not always significant in the REML analysis (Table 4.6). Anthesis tiller count was significantly ($p<0.05$) greater in Gregory compared to Kennedy, but was not significantly different between N rates and seed rates, despite being numerically greater at the highest N rate. Anthesis biomass and LAI was significantly greater at the highest N rate, but not significantly different between cultivars or seed rates ($p>0.05$).

At maturity, biomass was not significantly different ($p>0.05$) between cultivars or seed rates, but was significantly greater ($p<0.05$) for the medium N rate than the low N rate (Table 4.6). Biomass of the highest N rate was not significantly different to either the medium or low N rate due to its intermediate ranking. Harvest index was significantly greater for Kennedy than Gregory ($p<0.05$), but was not significantly different between N rates or seed rates, and no higher order interactions were observed either for maturity biomass or harvest index.

The main effects of cultivar, N rate and seed rate were significant ($p<0.05$) for plant height, but no significant higher order interactions were observed (Table 4.6). Gregory was significantly taller than Kennedy ($p<0.05$), and the low N treatment was significantly shorter than the medium and high N treatments. Surprisingly, the low seed rate treatments showed a small but significant ($p<0.05$) height increase of 3 cm compared to the high seed rate, that may have occurred due to increased competition for N (and hence increased N stress) among the higher plant populations, which could have led to decreased height.

No significant differences ($p>0.05$) were observed between any treatments for grain number in 2011 (Table 4.6). However average kernel weight varied substantially between treatments, exhibiting significant ($p<0.05$) cultivar × N rate interaction (Table 4.6). This interaction was observed as a substantial decline in average kernel weight for the Gregory low N rate treatment (33.6 mg) compared to the medium and high N rate treatments (37.9 and 36.9 mg - data not shown). In Kennedy, there was no significant difference in average kernel weight between N rates, with all three N rates producing kernel weights between 44.8 and 45.2 mg (data not shown). There was also a near significant main effect ($p=0.054$) of seed rate on average kernel weight, with the low seed rate having 1.3 mg heavier grains on average over cultivars and N rates.

4.3.3.5. Vegetative growth traits and their relationship to lodging

Cultivar, seed rate and sowing N rate generally had a significant ($p<0.05$) effect on biomass, tiller count and LAI at the end of the vegetative growth phase (Table 4.5). Increased application of N at sowing caused increase biomass and tiller production, and a subsequent increase in LAI in both cultivars, although the presence of significant cultivar × N rate interaction meant that the proportional response to increased N varied between cultivars for biomass and LAI (Table 4.5).

There was also significant interaction ($p<0.05$) between seed rate and cultivar for tiller count and biomass, and near significant interaction for LAI (Table 4.5). The interaction effect was observed due to Gregory having a significantly higher tiller count, biomass and LAI at the higher seed rate, while Kennedy did not have a significant response to increased seed rate ($p>0.05$) for any of these traits. This suggests that Kennedy seedlings had greater ability to adjust their tiller development in response to variable establishment, whereas Gregory seedlings tended to tiller prolifically even when establishment was higher.

As observed in 2009, a strong positive correlation was also observed in 2011 for the cultivar Kennedy between grainfill lodging and biomass, LAI and tiller number measured at the end of the vegetative growth phase (Figure 4.9). However in contrast to 2009, the same trend was not observed in Gregory, with little correlation evident between the same traits (Figure 4.9). This was probably related to the different progression of lodging in Gregory (Figure 4.10c,d), where the low N, low seed rate treatment initially did not lodge but then lodged heavily toward the end of grainfilling (Figure 4.10c), and because slight re-ranking between N treatments also occurred over time in combination with the high seed rate (Figure 4.10d). The progression of lodging in Kennedy was similar to that observed in 2009, with more lodging observed in treatments with higher levels of sowing N (Figure 4.10a,b).

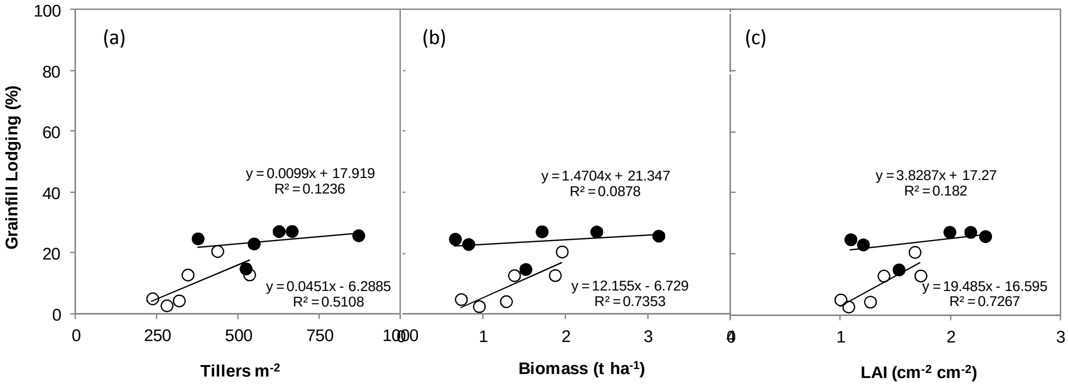


Figure 4.9. Grainfill lodging vs. (a) tiller count (b) biomass and (c) LAI measured at GS31 for the six N rate × seed rate treatments at Gatton in 2011 for (○) Kennedy and (●) Gregory.

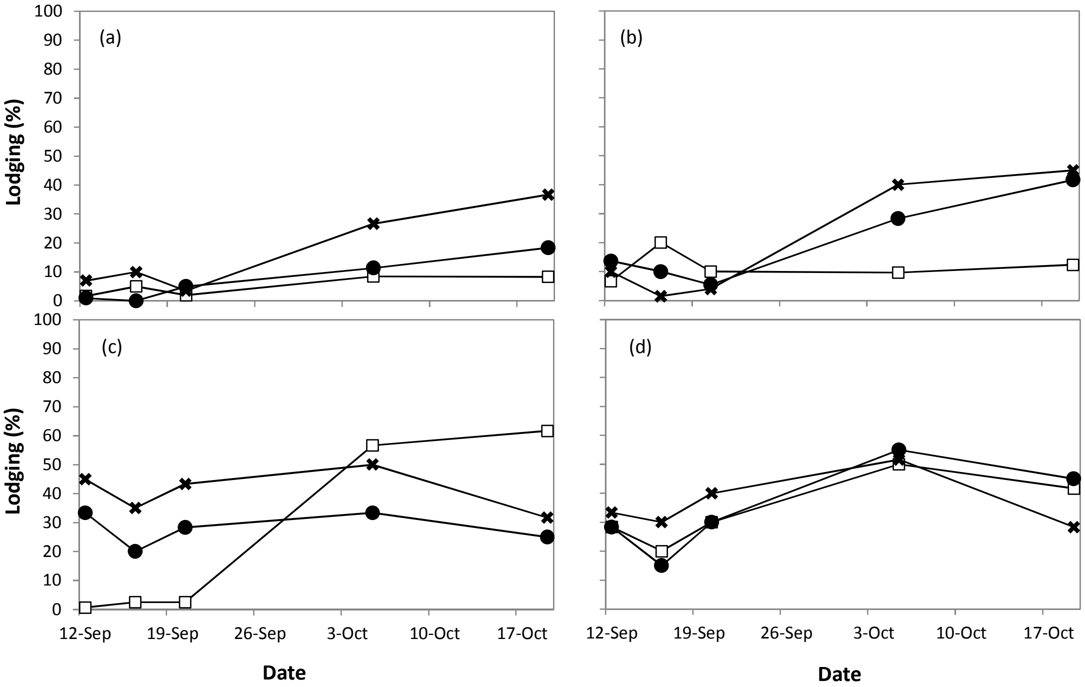


Figure 4.10. Progression of grainfill lodging at Gatton in 2011 for the (a,c) low and (b,d) high seed rate treatments of (a,b) Kennedy and (c,d) Gregory for (☐) low sowing N, (●) medium sowing N and (✖) high sowing N treatments.

4.4. Discussion

The objective of this study was to determine whether the canopy management techniques of in-crop N application and reduced plant population were able to reduce lodging without decreasing yield, in a sub-tropical environment relevant to the northern grains region. The results of this study showed that treatments with the highest level of sowing N were typically more lodging susceptible and lower yielding than in-crop N treatments, although these trends were less evident in the cultivar Gregory in the 2011 experiment.

The results from 2011 also showed that the high plant populations (from 120 to 170 plants m^{-2}, depending on cultivar) were significantly more lodging susceptible and lower yielding than the low plant populations (70 to 90 plants m^{-2}, depending on cultivar), which are more equivalent to those used in rainfed cropping in the northern grains region. However the two plant population treatments were not significantly different for lodging or grain yield in the 2009 experiment (although lodging was numerically greater in the high plant population). This result was potentially related to the poor establishment in 2009 that resulted in plant populations much lower than intended, which in turn may have negatively impacted on yield of the low plant population treatments. The additional bed-width comparisons made in 2009 also showed that crops grown on two metre wide beds were higher yielding but more lodging susceptible than crops grown on one metre wide beds.

The trends in yield were associated with changes in both grain number and kernel weight in 2009 when lodging occurred at (or slightly before) anthesis in many treatments. In 2011 when lodging occurred in mid grainfill for most treatments, the changes in yield were almost exclusvely related to changes in kernel weight. These results are unsurprising, given that grain number in wheat is determined in the weeks prior to anthesis (when the 2009 treatments began to lodge), and kernel weight is influenced by conditions experienced during grainfilling (when lodging began in 2011).

The results of this study agree with the experience in high-yielding winter-wheat production where canopy management practices are used routinely to maximise yield and decrease lodging risk (Sylvester-Bradley et al., 1997; Berry et al., 2000; Sylvester-Bradley et al., 2000), and confirm observations from the field monitoring study (Chapter 3) on the potential benefits of canopy management for irrigated wheat production in the northern grains region. The experiments also showed that the highest yielding treatments tended to have the lowest LAI at anthesis, with the highest yields in both years coming from treatments with anthesis LAI of 4.0 - 4.5. This is also in agreement with previous canopy management studies which have found that achieving maximum yield does not require maximum canopy development (Sylvester-Bradley et al., 1997).

Agronomic strategies such as high plant populations, decreased row spacing and increased soil residual N at sowing have also been associated with increased lodging susceptibility in other regions (Stapper and Fischer, 1990a; Easson et al., 1993; Berry et al., 2004). These strategies logically increase biomass production during the vegetative growth phase, however none of these studies measured vegetative growth or development at GS31. Sparkes and King (2007) demonstrated in pot trials that artificial shading could be used to alter light quantity (photosynthetically active radiation, or PAR) and quality (the ratio of red:far-red wavelengths) and influence lodging risk by modifying the structural characteristics of wheat plants that affect lodging susceptibility (e.g. stem strength and root plate spread). In a subsequent study, Sparkes et al. (2008) demonstrated that PAR intercepted at GS31 on a per plant basis was highly correlated with root plate spread measured just prior to maturity. Therefore the results of the present study support and extend the findings of these previous studies, as increased tiller density, biomass and LAI at GS31-32 were correlated with increased lodging. These findings suggest that it may be possible to develop calibrations for crop sensors to detect lodging risk on the basis of biomass development, for a specific growth stage.

While vegetative growth traits were related to increased grainfill lodging in both of cultivars in 2009, the same relationship was only observed in one cultivar (Gregory) in 2011, which may have been due to two factors. Firstly, a number of Gregory treatments lodged early but recovered somewhat due to phototropic stem straightening. This had the effect of mitigating average grainfill lodging in some of the earliest lodged treatments, and mirrors the results of Easson et al. (1993) who found that recovery from lodging was more likely in earlier lodged treatments. Secondly, the Gregory ‘low N and low seeding rate’ treatment showed almost no lodging for much of grainfilling, but then lodged heavily over the final three weeks. This increased its average grainfill lodging to levels comparable with other treatments that lodged mildly, early in grainfilling, without worsening in severity. Therefore it is possible that recovery of lodging susceptible treatments, combined with severe late lodging of treatments that showed little lodging early in grainfill, contributed to the weakness of the relationship between grainfill lodging and vegetative growth traits for Gregory in 2011.

However the weaker relationships between lodging and vegetative traits in 2011 could also be due to the effect of environmental variation on the development of lodging risk. As discussed by Baker et al. (1998) and Berry et al. (2003), other critical crop structures relating to lodging risk include stem height and centre of gravity, stem natural frequency, stem wall thickness, ear surface area and ear weight, among others. These crop structures and characteristics are developed after GS31, therefore environmental conditions during later growth stages (e.g. stem elongation, anthesis and grain filling) may mitigate or exacerbate the level of lodging risk that has developed during tillering, and may have contributed more significantly to lodging susceptibility in 2011 than in 2009. Further investigation is required to determine the relative importance of environmental conditions during different crop stages in the development of lodging risk.

In 2009, the highest yields were obtained in both cultivars on the low soil N field, when residual soil N was just 60 kg N ha^{-1}. In 2011, the highest yields for both cultivars were achieved when 50 kg ha^{-1} N was added at sowing to 15 kg ha^{-1} of soil residual N. Therefore the optimum soil + fertiliser N at sowing under non-limiting conditions for achieving maximum yield with low lodging risk is probably between 50-100 kg ha^{-1} N under fully irrigated conditions, given that the addition of an extra 50 kg ha^{-1} N at sowing increased lodging in 2009. This N level also agrees with that recommended for winter wheat (Berry et al., 2004). It is nevertheless noteworthy that some severely N-stressed treatments were able to recover and achieve high yields when soil N was just 15 kg ha^{-1} at sowing (in 2011) and no further N was applied until GS31. No studies were identified that have achieved near-maximum yields in treatments with such low levels of residual soil N.

In applying these results to a commercial production environment, it is important to remember that (1) these results were obtained under fully irrigated conditions that maximised N availability (and potentially soil N mineralisation) during vegetative growth, and (2) induced N deficiencies were relieved with non-limiting amounts of N (incorporated with irrigation) immediately following the end of the vegetative growth phase. These conditions mean that the results require further investigation for their applicability to furrow-irrigated production systems of the northern grains region, where regular application of small irrigation volumes is not possible.

Further investigation is also warranted into the lodging susceptibility of a wider range of commercial cultivars relevant to the northern grains region. While more severe lodging was observed in Gregory than Kennedy, rain at sowing prevented this assessment from being made under the conditions of synchronised anthesis. Such conditions are preferred when assessing cultivars with different phenological development patterns, to ensure that environmental conditions which cause lodging events and influence the development of grain yield are experienced at similar growth stages. Further comparison of these and other cultivars when sown on their optimum sowing dates would be beneficial to irrigated growers in identifying the most lodging resistant germplasm for use in irrigated wheat production.

When making recommendations to farmers in southern Australia, Lacy and Giblin (2006) recommended 100-120 kg ha^{-1} N at sowing, 150-200 plants m^{-2} established, and 500-800 tillers m^{-2} at GS31 for irrigated wheat production fields targeting 8 t ha^{-1} in southern NSW. The plant populations, N regimes and tiller numbers at GS31 identified herein for minimising lodging risk while maintaining yield potential were lower than those recommended for southern NSW. Unfortunately the soil mineral N content at the beginning of the 2008 season was already high in many fields (Chapter 3), as they had been prepared for cotton crops that were ultimately not sown. It is therefore important for the management of lodging to include pre-season testing for soil mineral N, as a prerequisite to developing a management strategy that will minimise lodging risk.

4.5. Conclusions

The results of the study demonstrate that the canopy management techniques of in-crop N application and reduced plant population can be used to decrease lodging while maintaining the yield potential of subtropical irrigated spring wheat. Variation in lodging susceptibility was also observed between the two subject cultivars, with the cultivar Gregory more prone to lodging than Kennedy, although further assessment is recommended to confirm this trend under conditions where anthesis of the two cultivars is synchronised. Additionally, the study demonstrated a close correlation between canopy development in the vegetative growth phase and lodging risk, which could potentially be used to develop lodging risk assessment tools for in-season detection of lodging risk. However this relationship did vary between cultivars and seasons, and further investigation is warranted to determine the relative importance of climatic conditions during different crop stages in the development of lodging risk.

The plant populations and N regimes identified in this study for minimising lodging risk while maintaining yield potential were lower than those recommended for irrigated wheat growing in temperate climates of southern Australia, and optimum sowing N levels were much lower than those measured on commercial production fields in 2008. It is therefore important for the management of lodging to include pre-season testing for soil mineral N, as a prerequisite to developing a management strategy that will minimise lodging risk. It is also important to note that the irrigation method used in this study (frequent overhead irrigation throughout the season) probably enhanced N availability in low N treatments. Further investigation is warranted to determine the importance of early-season irrigation in maintaining N availability in canopy managed fields in subtropical regions, to improve its applicability to furrow irrigated fields in which irrigation is applied less frequently.

Chapter 5 – An investigation into the whole-farm water productivity of alternative irrigation strategies relevant to the northern grains production region of eastern Australia

5.1. Introduction

Recent climate change projections suggest that by 2030 under median climate change scenarios, surface water availability will decrease by approximately 9% in the north-eastern districts of the Murray Darling basin, and in dry years this reduction could be as large as 20-50% (CSIRO, 2008). Such projections mean that irrigation enterprises may need to implement major changes to farming practices (e.g. the use of alternative crops or agronomic methods) to maintain water productivity (WP) and profitability of their enterprises.

Irrigated wheat is one such alternative that has recently generated interest among irrigation enterprises in the region, particularly in years such as 2014 when irrigation water storage levels are low in autumn. In such circumstances, irrigation farmers often consider it more profitable to use the remaining water on a wheat crop rather than conserving it over winter for use on a subsequent cotton crop (Jamie Street, pers. comm.). Unfortunately, the optimum irrigation strategy for wheat grown in such circumstances has not been established for the northern grains region.

As discussed in the literature review (Chapter 2), the profitability of irrigation enterprises relies on maximising economic water productivity (EWP) for an entire farm rather than an individual field. Maximum farm-level EWP for irrigated wheat has often been achieved through the use of deficit or supplemental irrigation (Zhang and Oweis, 1999; Tavvakkoli and Oweis, 2004; Geerts and Raes, 2009), although in dry seasons the advantage of deficit irrigation strategies are less apparent (Pereira et al., 2002).

Deficit irrigation is defined herein as the deliberate under-irrigation of the crop such that it receives less water than the amount required to achieve maximum evapotranspiration (English, 1990; Fereres and Soriano, 2007). It should also be noted that the terms ‘deficit’ and ‘supplementary’ irrigation have been used to describe various specific irrigation strategies. Geerts and Raes (2009) summarised this difference as follows: (a) supplemental irrigation generally refers to crops that rely primarily on rainfall, but have some irrigation applied, perhaps at drought sensitive growth stages, while (b) deficit irrigated crops generally receive close to the full irrigation water requirement, but have water withheld at certain growth stages that are less sensitive to water stress. For simplicity, ‘deficit irrigation’ is used to describe both types of strategy in the present study.

In practice, deficit irrigation under water-limited conditions enables irrigation and cropping over a larger area than could otherwise be achieved if the crop water requirement was fully met. This practice may be highly relevant to irrigated wheat growers in sub-tropical Australia, who consider that the typical water availability for an irrigated wheat crop would involve no more than a single furrow irrigation (or approximately 1.3 – 1.5 ML ha^{-1}) being available at sowing, per unit of irrigable farm area (Hamish Bligh, Rob Holmes, Phil Lockwood (pers. comm.)). Deficit irrigation of wheat in the northern grains region could also be advantageous due to its lower lodging risk (achieved through lower potential yield per unit area) compared to fully irrigated wheat crops.

As discussed in the literature review (Chapter 2), water productivity analyses of alternative irrigation strategies have frequently been conducted using crop production functions (sometimes combined with economic analyses that include additional cost and revenue functions) that examine the relationship between yield or economic return, and water consumed. Despite their prevalence in WP evaluations there are a number of disadvantages associated with their use, including variability between environments (Zhang, 2003) and seasons (Pereira et al., 2002). They are also unable to assess the system WP of alternative irrigation strategies that hold water in 'on-farm' storage for varying durations (section 2.3.4). Another disadvantage is that the analyses that use these functions typically assume that the irrigation water is applied uniformly across the entire study area, and thus do not account for alternative whole-farm management strategies available to irrigated farmers. Such alternatives include growing part of the farm as a rainfed crop, or leaving some of the arable area fallow to increase stored soil water reserves for a subsequent crop.

Additionally, evaluations of WP in wheat that have used crop production and cost-revenue functions have generally not accounted for the volume of water stored in the soil at the end of the cropping season (e.g. Zhang and Oweis, 1999; Tavvakkoli and Oweis, 2004; Ali et al., 2007). Such analyses are often conducted by calculating water consumption as in-season precipitation + applied irrigation water, or by estimating evapotranspiration. However, if end-of-season stored soil water were assigned an intrinsic value in economic analyses, full irrigation strategies could be relatively more profitable because they are more likely to leave water in the soil at physiological maturity (Zhang et al., 2004). Such considerations are important to irrigation areas of the northern grains region, as late sown summer crops (e.g. sorghum, maize, mungbeans) are legitimate cropping options immediately following a wheat crop, and the presence of stored soil water increases the likelihood of sowing the subsequent crop.

These deficiencies can however be addressed with the use of a validated cropping system model. For example, Lobell and Ortiz-Monasterio (2006) optimised on-farm WP for farmers in the Yaqui Valley, Mexico, by conducting simulation experiments using varying irrigation volumes and application dates. Their results showed that the most profitable irrigation strategy varied depending on the amount of stored soil water at sowing, with deficit irrigation more profitable when stored soil water at sowing was plentiful.

Unfortunately the limited scope of previous WP analyses along with the variability of optimum irrigation strategies between different regions, indicates that it is uncertain as to whether deficit irrigation is a more profitable strategy than full irrigation in the northern grains region. Therefore, the objective of this study was to determine whether whole-farm economic water productivity (EWP) under water-limited conditions is maximised through deficit irrigation of a larger cropping area, as opposed to fully irrigating a smaller area. The study was conducted in the context of broad-scale furrow-irrigated farms of the northern grains region (where irrigation water rather than land is the limiting factor to production), using the APSIM farming systems model.

5.2. Materials & Methods

5.2.1. Overview

A key component of simulation model experiments is that the model must first be 'validated' – that is, the model needs to accurately simulate the system being investigated. The APSIM farming systems model used in this study (Keating et al., 2003; Carberry et al., 2009) is the most widely used crop model in Australia, and has accurately predicted grain yield of high-yielding rainfed and irrigated wheat plot trials in sub-tropical and temperate regions of Australia (Asseng et al., 1998; Chenu et al., 2011; Peake et al., 2011), as well as in Europe and India (Asseng et al., 2000; Balwinder Singh et al., 2011). APSIM has also been successfully utilised by commercial cropping enterprises to identify optimum rainfed and irrigated cropping strategies (e.g. Carberry et al., 2009; Power et al., 2011; Gaydon et al., 2012).

In Chapter 3, APSIM was evaluated in irrigated spring-wheat production systems of the northern grains region, and was found to simulate yield, biomass and soil water content satisfactorily for irrigated fields, in the absence of lodging and severe N stress. However as the previous evaluation of APSIM's ability to predict water use (Chapter 3) was conducted on three separate commercial fields, it was necessary in the present chapter to examine the ability of APSIM to predict water use under multiple irrigation regimes in the same field, to confirm its suitability for predicting crop water use over a range of irrigation treatments.

After validation of the APSIM model, simulation experimentation was conducted to determine the optimum irrigation strategies for maximising whole-farm EWP. This first involved the simulation of six possible land uses (fallow land, rainfed production, two partial and one fully irrigated land-use). Different combinations of these land-uses were then evaluated to determine which combination resulted in the highest whole-farm EWP.

The simulations were conducted across multiple environments with two alternative levels of stored soil water at sowing, in order to assess the applicability of alternative irrigation strategies at a range of locations and sowing conditions. Whole-farm EWP was then assessed for alternative economic analyses where different values (inexpensive vs. expensive) were assumed for both irrigation water and stored soil water.

5.2.2. Validation of the APSIM model

5.2.2.1. Field experiments

A field experiment was conducted at the Australian Cotton Research Institute farm (S 30°12' 22.24", E 149°35' 55.34") near Wee Waa, NSW in 2011. Three furrow irrigation treatments were applied in a completely randomised block design across three replicates, such that the 9 plots of the cultivar Spitfire (sown on 6th-7th June) were aligned in a single row, and furrow irrigation treatments could be applied to individual plots. Ten metre wide sections of wheat were sown as buffer between irrigation treatments to prevent sub-surface flow of irrigation water between plots. Plots were eight metres long and two metres wide, sown on raised beds with 7 rows of wheat spaced 25 cm apart, and separated by 50 cm wide 'furrow gaps'

The three treatments consisted of a (1) a single irrigation at sowing, (2) an irrigation at sowing followed by a single in-crop irrigation, and (3) sown into stored soil water, and fully irrigated after GS32 (Tottman, 1987). Nitrogen application occurred at sowing for the partially irrigated treatments, and during the season for the fully irrigated treatment in order to reduce lodging risk.

The soil was a brown vertosol, with plant available water capacity (PAWC) of 248 mm measured to 180 cm, and bulk density ranging from 1.31 g cm^{-3} in the surface (0-15 cm) layer to 1.47 g cm^{-3} in the deepest layer measured (150–180 cm). Meteorological data were collected at the site using an automated weather station. Grain yields are reported at 12% moisture.

Soil water content was measured using the same method described in section 3.2.2 for soil layers deeper than 15 cm. Neutron moisture meter (NMM) readings with a CPN 503 DR Hydroprobe (CPN International, Martinez, USA) were taken with a 16-second count at regular intervals during the season. NMM data were calibrated to gravimetric soil water content using soil cores taken at sowing and periodically during the season to sample a range of moisture contents. For calibration, access tubes were installed in the holes from which the samples for gravimetric analysis were collected, and NMM readings immediately taken. The surface layer (0-15 cm) was monitored using a ML2x Theta probe (Delta-T Devices, Cambridge, UK) calibrated on the same cores used to calibrate the NMM. Soil characterisation data for Drained Upper Limit (DUL) and Crop Lower Limit (CLL) were obtained as described by Dalgliesh and Foale (1998) for DUL, and by using the lowest NMM moisture readings in the rainfed treatments to determine CLL.

5.2.2.2. APSIM validation simulations

Experimental results from the field trials were compared to APSIM simulations of each experimental treatment. Measured plant-available soil water and soil mineral N at sowing, plant available water capacity, sowing dates, plant populations, meteorological data, irrigation dates and irrigation volumes from the field experiments were used to parameterise each simulation as appropriate. The APSIM ‘‘skip_row_factor’’ parameter (set at 0.2) was used to simulate the decreased light interception due to 50cm ‘furrow gaps’ between the irrigation beds as discussed in Chapter 3 and Appendix B. The cultivar Spitfire has not been previously parameterised for use in APSIM, so the cultivar H45 was used within the simulations for the 2011 experiments on the basis of its appropriate representation of Spitfire’s flowering date.

5.2.3. Investigation of whole-farm economic water productivity using long-term APSIM simulation experiments

The investigation of whole-farm EWP first required simulation of six land-uses with varying levels of irrigation input.; fallow land, rainfed cropping, three deficit irrigation land-uses, and a fully irrigated land-use. Varying ratios of these alternative land-uses were investigated to determine how best to use irrigation water for obtaining the maximum partial gross margin for an entire 1000 hectare farm, where 1400 ML was stored in an on-farm water storage at the beginning of June (the time of sowing). This represents a typical limited water availability status for broad-scale furrow irrigators of the northern grains region, in which more land is available for irrigation than the area which can be irrigated with a single furrow irrigation (which typically requires 1.3-1.5 ML of irrigation water in storage, per hectare of land to be irrigated). Many of these irrigators are reliant on capturing water during occasional flood events and storing it on-farm for use in subsequent cropping seasons, when water availability is insufficient to fully irrigate the crops. Furrow irrigation was the focus of this study as it is the predominant form of irrigation infrastructure deployed across the region.

5.2.3.1. Land-use simulations

A series of long-term APSIM simulations were conducted for three locations (Goondiwindi, Gunnedah and Emerald) and each of the six land-uses, using two levels of stored soil water at sowing (100mm or zero). The exception was rainfed cropping, which was not simulated in conjunction with zero stored soil water at any location as it is known to be substantially unviable (Moeller et al., 2009).

The four irrigated land-uses were simulated in conjunction with 100 mm of stored soil water as follows: (1) ‘One irrigation’, a deficit irrigation land-use involving a single irrigation where the entire irrigation supply (1400 ML) was applied evenly across the entire 1000 ha farm, (2) ‘Two irrigations’, a partially irrigated land-use that applied the irrigation water across half of the farm (500 ha), split into two applications, and (3) ‘Three irrigations’, a land-use that involved up to three irrigation events on one third of the farm area (333 ha), and (4) ‘Fully irrigated’, a land-use that used up to four irrigations on one quarter (250 ha) of the farm area. In a small number of seasons which experienced high levels of growing season rainfall, the second, third or fourth irrigation were not always applied due to high levels of soil moisture. In such cases the simulation was still included as part of the analyses, hence the number of irrigations in the title of the land-use simulation represent a potential maximum, rather than the actual number of irrigations applied in all simulations.

Similar land-use simulations were also conducted under the assumption that zero soil water was available at sowing prior to irrigation. However for these land-use simulations the area grown was adjusted to account for the larger sowing irrigation of 230 mm that was required to fill a completely dry profile, compared to the irrigation of 140 mm that was required to fill the soil profile when 100 mm of soil water was stored at sowing (Table 5.1, 5.2).

5.2.3.2. Farm-management strategies

Seven farm-management strategies were developed for investigation in conjunction with 100 mm of stored water at sowing; one irrigating the entire farm area, and six derived from the factorial combination of three irrigated land-uses in conjunction with the two remaining land-uses; rainfed cropping or fallow land (Table 5.1). Only four farm-management strategies were developed for the zero soil water simulations (Table 5.2), all of which included fallow land as the sole alternative land-use because rainfed cropping was not a realistic option in the absence of stored soil water at sowing.

Table 5.1. Proportion of land-use areas used for the seven farm-management strategies when 100 mm of stored soil water was available at sowing prior to irrigation, and 140 mm of irrigation was applied on average for both sowing and in-crop irrigations.

Farm-management strategy	Irrigation land-use	Alternative land-use	Irrigated area (ha)	Maximum no. of irrigations	Associated area of fallow or rainfed land-use (ha)
S	Sowing Irrigation only	S	1000	1	None
S+1/F S+1/R	Sowing + 1 in-crop irrigation	Fallow Rainfed	500	2	500
S+2/F S+2/R	Sowing + 2 in-crop irrigations	Fallow Rainfed	333	3	667
S+3/F S+3/R	Sowing + 3 in-crop irrigations	Fallow Rainfed	250	4	750

Table 5.2. Proportion of land-use areas used for farm-management strategies when zero stored soil water was available prior to sowing, an irrigation of 230 mm was applied at sowing, and average in-crop irrigation was 140 mm.

Farm Management Strategy	Irrigation Land-Use	Alternative land-use	Irrigated area (ha)	Maximum no. of irrigations	Associated area of fallow (ha)
S	Sowing Irrigation only	Fallow	600	1	400
S+1/F	Sowing + 1 in-crop irrigation	Fallow	375	2	625
S+2/F	Sowing + 2 in-crop irrigations	Fallow	273	3	727
S+3/F	Sowing + 3 in-crop irrigations	Fallow	214	4	786

5.2.3.3. General methods for land-use simulations

All long term simulations were conducted using a 110 year historical weather data set for the three locations; Emerald, Goondiwindi and Gunnedah, representing locations to the north, middle and southern end of the northern grains region. The use of such data sets allows the simulated agronomic regime to be tested in the full range of weather conditions that have been experienced in the last 110 years. Weather data were obtained for each location from the SILO database (Jeffrey et al., 2001). Representative APSIM soil types (Peake et al., 2010) (Appendix A) were used for each location, with Gunnedah simulations using Typical Vertosol #3 (PAWC = 255 mm to a depth of 180 cm), while the Emerald and Goondiwindi simulations used

Typical Vertosol #7 (PAWC = 204 mm to a depth of 180 cm). Kennedy was the cultivar simulated for all long term experiments, for which the maximum kernel weight was increased to 45 mg due to the capability of Kennedy to produce 45 mg grains under irrigation as observed in Chapter 3. The APSIM ‘‘skip_row_factor’’ parameter (set at 0.2) was used to simulate the decreased light interception due to 50cm ‘furrow gaps’ between the two metre wide irrigation beds, as discussed previously (section 3.2.2, Appendix B).

Previous validation of APSIM for irrigated spring wheat (Chapter 3) observed under-prediction of grain yield in fields managed using low levels of soil N (approximately 50 kg ha^{-1} N or less) for the reduction of lodging risk. Therefore all long-term simulations conducted in this study were carried out assuming moderate levels of soil + fertiliser N at sowing for fully irrigated treatments (100 kg ha^{-1} N). Higher levels of soil + fertiliser N at sowing were used for rainfed and partially irrigated treatments (120 and 150 kg ha^{-1} N). The sowing and in-crop N application schedule (Table 5.3) aimed to replicate farmer best-practice for rainfed and irrigated wheat production, and thus varied between land-uses depending on the yield expectation of the irrigation strategy, and whether the in-crop N strategy was likely to be used for lodging-risk reduction (i.e. in the land-uses with three and four irrigations) .

Table 5.3. Fertiliser N application regime for the different land-use simulations

Land-use	Soil + fertiliser N available at sowing (kg ha^{-1})	Scheduled in-crop N Application (kg ha^{-1})	Tactical in-crop N application^{++}
Rainfed	120	-	30 kg N ha^{-1} per application
Sowing irrigation only	150	-	30 kg N ha^{-1} per application
Sowing + 1 in-crop irrigation	150	50 (with in-crop irrigation, variable growth stage)	30 kg N ha^{-1} per application
Sowing + 2 in-crop irrigation	100	100 (GS31)	30 kg N ha^{-1} per application
Sowing + 3 in-crop irrigation	100	100 (GS31)	30 kg N ha^{-1} per application

$^{++}$ Tactical in-crop N was only applied if total soil N was below 50 kg N ha^{-1} between the end of tillering and the beginning of flowering, and either 10 mm of rain or an irrigation event occurred.

In addition to the scheduled N applications, ‘tactical’ N applications were also applied within each simulation when residual soil N decreased below 50 kg N ha^{-1} prior to anthesis, to simulate the use of additional in-crop N application when yield expectation increased in high rainfall years (Table 5.3). N application strategies were the same for a given land-use regardless of the level of sowing soil water, because the higher sowing irrigation applied to the zero soil water simulations meant that water-input remained the same per unit of land area.

The 1400 ML of irrigation water stored at the beginning of the season was assumed to be stored in a single dam 33 ha in area with a maximum storage capacity of 2800 ML, a slightly above average storage capacity for the broad-scale irrigated farms of the northern grains region (CCCCRC, 2011). APSIM manager-logic was used to reduce the amount of water in storage by 2 mm per day, the median seepage for farm storages in the region (CCCCRC, 2011), and increase the water level in the storage by the equivalent depth of rainfall. APSIM manager-logic was also used to reduce the volume of water in storage by evaporation as calculated using the FAO56 method (Allen et al., 1998) for calculating potential evapotranspiration. Differences in mean long-term runoff from each of the farm-management strategies at each location were negligible (between zero and 5 mm), and were not accounted for in the modelling of irrigation water storage volumes.

The irrigated land-use simulations each assumed that the first irrigation was applied one-day after sowing, in part to simulate the practice of ‘watering up’ after dry sowing. This often occurs on irrigation farms of the northern grains region when wheat is sown 6-8 weeks after cotton has been harvested and insufficient rainfall has fallen to moisten the seed bed sufficiently to germinate the seed. However it is also a common practice for irrigated wheat growers to irrigate soon after sowing even when stored soil moisture at sowing would be considered adequate to germinate the seed. In the case of a fully irrigated crop the technique ensures that early crop growth is not water limited. In the case of a deficit irrigated crop, applying an irrigation soon after sowing ensures that the irrigation water is applied before the soil water deficit becomes larger than the amount of water available for irrigation (per unit area), in which case the volume of irrigation water in storage may no longer be sufficient to irrigate the entire crop area.

The default APSIM irrigation efficiency for each irrigation event was set at 0.75 for all simulations; hence for irrigation events of 120 mm, 90 mm was added to the crop root zone, and 30 mm was assumed lost to the cropping system as evaporation, deep drainage, and tail drain losses. The APSIM term ‘irrigation efficiency’ therefore encompasses both distribution efficiency and application efficiency (section 2.1.1.; Dalton et al., 2001). In-season irrigations were applied when the soil water deficit to a soil depth of 120 cm was greater than 100 mm or 1 ML ha^{-1}, the typical irrigation ‘refill point’ used by furrow irrigators throughout the region.

Irrigated land-uses that stored water later into the cropping season (in order to apply a second, third or fourth irrigation) had a lower proportion of the initial 1400 ML applied during the first irrigation of the season. This was necessary in order to compensate for the greater storage losses that occurred during the season in land-uses with multiple irrigation events, and ensure that irrigation-event volume was approximately the same for each irrigation event within a given land-use. This was achieved by parameterising APSIM to apply irrigations as a proportion of the remaining stored irrigation water. For example, the ‘single irrigation at sowing’ land-use had 100% of the available irrigation water applied to the entire 1000 hectare farm on the date of irrigation (equating to 1.4 ML ha^{-1} × 0.75 (irrigation distribution and application losses)). Subsequently the ‘sowing + 1 in-crop’ irrigation treatment had approximately 45 % of the available irrigation water applied on the first irrigation date to the cropped area, and 100 % of the remaining water applied on the second irrigation date. This meant that the average irrigation-event volume for the ‘sowing + 1 in-crop’ irrigation land-use was 1.3 ML ha^{-1} before irrigation application and distribution losses were accounted for, whereas the average irrigation-event volume applied for the fully irrigated land-use (which had up to four irrigation events) was approximately 1.15 ML ha^{-1}. Any water remaining at the end of wet seasons was credited to gross margin analyses at the relevant price of irrigation water.

It should be noted that furrow irrigators have only a limited ability to adjust irrigation timing, as the size of the soil water deficit is closely related to the amount of irrigation water that can be applied in practice. Growers who delay their irrigation in an attempt to conserve it for later growth periods typically end up applying more water per unit area than intended, and then have insufficient water remaining to irrigate the entire cropped area. Hence this study did not attempt to optimise the timing of these in-crop irrigations during the growing season.

Irrigation scheduling was modified slightly for the three and four irrigation land-uses to allow application of irrigation at a smaller soil water deficit than normal, in years when insufficient rain fell to allow incorporation of scheduled N applications at the beginning of stem elongation (GS31). If the soil water deficit was less than 50 mm, an 80 mm irrigation was applied to incorporate N, at an irrigation efficiency of 0.6. If the soil water deficit was greater than 50 mm, the full irrigation amount for the first scheduled irrigation was applied, also at an irrigation efficiency of 0.6. This allowed the simulation of larger application and distribution losses that occur when applying irrigation to moist soil early in the growing season, solely for the purpose of incorporating the in-crop N application.

5.2.3.4. Determination of partial gross margins.

Partial gross margins (GMs) were used to evaluate the economic return of different farm-management strategies by subtracting the costs involved in preparing land and managing the wheat crops from the income generated by the wheat production. It was appropriate to use the word ‘partial’ to describe these gross margins because long term costs associated with infrastructure (e.g. depreciation) and other farm overheads were not included in the analysis. The pricing of each operation was based on gross margins prepared for irrigated wheat in northern New South Wales (Scott et al., 2012) but modified slightly to reflect grower practices across all irrigation areas of the northern grains region.

Consultation with irrigation agronomists revealed that the fixed cost per unit area of irrigated and rainfed production would be similar. Extensive tillage operations are necessary following a cotton crop, and these were considered to fully apply to a subsequent crop regardless of whether the field was to be irrigated. Base harvest costs were the same for both rainfed and irrigated land-uses, and set at the price normal for irrigated fields due to the difficulty of turning harvesting machinery adjacent to irrigation channels at the end of a field, a technical issue that would also affect rainfed crops grown in a field traditionally reserved for irrigated cropping. The only differences between the fixed cost (per unit area) of irrigated and rainfed cropping were an additional fungicide applied to irrigated crops at \$6 ha^{-1}, and an insecticide application at \$5 ha^{-1} to prevent build-up of an aphid population. As such the base cost applied was \$236.24 ha^{-1} for rainfed crops, and \$247.24 ha^{-1} for irrigated crops.

The cost of fertiliser and water (and their application) were the primary costs that varied between simulations. Nitrogen (priced at \$1.32 per kilogram of N) was assumed to be applied as urea, with no cost of application if applied with an irrigation, and a cost of \$8 ha^{-1} for applying 65 kg ha^{-1} of urea before a rain event. Phosphorus, potassium, sulphur and zinc are the predominant nutrients other than N that are frequently applied in fertiliser products by grain producers of the northern grains region. For the purposes of the gross margin analyses, fertilisers containing these elements were assumed to be applied at a rate identical to the amount of these nutrients removed per tonne of grain. The nutrient removal rate was assumed to be 10% above their critical concentration in grain as reported by Lester and Bell (2010) for fields in the region, and the total cost of their replacement was calculated to be $21 per tonne of grain. The cost of insurance and levies were applied at 3.07% of the price of grain (which was $250 per tonne), while the variable cost of harvesting was applied at $10 per tonne of yield above 2.5 t ha^{-1} (the minimum yield level to which fixed harvesting costs were applied). The price assumed that the same quality grain could be produced with each strategy and in each year, reflecting the lack of importance placed on grain protein concentration by local growers during the period encompassed by this study. This was due to the small price differences available for higher quality grades that gave little incentive to achieve specific grain protein and end-user quality requirements.

Four alternative EWP analyses were developed using a factorial combination of high vs. low water price, and including/excluding the application of this price to the net usage of stored soil water through the wheat growing season. The irrigation water price was applied to the net usage of soil water in order to reflect that stored soil water has an economic value, because it decreases the amount of water required to sow the next crop. The use of APSIM allowed the simulation of water accumulation in fallow fields according to the specific curve number characteristics associated with each of the ‘Typical Vertsol’ soil types as per the APSOIL database (Appendix A, Dalgliesh et al., 2006). The length of the simulated wheat growing season was determined as the time between sowing and physiological maturity, and used to calculate crop evapotranspiration as well as the net usage of soil water.

Low-priced water was assumed to cost $40 per megalitre, a price that covers the cost of pumping the water in and out of the farm storage, assuming that no price was applied directly to the water because it was harvested from a flood event. High-priced water was assumed to cost $120 ML^{-1}, incorporating pumping costs as well as an $80 ML^{-1} price directly applied to the water, as sometimes occurs when river flow volumes are low and irrigated producers need to purchase water from a limited pool available to growers within a district.

5.2.3.5. Evaluation terminology

Crop Water Productivity (CWP) is a broad term that can be defined in many ways. For simplicity of communication, the following terms are used in the remainder of this chapter to describe different forms of CWP:

1. CWP_{ET} –measured as yield divided by evapotranspiration (kg^{-1} mm^{-1} ha^{-1}); used only to evaluate individual land-uses.
2. CWP_{ET+IE} –measured as yield divided by the sum of evapotranspiration, irrigation storage/distribution losses, and infield drainage losses (kg^{-1} mm^{-1} ha^{-1}); used to evaluate either individual land-uses or the whole-farm management strategies.
3. EWP – ‘economic’ water productivity calculated using one of the partial gross margin (GM) analyses. Effectively the unit measure for EWP is partial GM ($) per 1400 ML of irrigation water, for the entire 1000 hectare farm. However for simplicity in discussion of the results, the measure of partial GM will be stated only as a dollar value.

5.3. Results

5.3.1. APSIM Validation

5.3.1.1. Field observations and agronomic management

The 2011 validation experiment received higher than average rainfall, although the month of July was dry (Figure 5.1). Although cold temperatures were experienced just prior to anthesis, no visible frost damage symptoms were observed. Substantial rainfall in late November after physiological maturity delayed harvest, but was not observed to cause any grain sprouting that could have affected measurement of grain yield.

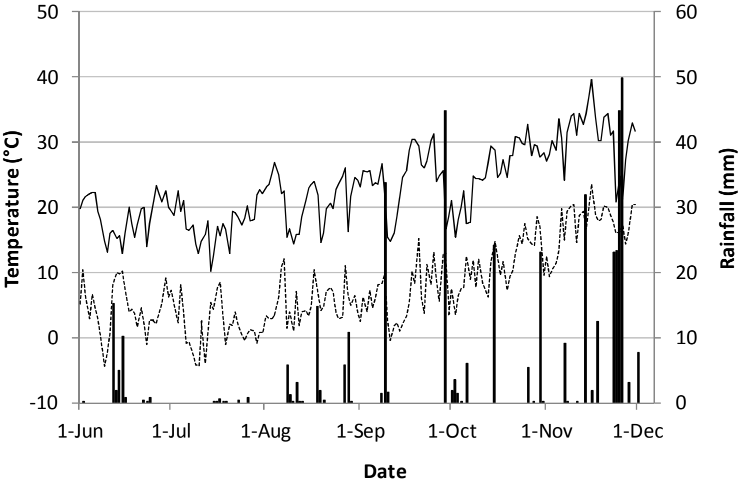


Figure 5.1. Maximum and minimum temperature and daily rainfall for the 2011 field experiment.

The validation experiment was conducted on soil with low levels of residual soil N, as the experiment was sown soon after the harvest of a cotton crop. Soil and fertiliser N and irrigation volumes for the three irrigation treatments are listed in Table 5.4. The fully irrigated treatment was grown using the canopy management technique of in-crop N application (Sylvester-Bradley et al., 2000) for the reduction of lodging risk. As such, the fully irrigated treatment was visibly N stressed by the end of tillering, and remained visibly N stressed until after the application of in-crop N in early August, after which it recovered rapidly and showed no visible sign of N stress by the beginning of September. The ‘sowing’ and ‘sowing + 1 in-crop’ irrigation treatments showed no signs of visible N stress, having had the majority of their N applied at sowing. No significant lodging was observed in any of the irrigation treatments prior to harvest.

Table 5.4. Soil mineral N status, fertiliser N and irrigation water volumes for the validation experiment at Narrabri in 2011.

Irrigation Treatment	Soil Residual N prior to sowing (kg N ha^{-1})	Fertiliser N applied prior to sowing (kg N ha^{-1})	In-crop fertiliser N (kg N ha^{-1}, Date)	Irrigation (mm, date)
Sowing Irrigation	36	150	--	#, 9-Jun
Sowing + 1 in-crop irrigation	36	150	50, 5th Sep	#, 9-Jun 100, 6th Sep
Sown on rain moisture, full 'in-crop' irrigation	36	10	150, 5th Aug 50, 5th Sep	50, 9th Aug 40, 6th Sep 40, 27th Sep 75, 20th Oct

The sowing irrigation was not measured, as it was applied before the initial measurement of soil water

5.3.1.2. Comparison of simulated and observed yield and water use

Anthesis date for the sowing irrigation and 'sowing + 1 in-crop' irrigation treatments was 15-September, with the fully irrigated treatment reaching anthesis seven days later, probably due to the effect of the in-crop N regime. APSIM was parameterised to accurately simulate the anthesis date of the two partially irrigated treatments, such that the simulated anthesis date was the same day as the observed data (data not shown). However the same parameterisation did not accurately simulate anthesis for the fully irrigated treatment, which was simulated to occur 1 day later than the partially irrigated treatments; 6 days earlier than observed. While the yield of the partially irrigated simulations was close to the observed grain yield, simulated yield of the fully irrigated simulation was 2.2 t ha^{-1}, nearly 4 t ha^{-1} below the observed grain yield (Figure 5.2). This is a similar result to that observed when simulating severe early season N stress in Chapter 3.

An optional APSIM routine was applied to increase the sensitivity of phenology response to N stress, and better simulate the observed delay in flowering date as a consequence of the early season N stress. This was achieved by setting the APSIM parameter "N_fact_pheno description" to 2, rather than the default setting of 100 which does not invoke a N stress effect on phenology. The amended simulation accurately predicted the delay in flowering date of the fully irrigated treatment without altering the anthesis date of the 'sowing' and 'sowing + 1 in-crop' irrigation treatments. However despite the delay in flowering date, it only increased simulated yield to 3.3 t ha^{-1}, still 2.8 t ha^{-1} below the observed grain yield of 6.1 t ha^{-1}.

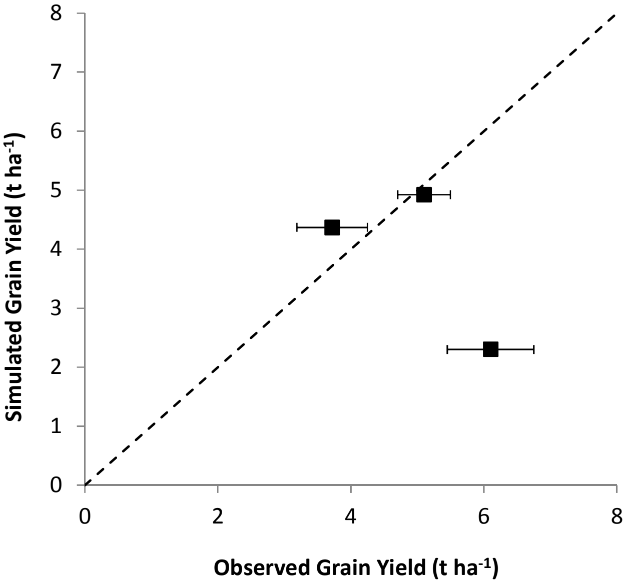


Figure 5.2. Simulated vs. observed grain yield for the three irrigation treatments in the 2011 field experiment, prior to applying corrections to the simulation of the in-crop N application treatment. The dashed line (- - - -) represents the 1:1 ratio between observed and simulated data, the horizontal error bars represent the standard error of the mean observed grain yields.

APSIM accurately simulated water use in the ‘sowing irrigation’ and ‘sowing + 1 in-crop irrigation’ treatments (Figure 5.3a,b). However, water use for the fully irrigated treatment was initially under-simulated (Figure 5.3c, solid line), due to the inability of APSIM to simulate the recovery from severe early-season N stress as observed herein, and discussed in Chapter 3.

In this instance APSIM was able to predict the observed water use during early-season growth as N stress was beginning to develop. However, the predicted and observed water use diverged markedly in late August as APSIM was unable to simulate the recovery in crop biomass that was observed in the field.

An amended simulation of the full irrigation treatment was conducted to determine whether APSIM was able to simulate late-season water use. This was achieved by (1) changing the date of N application in the simulation to the day of sowing, and (2) resetting soil water after each of the first two irrigation events, which compensated for the subsequent over-simulation of early-season water-use which had been satisfactory in the initial simulation. As shown in Figure 5.3c (dotted line), the simulation of late season water use for the fully irrigated treatment was satisfactory once these compensations were made. The amended simulation also improved the prediction of grain yield to 5.6 t ha^{-1}, close to the observed yield of 6.1 t ha^{-1}.

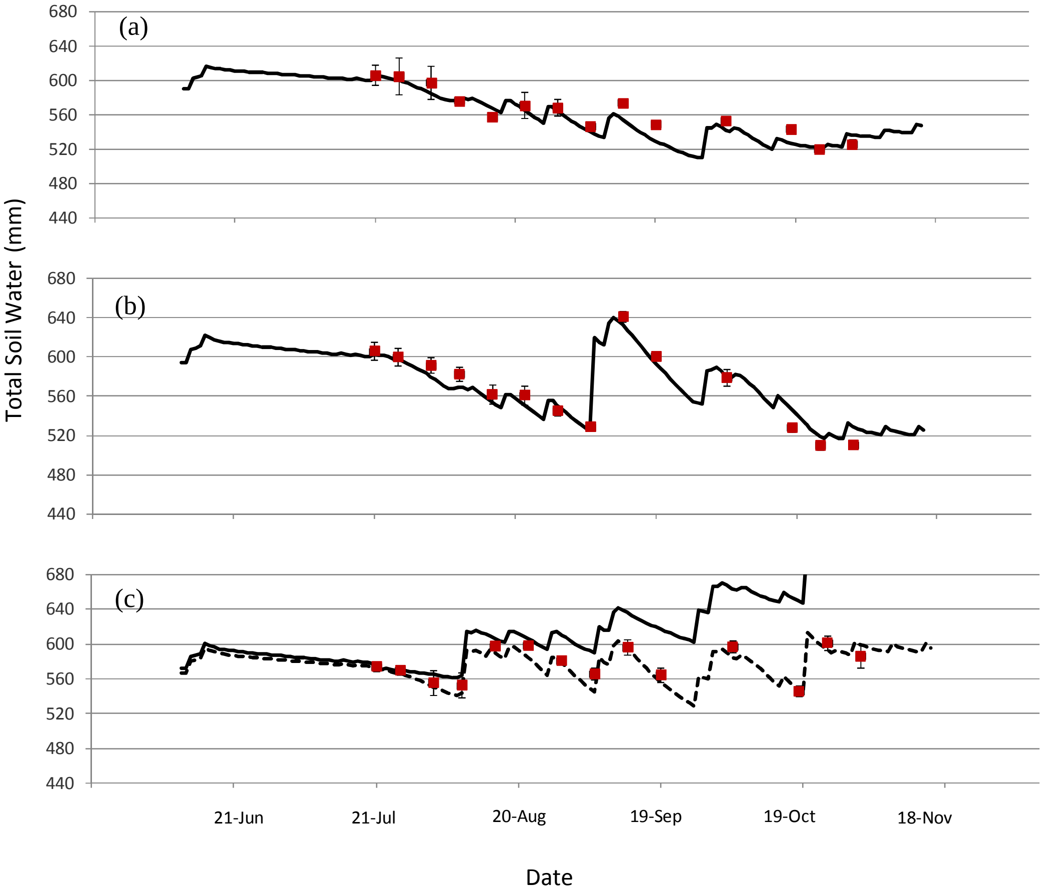


Figure 5.3. APSIM simulated total soil water (solid line) and measured total soil water (red squares) for a range of management regimes at Narrabri in 2011: (a) irrigated at sowing with all N applied at sowing (b) irrigated at sowing with one in-crop irrigation, and all N applied at sowing, and (c) sown into stored moisture at sowing with low residual soil N levels, with four in-crop irrigations and two in-crop N applications. The dotted line in (c) shows simulated water use from an additional APSIM simulation that was amended to prevent the underestimation of biomass in response to severe early N stress.

5.3.2. Land-use simulations

5.3.2.1. Environmental characterisation

The three environments used for the long-term land-use simulations differed in terms of temperature, radiation and rainfall data through the wheat growing season from June to October, as obtained from the SILO database (Jeffrey et al., 2001). Average daily temperature and radiation decreased from north to south, with Emerald having higher average temperatures and receiving more radiation than Goondiwindi and Gunnedah (Figure 5.4 and 5.5). Average rainfall from June to October (Figure 5.6) was similar at Goondiwindi at Gunnedah (212 and 237 mm) but lower at Emerald (156 mm).

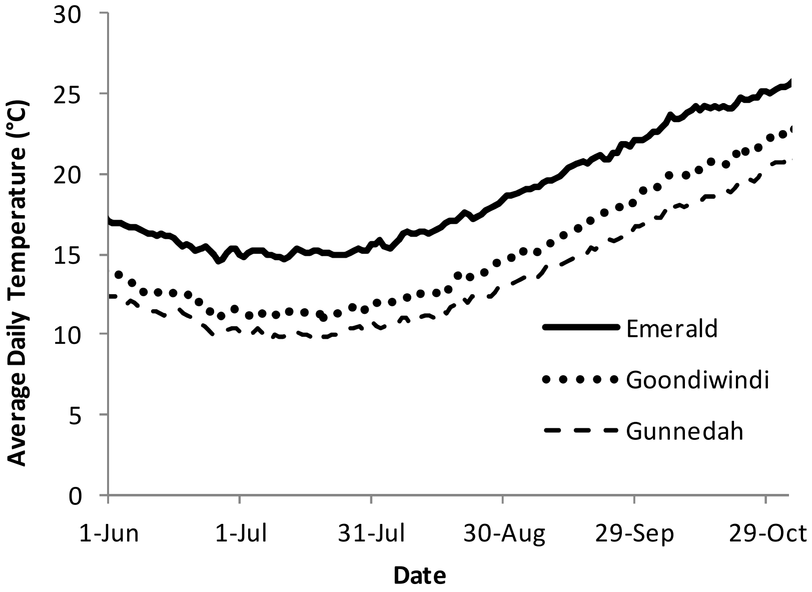


Figure 5.4. Average daily temperature (June to November) as obtained from the SILO database (Jeffrey et al., 2001) from 1889-2013 for Emerald, Goondiwindi and Gunnedah.

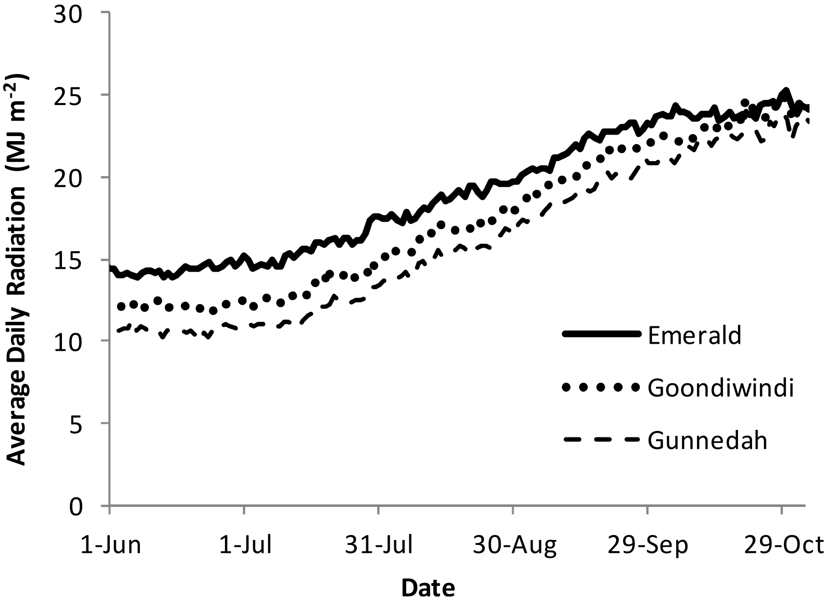


Figure 5.5. Average daily radiation (June to November) as obtained from the SILO database (Jeffrey et al., 2001) from 1889-2013 for Emerald, Goondiwindi and Gunnedah.

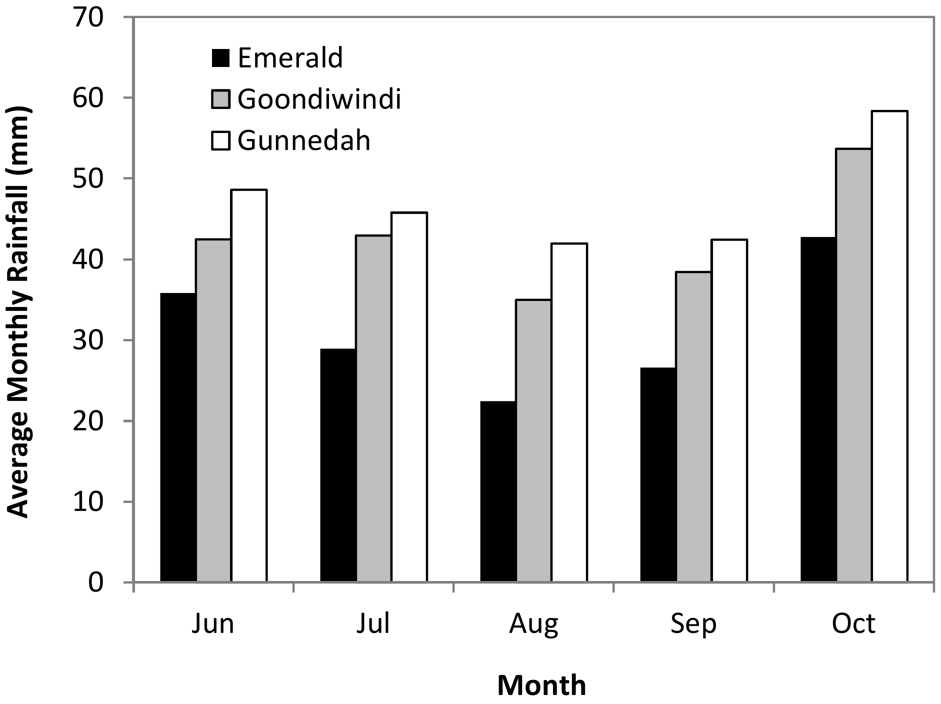


Figure 5.6. Average monthly rainfall (June to October) as obtained from the SILO database (Jeffrey et al., 2001) from 1889-2013 for Emerald, Goondiwindi and Gunnedah.

The higher temperatures at Emerald (Figure 5.4) led to decreased duration of the simulated wheat growing season, with the average number of days from sowing to harvest being 128 days, compared to 142 and 153 at Goondiwindi and Gunnedah. As a result, growing season rainfall (calculated as cumulative rainfall between the date of sowing and physiological maturity in each simulation) showed greater differences between environments than June to October rainfall, at 101, 174 and 212 mm, respectively for Emerald, Goondiwindi and Gunnedah.

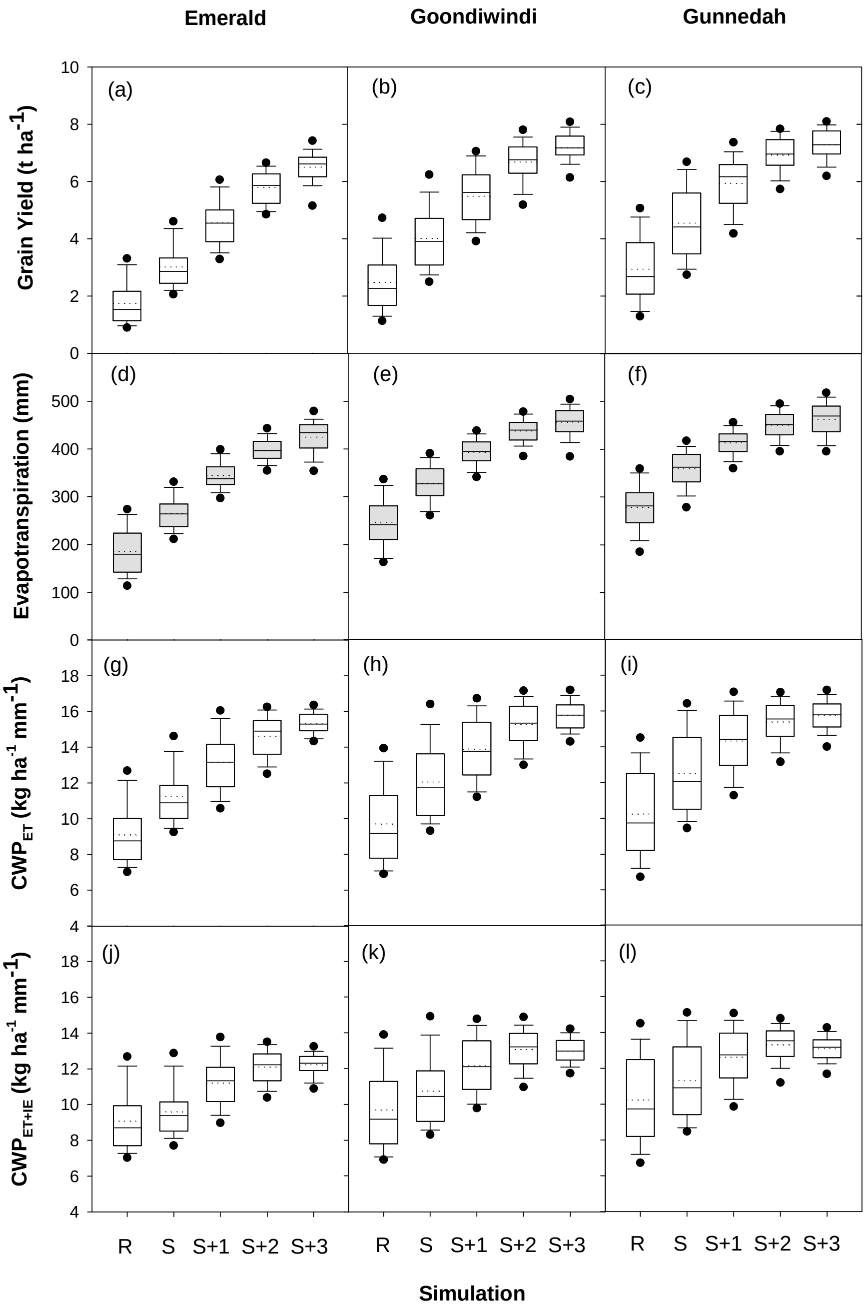
5.3.2.2. Comparison of land-use simulations.

Irrigation storage losses were greater in the more frequently irrigated land-uses, as they required water to be held in storage for longer to allow irrigation later in the growing season (Table 5.5). Up to 11% of the 1400 ML of irrigation water stored at sowing was lost to seepage and evaporation in the ‘Four irrigations’ land-use, compared to between 5% and 7% being lost when the irrigation was applied earlier in the season across a larger land area in the ‘Two irrigations’ land-use.

Table 5.5. Simulated water lost (as % of the 1400 ML of irrigation water stored at sowing) from storage as evaporation or seepage for the simulated irrigated land-uses at Emerald, Goondiwindi and Gunnedah

Location, and stored soil water at sowing (mm)	Land use simulation			
	One irrigation (at sowing)	Two irrigations (sowing + one in-crop)	Three irrigations (sowing + two in-crop)	Four irrigations (sowing + three in-crop)
Emerald (100)	0.0	6.0	8.3	11.4
(Zero)	0.0	6.5	7.9	11.0
Goondiwindi (100)	0.0	6.5	8.1	11.1
(Zero)	0.0	6.0	7.5	10.3
Gunnedah (100)	0.0	7.2	8.2	11.1
(Zero)	0.0	5.0	7.7	10.6

Unsurprisingly, grain yield and evapotranspiration increased in land-uses with greater irrigation input at each location (Figure 5.7a-f), for the simulations that had 100 mm of stored soil water at sowing. $\mathrm{CWP}_{\mathrm{ET}}$ (grain yield per unit of evapotranspiration) was also greater in the land-uses that involved higher levels of irrigation (Figure 5.7g-i). However $\mathrm{CWP}_{\mathrm{ET+IE}}$ (which included seepage and storage losses of irrigation water in the denominator term) peaked in the second most heavily irrigated treatment (S+2) (Figure 5.7j-l). This was due to the increased seepage and storage losses incurred by the most frequently irrigated treatment (S+3), which had similar grain yield to S+2. These trends were almost identical to those found in the simulations where zero stored soil water was available at sowing, hence the data for the zero soil-water simulations is not shown.



Key:

R = Rainfed
S = Sowing Irrigation
S + 1 = Sowing + 1 x in-season irrigation
S + 2 = Sowing + 2 x in-season irrigations
S + 3 = Sowing + 3 x in-season irrigations

Figure 5.7. Boxplots for grain yield, evapotranspiration, CWP_{ET} (Grain yield/ ET) and CWP_{ET+IE} (Grain yield/(ET + drainage + irrigation storage losses)) for the five cropped land-use options and three locations, for long term simulations using 100 mm of stored soil water at sowing. Boxed areas indicate the upper and lower quartiles, whiskers represent the upper and lower deciles, and the area bounded by circles represents 90% of all years. Median year is represented by the solid line within the interquartile range box, while the mean value is represented by the dotted line.

5.3.3. EWP analysis of farm-management strategies

As discussed in section 5.2.3.4, four alternative EWP analyses were conducted by calculating partial gross margins (GMs) from a factorial combination of the relative values used for irrigation water (inexpensive vs. expensive), and whether this value was applied to the net change in stored soil water between sowing and harvest (Table 5.6). However a disadvantage of using mean partial GM as a measure of EWP is that the mean value does not demonstrate the season to season variability associated with alternative management options.

Table 5.6. The four alternative analyses used for calculating whole-farm EWP.

EWP analysis	Calculation method
GM_{40}	Irrigation water price of \$40 ML^{-1}, △SW not priced
GM_{40}+△SW	Irrigation water price of \$40 ML^{-1} with △SW also priced at \$40 ML^{-1}
GM_{120}	Irrigation water price of \$120 ML^{-1}, △SW not priced
GM_{120}+△SW	Irrigation water price of \$120 ML^{-1} with △SW also priced at \$120 ML^{-1}

△SW: the net change in stored soil water between sowing and harvest

In order to illustrate this variability, the relationship between gross margin and growing season rainfall is presented (Figure 5.8) for the 'GM_{40}' analysis of the 'zero soil water at sowing' simulations for Goondiwindi. While the difference between mean partial GM for farm-management strategies in this analysis was small (\$5000, or \$5 per hectare), it is apparent that the optimum farm-management strategy varies substantially between low and high rainfall years. In high rainfall years, applying a single irrigation to the entire farm at sowing would be most profitable, however the same strategy would be least profitable in low rainfall years. In median years (decile 0.5 in Figure 5.8b), all farm-management strategies exhibit similar partial GM.

In order to encapsulate this risk/return trade-off, a commonly used modified mean-variance approach (e.g. Barah et al., 1981; McCown et al., 1991; Carberry et al., 1993; Hammer et al., 1996) was used to identify optimum farm management strategies. The approach (demonstrated in Figure 5.9 re-using the data from Figure 5.8) first involves plotting mean gross margin vs. standard deviation of the mean for each farm-management strategy. A line (termed the risk/return frontier) is then drawn, beginning at the origin, after which it is then joined to the farm-management strategy with the smallest coefficient of variation (CV, i.e. standard deviation / mean), labelled point 1 in Figure 5.9. The frontier then proceeds to the farm-management strategy with the next lowest CV that has a higher GM and standard deviation than the previous point on the frontier (labelled point 2).

This rule is applied until no further farm-management strategies have both a greater partial GM and standard deviation. Strategies situated on this frontier are potentially logical choices for a grower depending on their level of risk aversion, whereas strategies lying beneath the frontier (e.g. point 4) would be illogical in terms of maximising mean partial GM or reducing risk, as alternative strategies exist that fulfil either criteria.

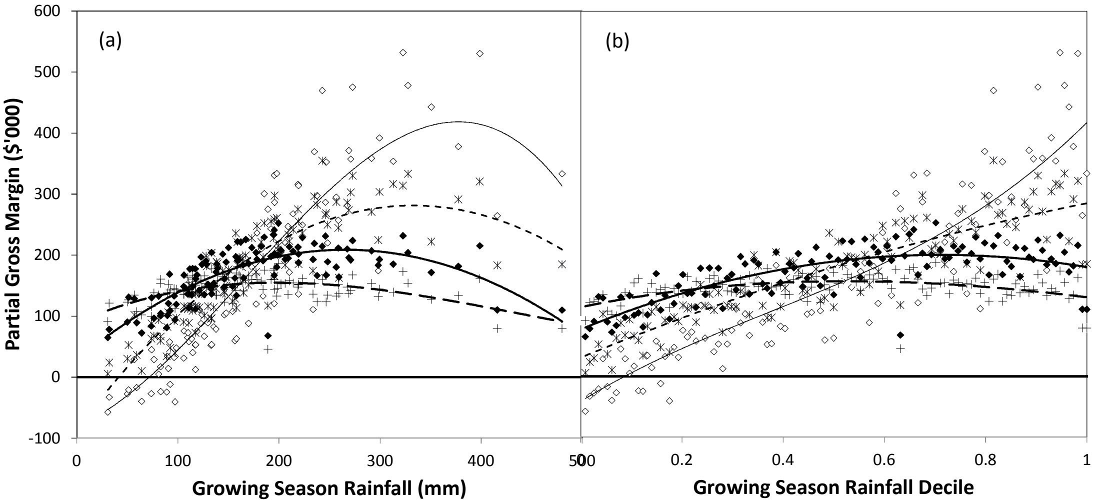


Figure 5.8. Partial GM (‘GM$_{40}$’) vs. (a) growing season rainfall, and (b) growing season rainfall decile, for the farm-management strategies compared at Goondiwindi when zero soil water was available at sowing. (◇—) = ‘S’, i.e. all irrigation at sowing; (✳- - -) = S+1/F; (◆—) = S+2/F; (+– – –) = S+3/F

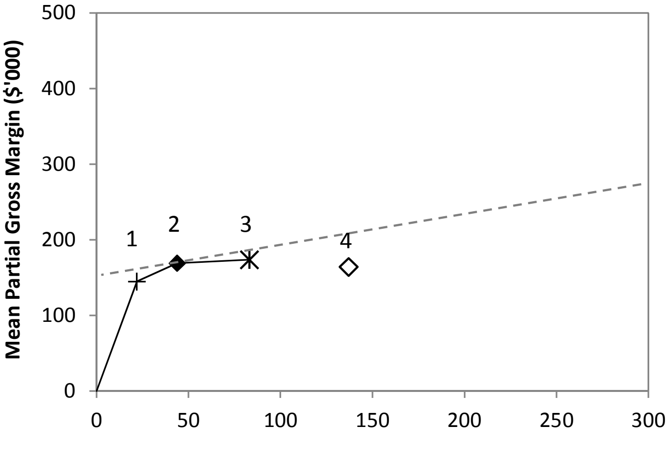


Figure 5.9. Mean partial GM (GM$_{40}$) vs. standard deviation of the mean for farm-management strategy comparison at Goondiwindi when zero soil water was available at sowing. (——) Risk/return frontier; (- - - -) 1:2 line of indifference; ▲ = all irrigation at sowing (‘S’); ■ = S+1/F, ● = S+2/F, × = S+3/F. Points 1-3 lie on the risk/return frontier, while point 4 lies slightly below and is not joined to the risk/return frontier.

An additional frontier used in the analysis is termed the ‘line of indifference’ (the dashed line in Figure 5.9) This line represents the 1:2 ratio between gross margin and standard deviation that has been found to represent the intermediate level of risk/return trade-off preferred by the majority of growers in multiple cultures (Barah et al., 1981; Ryan, 1984; McCown et al., 1991) and has previously been used in conjunction with the risk frontier (McCown et al., 1991; Carberry et al., 2000).

In the particular example in question (Figure 5.9) it can be seen that point 2 (S+1/F) is the farm-management strategy with the most favourable position on the risk/return frontier, as its mean partial GM is close to the highest, possessing the second lowest standard deviation and a noticeably larger mean partial GM than the strategy with the lowest standard deviation. For the remainder of this study these ‘optimum’ strategies are referred to as the most ‘risk-efficient’ strategies. For simplicity of presentation, only the 1:2 line of indifference will be presented on remaining risk/return graphs.

5.3.3.1. Risk/return analyses - Emerald

When evaluating CWP_{ET+IE} at Emerald, the ‘irrigation + rainfed’ strategies were more risk efficient (Figure 5.10a) than the ‘irrigation + fallow’ strategies, each having CWP_{ET+IE} of approximately 10 kg mm^{-1} when 100 mm of soil water was available at sowing. The strategy with the highest mean CWP_{ET+IE} (S+2/R) also had the second lowest variance, and was considered the most risk efficient strategy as it was closest to the 1:2 line of indifference.

When calculating EWP, different irrigation strategies were closest to the 1:2 line of indifference depending on the particular EWP analysis used (Figure 5.10b-e). When $\triangle$SW was not priced in the calculation of partial GM, most farm-management strategies lay close to the 1:2 line of indifference (Figure 5.10b,d). However when $\triangle$SW was included in the calculation of partial GM, the single sowing irrigation and partially rainfed strategies were less risk efficient than the strategies that incorporated an area of fallow land (Figure 5.10c,e). The S+2/F strategy was consistently located on or near the line of indifference for each of the EWP analyses. The S+1/F and S+3/F strategies were also close to the line of indifference in most analyses, with the exception of S+1/F which was noticeably further from the line of indifference in the $GM_{120}+\triangle SW$ analysis (Figure 5.10e).

When zero soil water was available at sowing at Emerald, all strategies except S+3/F were situated on the line of indifference in the CWP_{ET+IE} analysis. Two strategies (S+2/F and S+3/F) were closest to the line of indifference in each of the EWP analyses (Figure 5.10f-j). While the ‘S’ and S+1/F strategies were considered risk efficient in the CWP_{ET+IE} analysis, they were substantially below the line of indifference in the EWP analyses.

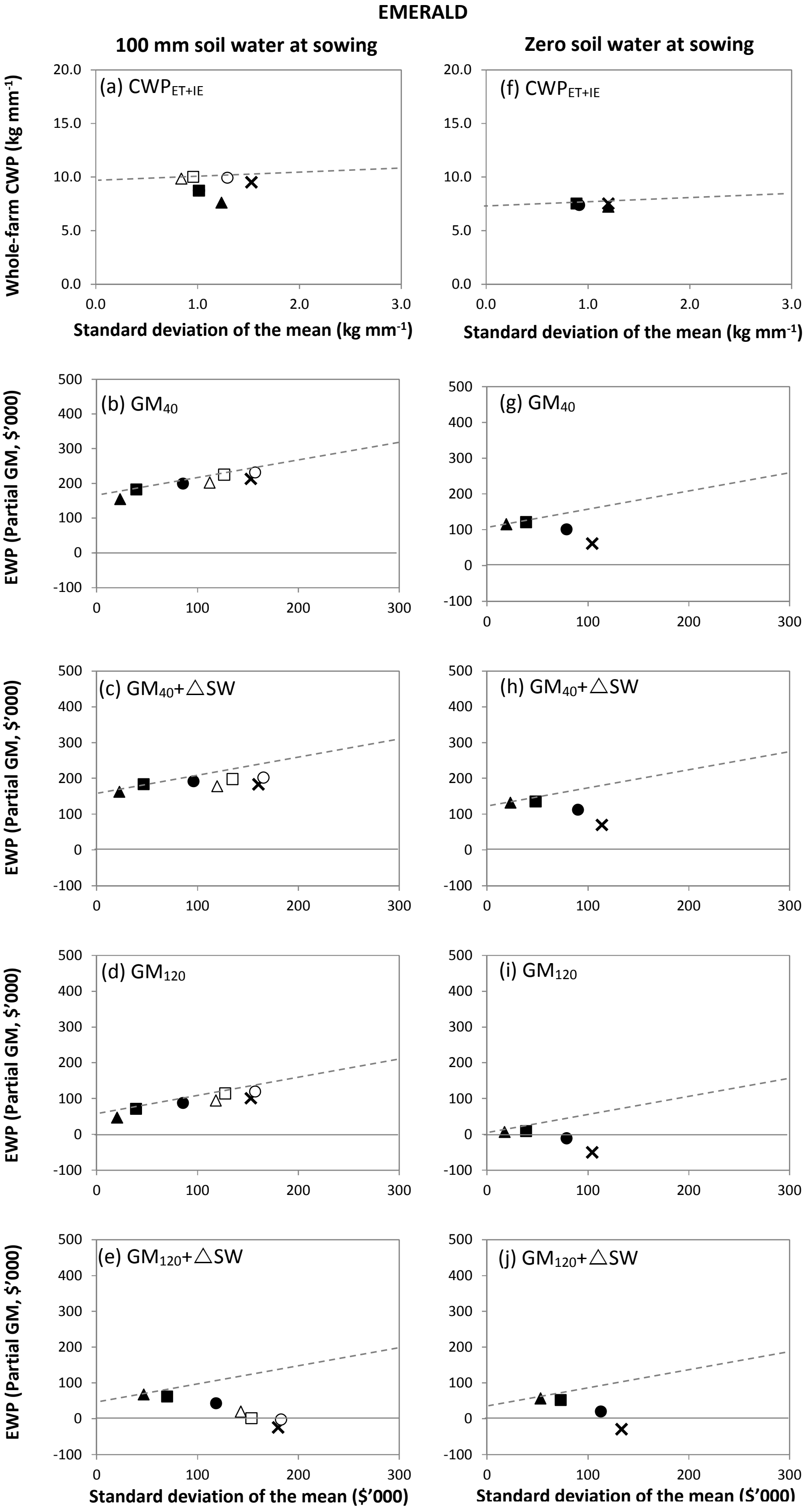


Figure 5.10. (a,f) Farm scale CWP_{ET+IE} vs. standard deviation of the mean, and (remaining graphs) EWP vs. standard deviation of the mean, from the comparison of farm-management strategies at Emerald with (a-e) 100 mm or (f-j) zero soil water at sowing. The alternative methods of calculating EWP were (b,g) GM_{40}; (c,h) GM_{40}+△SW; (d,i) GM_{120}; (e,j) GM_{120}+△SW. Farm-management strategies are denoted as follows: × = S (a-e) or S+F (f-j), ● = S+1/F; ■ = S+2/F, ▲ = S+3/F; ○ = S+1/R; □ = S+2/R, △ = S+3/R

5.3.3.2. Risk/return analyses - Goondiwindi

When 100 mm of soil water was available at sowing, greater differences were observed between farm-management strategies in both the CWP_{ET+IE} and EWP analyses at Goondiwindi, than observed at Emerald. Four strategies ('S', S+1/R, S+2/R, S+3/R) were markedly closer to the line of indifference in the CWP_{ET+IE} analysis than the remaining farm-management strategies (Figure 5.11a). Of these, the S+1/R and S+2/R strategies were also at or near the line of indifference for all of the EWP analyses. The three strategies involving areas of fallow land were not close to the line of indifference except in the $GM_{120}+\triangle SW$ analysis (Figure 5.11e). As was the case in Emerald, the valuation of △SW within the EWP analyses improved the relative profitability of the three strategies involving fallow land, but they were only close to the line of indifference when the price of water was high (Figure 5.11e).

Similar trends were observed within the zero soil water simulations at Goondiwindi (Figure 5.11f-j) to those observed at Emerald. In the CWP_{ET+IE} analysis all farm-management strategies except the S+3/F strategy were close to the line of indifference, although the 'S' strategy was slightly more risk efficient than the S+1/F and S+2/F strategies. However in the EWP analyses, the 'S' and S+1/F strategies receded from the line of indifference when △SW was priced, and when the price of water increased (Figure 5.11g-j). The S+2/F strategy was the most consistent, being situated on the line of indifference for all the EWP analyses.

5.3.3.3. Risk/return analyses - Gunnedah

The trends for data at Gunnedah were similar to those at Goondiwindi whether 100 mm or zero soil water was available at sowing (Figure 5.12). The same four farm-management strategies ('S', S+1/R, S+2/R, S+1/F) were closest to the line of indifference in the CWP_{ET+IE} analysis when 100 mm of soil water was available at sowing (Figure 5.12a). Of these, the S+1/R and S+2/R strategies were also at or near the line of indifference for all of the EWP analyses (Figure 5.12b-e), with the S+1/R strategy situated on the line of indifference for each analysis.

When zero soil water was available at sowing, the 'S' strategy was the most risk efficient in the CWP_{ET+IE} analysis (Figure 5.12f). As with the Emerald and Goondiwindi EWP analyses, the 'S' and S+1/F strategies receded from the line of indifference as the price of water increased and △SW was priced into the EWP analyses (Figure 5.12g-j). The S+1/F and S+2/F strategy were equally consistent, situated on the line of indifference for three of the four EWP analyses.

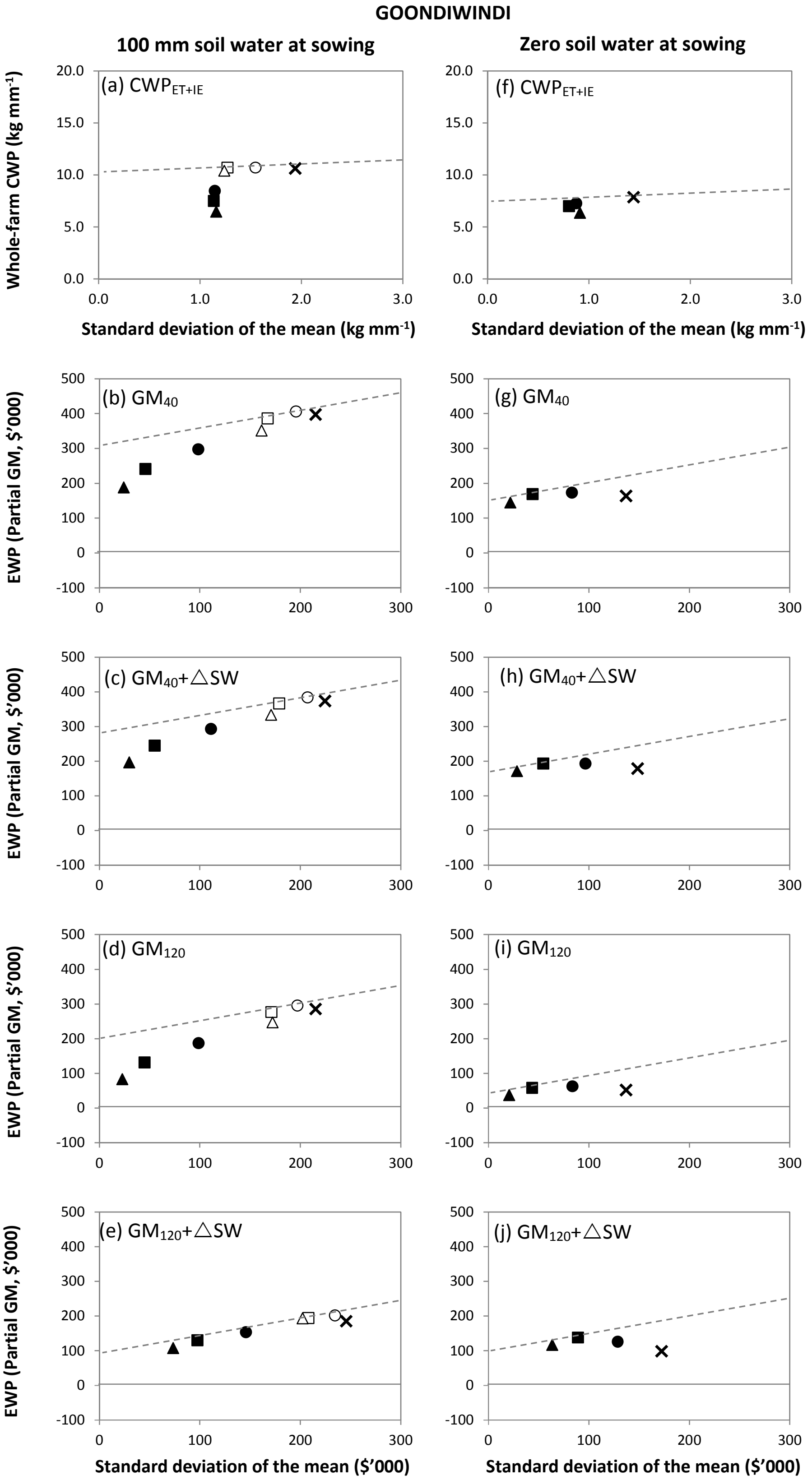


Figure 5.11. (a,f) Farm scale CWP_{ET+IE} vs. standard deviation of the mean, and (remaining graphs) EWP vs. standard deviation of the mean, from the comparison of farm-management strategies at Goondiwindi with (a-e) 100 mm or (f-j) zero soil water at sowing. The alternative methods of calculating EWP were (b,g) GM40; (c,h) GM40+△SW; (d,i) GM120; (e,j) GM120+△SW. Farm-management strategies are denoted as follows: × = S (a-e) or S+F (f-j), ● = S+1/F; ■ = S+2/F, ▲= S+3/F; ○ = S+1/R; □ = S+2/R, △ = S+3/R

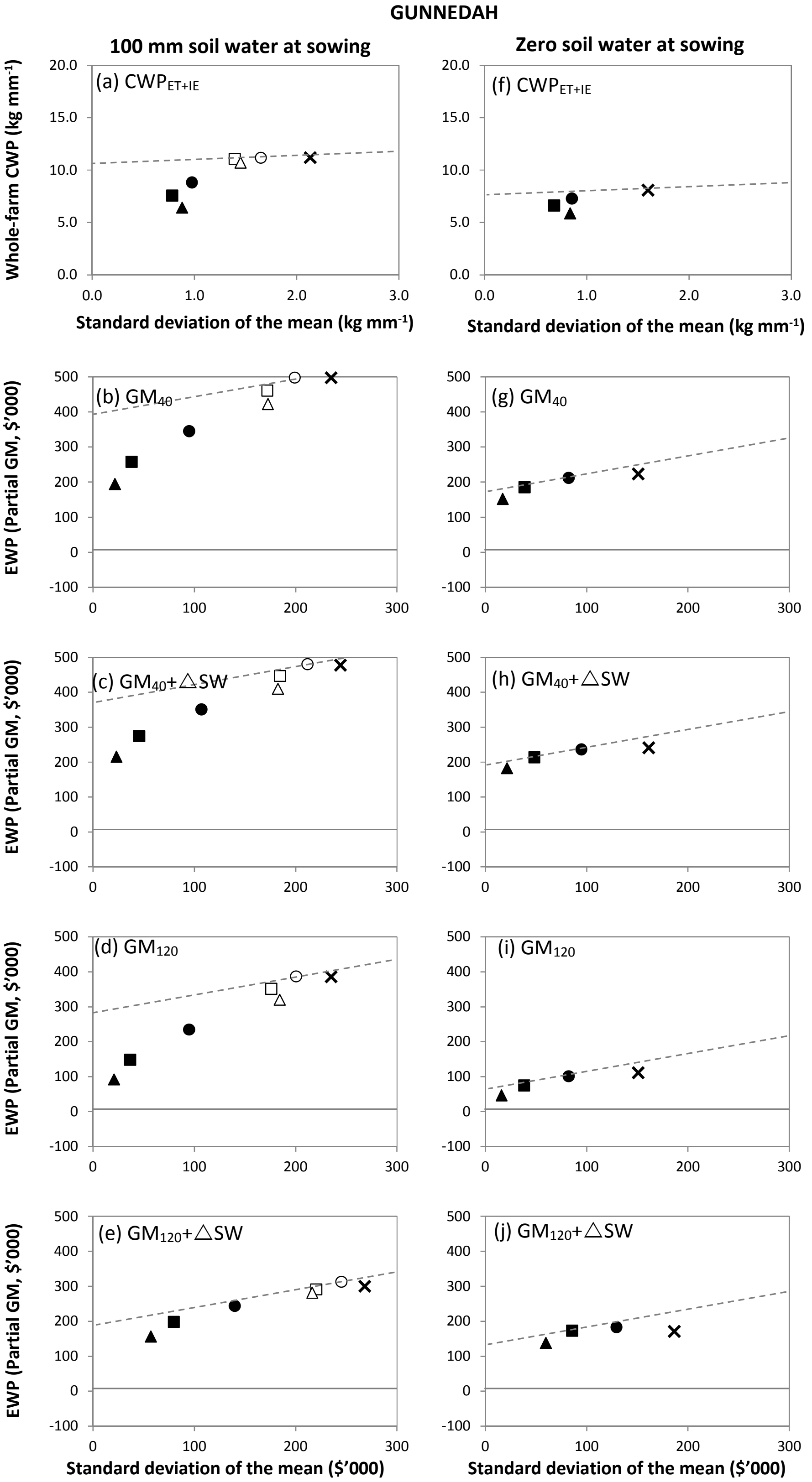


Figure 5.12. (a,f) Farm scale CWP_{ET+IE} vs. standard deviation of the mean, and (remaining graphs) EWP vs. standard deviation of the mean, from the comparison of farm-management strategies at Gunnedah with (a-e) 100 mm or (f-j) zero soil water at sowing. The alternative methods of calculating EWP were (b,g) GM_{40}; (c,h) GM_{40}+△SW; (d,i) GM_{120}; (e,j) GM_{120}+△SW. Farm-management strategies are denoted as follows: × = S (a-e) or S+F (f-j), ● = S+1/F; ■ = S+2/F, ▲ = S+3/F; ○ = S+1/R; □ = S+2/R, △ = S+3/R

5.3.3.4. Sensitivity analysis to increased farm water allocation

The over-arching whole-farm situation investigated thus far represents the most limited water situation faced by growers in the target region: a single application of irrigation water possible per hectare of irrigable land, equating to 1400 ML of irrigation water available to a 1000 hectare farm at the beginning of the season. However in order to understand the applicability of the results to alternative situations where a greater volume of water were available per unit of land area, an additional analysis was carried out in which the amount of irrigation water stored at sowing was 2800 ML, or 2.8 ML (two irrigation applications) per hectare of irrigable land. This analysis was carried out solely for farm-management strategies that had 100 mm of soil water at sowing at Goondiwindi. It allowed the S+1 strategy to be applied to 1000 hectares, while the S+2 strategy was applied to 666 hectares, and the S+3 strategy applied to 500 hectares. These strategies had double the irrigated area of the equivalent farm-management strategies from the original analyses (which had 1400 ML of irrigation water available at sowing). The 'S', S+1/F and S+1/R strategies were no longer applicable due to the greater volume of water available.

The results of this additional analysis (Figure 5.13) showed that the predominant effect of the additional irrigation water was a substantial increase in both CWP_{ET+IE} and EWP in absolute terms, necessitating the use of a different scale for the y-axes of Figure 5.13. The CWP_{ET+IE} of 15.9 kg ha^{-1} mm^{-1} (Figure 5.13a) observed for the most risk-efficient strategy was nearly 50% greater than the CWP_{ET+IE} of the equivalent strategy in the original limited water analysis (Figure 5.11a), and whole-farm partial GMs were typically $250,000 to $300,000 greater (Figure 5.13b-e).

Farm management strategies were ranked similarly to the original 1400 ML analysis for both the CWP_{ET+IE} and EWP analyses (Figure 5.13), with the S+2/R and S+1 strategies being closest to the line of indifference in most of the analyses. However, slight differences were observed in the relative risk-efficiency of farm-management strategies within the EWP analyses. In particular, the S+3/F and S+3/R strategies receded slightly from the line of indifference in comparison to the other strategies, demonstrating that the additional irrigation water was not used as effectively when concentrated on a smaller area.

In order to better ascertain the trends across all of the CWP and EWP analyses conducted in this chapter, the results from each of the analyses have been summarised in Table 5.7 by showing the difference in CWP (or EWP) between the optimum farm management strategy and each of the other farm management strategies, for a given analysis. Effectively this difference is calculated as the difference between the y-intercept for the 1:2 line of indifference that intersected the optimum farm-management strategy (displayed in Figures 5.10-5.13), and the y-intercept calculated for the 1:2 line of indifference that intersected each of the other farm-management strategies in the same analyses (data not shown). Results from all analyses that had 1400 ML of irrigation water available at sowing (i.e. Figures 5.10–5.12) have been summarised in Table 5.7, while the results of the analyses which had 2800 ML of irrigation water available at sowing (Figure 5.13) have been summarised in Table 5.8.

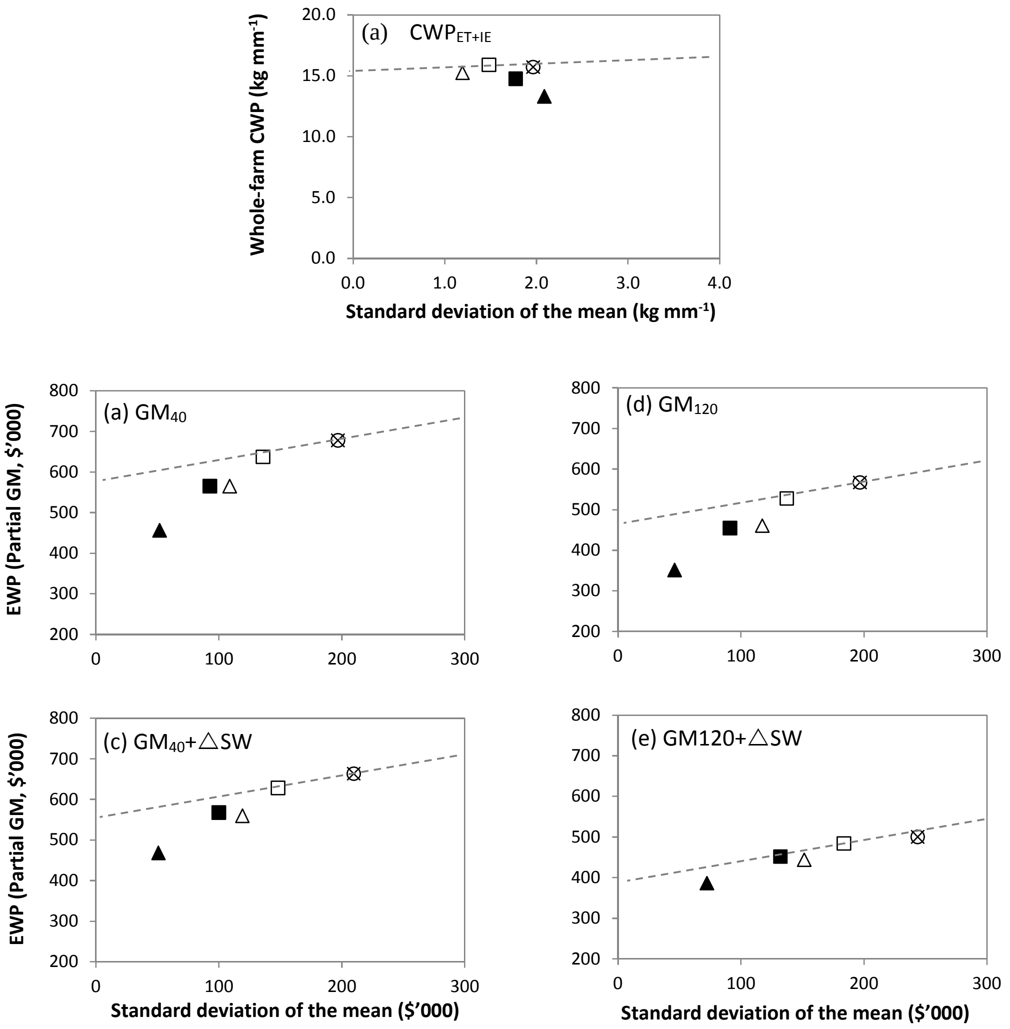


Figure 5.13. (a) Farm scale CWP$_{ET+IE}$ vs. standard deviation of the mean, and (b-e) EWP vs. standard deviation of the mean, for the alternative whole-farm analysis where 2800 ML of irrigation water was available at sowing at Goondiwindi, in which 100 mm of soil water was available at sowing. The alternative methods of calculating EWP were (b) GM$_{40}$; (c) GM$_{40}$+△SW; (d) GM$_{120}$; (e) GM$_{120}$+△SW. Farm-management strategies are denoted as follows: ⊗ = S+1; ■ = S+2/F, ▲ = S+3/F; □ = S+2/R, △ = S+3/R;

Table 5.7. The difference between the y-intercept of the 1:2 line of indifference which intersected the optimum farm management strategy, and the y-intercept of the line of indifference that intersected each of the remaining farm management strategies, when 1300 ML of water was available at sowing. The unit of measure was kg mm^{-1} in the CWP analyses, and ($'000) in the EWP analyses. The optimum strategy (where difference = zero) is highlighted in dark grey, while near-optimum strategies (within 0.5 kg mm for the CWP analyses, or within $10/ha for the EWP analyses) are highlighted in light grey.

Site, and CWP/EWP analysis	Farm management strategy						
	S	S+1/F	S+2/F	S+3/F	S+1/D	S+2/D	S+3/D
Emerald (100mm of PAW at sowing)							
CWP_{ET+IE}	-0.8	-1.3	-1.3	-2.6	-0.3	0	-0.1
GM_{40}	-26.6	-5.9	0	-19.7	-9.9	-0.9	-16.4
$GM+\triangle SW$	-58	-17	0	-9.8	-41	-29.7	-42.5
GM_{120}	-27.5	-6.7	0	-15.1	-10.7	-1.5	-16.3
$GM_{120}+\triangle SW$	-158.8	-60.5	-17.6	0	-138.2	-119.6	-96.1
Emerald (Zero PAW at sowing)							
CWP_{ET+IE}	-0.2	-0.2	0	-0.5	na	na	na
GM_{40}	-96.2	-44	-4	0	na	na	na
$GM+\triangle SW$	-107.5	-53.5	-9.4	0	na	na	na
GM_{120}	-99.9	-47.7	-7.5	0	na	na	na
$GM_{120}+\triangle SW$	-126	-66.2	-13.8	0	na	na	na
Goondiwindi (100mm PAW at sowing)							
CWP_{ET+IE}	-0.4	-2.2	-3.1	-4.2	-0.1	0	-0.3
GM_{40}	-18.7	-60	-90.3	-132.2	0	-5.9	-37.8
$GM+\triangle SW$	-19.4	-43.4	-63.5	-99	0	-3	-32.2
GM_{120}	-18.9	-59.4	-88.2	-124.8	0	-6	-36.7
$GM_{120}+\triangle SW$	-30.2	-11.5	-11.3	-21.6	-7.7	-1.9	0
Goondiwindi (Zero PAW at sowing)							
CWP_{ET+IE}	0	-0.3	-0.5	-1.2	na	na	na
GM_{40}	-51.7	-15.1	0	-13.2	na	na	na
$GM+\triangle SW$	-60.9	-20.7	0	-8.1	na	na	na
GM_{120}	-53.1	-16.1	0	-9.7	na	na	na
$GM_{120}+\triangle SW$	-81.2	-31.8	0	-8.9	na	na	na
Gunnedah (100mm PAW at sowing)							
CWP_{ET+IE}	-0.3	-2	-3.2	-4.4	0	0	-0.4
GM_{40}	-18	-100	-159.5	-214.4	0	-23.4	-61.7
$GM+\triangle SW$	-19	-76.7	-122.9	-170	0	-20	-56.1
GM_{120}	-18.7	-99.3	-156.7	-205.1	0	-23.2	-58.7
$GM_{120}+\triangle SW$	-24.4	-16.8	-31.9	-62.6	0	-9.4	-17.6
Gunnedah (Zero PAW at sowing)							
CWP_{ET+IE}	0	-0.4	-1	-1.8	na	na	na
GM_{40}	-23.8	0	-5.3	-27.9	na	na	na
$GM+\triangle SW$	-29.1	-0.4	0	-17.6	na	na	na
GM_{120}	-24.2	0	-4.2	-21.7	na	na	na
$GM_{120}+\triangle SW$	-52.7	-11.6	0	-22	na	na	na

‘na’ = not applicable for the analyses with zero PAW at sowing

Table 5.8. The difference between the y-intercept of the 1:2 line of indifference which intersected the optimum farm management strategy, and the y-intercept of the line of indifference that intersected each of the remaining farm management strategies, when 2600 ML of irrigation water and 100 mm of soil PAW was available at sowing at Goondiwndi. The unit of measure was kg mm^{-1} in the CWP analyses, and ($'000) in the EWP analyses. The optimum strategy (where difference = zero) is highlighted in dark grey, while near-optimum strategies (within 0.5 kg mm for the CWP analyses, or within $10/ha for the EWP analyses) are in light grey.

Site, and CWP/EWP analysis	Farm management strategy				
	S+1	S+2/F	S+3/F	S+2/D	S+3/D
CWP_{ET+IE}	-0.4	-1.3	-2.9	0	-0.5
GM_{40}	0	-61.1	-149.1	-10.3	-68.9
GM+△SW	0	-41.1	-115.8	-4.2	-58.3
GM_{120}	0	-59.3	-140.3	-9.9	-67.2
GM_{120}+△SW	-13.5	-6.4	-41.6	0	-23.8

5.4. Discussion

5.4.1. APSIM validation

One of the objectives of this study was to confirm the ability of APSIM to simulate water use of irrigated wheat when comparing multiple irrigation treatments at the same location. As demonstrated in the results, APSIM closely simulated grain yield and water use of the irrigated experiment in Narrabri for the rainfed and single in-crop irrigation treatments, which were grown with high levels of sowing N. Although the model was initially unable to simulate the grain yield and water use of the fully irrigated treatment (grown using the canopy management strategy of in-crop N application), satisfactory simulation of grain yield and water use for this treatment was ultimately achieved when N was assumed to be non-limiting for the entire growth period.

This finding adds further evidence to the observations made in Chapter 3 of this dissertation (section 3.4.1.4), that the APSIM wheat module under-estimates the ability of spring wheat cultivars to recover from severe N stress during tillering, when fertiliser N is subsequently applied during the cropping season and incorporated under ideal (irrigated) conditions for rapid N uptake.

It should also be remembered that the analyses herein assume that lodging is avoided through the use of agronomic methods such as cultivar choice, in-crop N application and reduced plant populations. These strategies must therefore be successfully applied in production fields in order to maximise the relevance of the simulation experiments discussed herein.

5.4.2. Water productivity analyses

The results of the initial water productivity analyses conducted on alternative land-uses at an individual field scale, showed that the more heavily irrigated land-uses had the highest water productivity when measured as CWP_{ET} (grain yield/evapotranspiration). When irrigation inefficiencies were incorporated into the denominator term (as CWP_{ET+IE}), water productivity decreased in the most frequently irrigated treatment, compared to the next most irrigated treatment. These results agreed with trends previously demonstrated in multiple field studies (e.g. Steiner et al., 1985; Musick et al., 1994; Zhang and Oweis, 1999) that increasing irrigation increases water productivity of spring wheat when calculated on a single field basis, until yields approach yield potential.

However, the profitability of irrigation enterprises is dependent on maximising EWP for an entire farm rather than CWP for an individual field, the importance of which can be demonstrated in several ways from the results of the current study. For example at Gunnedah and Goondiwindi when 100 mm of soil water was available at sowing, one of the irrigation strategies (S+3/R) was on or near the line of indifference in each of the CWP_{ET+IE} risk/return analyses, yet was not one of the most risk-efficient strategies for three of the four EWP analyses. Additionally at Emerald when 100 mm of soil water was available at sowing, the S+2/F strategy was considered sub-optimal in the CWP_{ET+IE} analysis but was one of the most risk-efficient strategies in three of the four EWP analyses. Re-ranking between the CWP_{ET+IE} and EWP analyses was also observed in the ‘zero soil water’ analysis at Emerald and Goondiwindi, where the ‘S’ strategy was on the line of indifference in the CWP_{ET+IE} analysis, but was the least risk-efficient irrigation strategy in each of the EWP analyses. Similar results were obtained in maize by Rodrigues et al. (2013) and Paredes et al. (2014) who found re-ranking of optimal strategies depending on whether CWP or EWP analyses were used.

The primary objective of this study was to determine whether deficit irrigation of larger areas of wheat is more profitable than full irrigation of a smaller area. The results of the whole-farm EWP analyses demonstrated that deficit irrigation strategies involving larger areas of wheat were more profitable on average than smaller areas of full irrigation in the two environments with higher in-season rainfall (Goondiwindi and Gunnedah), and also more risk-efficient. At these environments, one of the deficit irrigation strategies was more profitable and risk-efficient than full irrigation for all permutations of sowing soil water and method of calculating EWP, regardless of whether rainfed wheat or fallow land was used as the supplementary land-use to the fully irrigated area. Deficit irrigation strategies were also superior for most EWP analyses at the environment with lower in-season rainfall (Emerald), although growing a smaller area of fully irrigated wheat was the most profitable strategy in the $GM_{120}+\triangle SW$ analysis, where irrigation water was expensive and the stored soil water remaining at the end of the season was assigned the same value.

These results broadly agree with the field-based studies of Zhang and Oweis, (1999) and Ali et al. (2007) who also found that EWP was maximised under deficit irrigation. However, it is important to note that the present study demonstrated the importance of several aspects of deficit irrigation analysis that have rarely been considered by other studies on deficit irrigation in wheat, and the inclusion of these factors frequently altered the choice of optimum deficit irrigation strategy. In particular, the strategies considered the most risk-efficient in the current study incorporated rainfed crops sown on the unirrigated area.

5.4.2.1. The effect of rainfed cropping on the selection of optimum farm-management strategy

In the current study the intrinsic value of stored soil water was investigated through (1) the inclusion of rainfed cropping on unirrigated land, allowing an assessment of the value of stored soil water across the entire farm by evaluating its crop production potential, and (2) assigning an economic value to soil water, such that the net change in stored soil water through the season was given the same monetary value as irrigation water. While Lobell and Ortiz-Monasterio (2006) examined the interaction between varying levels of soil water at sowing on the success of different irrigation strategies, they did not specifically investigate the amount of soil water remaining at the end of the season, or account for the value of this water.

An inherent disadvantage of the cost/revenue function approach to optimising deficit irrigation, is that the response curve is derived from the crop grain yield response to potentially four sources of water depending on the farming system: precipitation, irrigation water, stored soil water at sowing, and/or water accessed from a water table at the bottom of the root zone – yet only the irrigation water is assigned an economic value. The use of deficit irrigation across a greater area accesses a greater absolute volume of precipitation and stored soil water (and potentially in some farming systems, water from a subterranean water table). The value of this additional water has traditionally not been accounted for in fully irrigated strategies that utilise a smaller land area.

This is best illustrated in the current study by considering the four farm-management strategies that consisted of irrigated land in conjunction with fallow land. When 100 mm of stored soil water was available at sowing, the optimum irrigation + fallow strategy was generally one that spread the water over a wider area (i.e. ‘S’, or S+1/F), although at Emerald S+2/F was also risk efficient. These strategies accessed additional water that was equivalent to the difference in the cropping area multiplied by the volume of stored soil water and precipitation, per unit area. In the present case study involving a farm with 1000 hectares and 100 mm (or 1 ML ha^{-1}) of stored soil water per hectare, this equated to an additional 500 ML of stored soil water available for crop use in the sowing irrigation (‘S’) strategy that irrigated 1000 hectares, compared to the ‘S+1/F’ strategy that applied two irrigations to 500 hectares of land. Additionally, at Gunnedah for instance, a further 212 mm of rainfall fell on average during the growing season equating to a further 1060 ML available to crop production in the sowing irrigation strategy. The difference in partial GM between the ‘S’ and S+1/F strategies was large in some EWP analyses (e.g. \$150,000 at Gunnedah in the GM_{40} analysis), but heavily biased due to the additional soil water and precipitation used to grow crops over the wider area of the ‘S’ strategy that was unavailable to the S+1/F strategy. The equivalent strategy that included rainfed cropping (S+1/R) had an almost identical gross margin to the ‘S’ strategy at Gunnedah because it was able to use the additional precipitation and stored soil water in producing the rainfed crop, and was more risk-efficient due to its lower year-to-year variability.

Ultimately the analyses showed that rainfed cropping was either similar to or more profitable than fallow land when used in conjunction with deficit irrigation strategies in most of the EWP analyses, and was also more risk-efficient. It is important to note however that the ability to choose rainfed cropping alongside an irrigated area will fluctuate between seasons due to variability in soil moisture at sowing (required both for seed germination and as a stored soil moisture 'buffer' for reliable crop production). Irrigated growers may therefore prefer to irrigate the entire cropping area in certain seasons in response to these practical limitations.

5.4.2.2. The effect of assigning an economic value to soil water on the selection of optimum irrigation strategy

Including an economic value for stored soil water in the EWP analyses also impacted on the choice of the most risk-efficient farm-management strategy, in particular by reducing the relative profitability of strategies that cropped larger farm areas (i.e. the 'S' sowing irrigation treatment, and the 'irrigation + rainfed' strategies) in comparison to the irrigation + fallow strategies. In the higher rainfall environments, this did not cause significant changes to the relative risk efficiency of the alternative farm-management strategies, but did increase the number of strategies at or near the line of indifference when the price of water was high.

At the low rainfall environment however, assigning a value to stored soil water altered the risk-efficiency of the irrigation + fallow strategies such that they became more risk efficient than the irrigation + rainfed strategies, when either the high or low value was assigned to water. When the price of water was high, the relative risk-efficiency of individual irrigation + fallow strategies also changed such that the full irrigation strategy was the most risk-efficient, whereas the S+2/F treatment had been the most risk-efficient when the price of water was low.

5.4.2.3. The effect of additional irrigation water and stored soil water at sowing

Increased access to irrigation water had little impact on the relative risk-efficiency of irrigation strategies. While doubling the irrigation volume available at sowing increased EWP and CWP of all farm-management strategies, this did not alter the choice of the most risk-efficient strategy. However it did increase the relative advantage of strategies that spread water across a wider area. The range of strategies investigated when 1400 ML of irrigation water was available at sowing already included spreading water across the widest area available. Therefore no new strategy was available that could further improve EWP when the volume of irrigation water was increased.

The importance of stored soil water at sowing in determining the optimum farm-management strategy was first apparent when developing simulation scenarios for the study, with rainfed cropping strategies not considered viable (and hence, not simulated) when there was zero stored soil water at sowing, a well understood principle in the region (e.g. Moeller et al., 2009). In order to assess the effect of additional soil water at sowing, it is necessary to compare farm-management strategies that were simulated for both levels of sowing soil water, i.e. only the strategies that incorporated irrigation in conjunction with fallow land. Comparison of these strategies for the two levels of sowing soil water showed that increasing soil water at sowing changed the most risk-efficient strategy to one which had a larger deficit irrigated area with reduced frequency of irrigation, for each of the environments studied. These results agree with those of Lobell and Ortiz-Monasterio (2006), who also showed that deficit irrigation was more profitable in conjunction with high levels of stored soil water at sowing.

5.4.2.4. The effect of environment and year-to-year variability on the choice of risk-efficient irrigation strategies

The interaction of environment with the optimal irrigation strategy was associated with the relative difference in average rainfall between the environments. When 100 mm of soil water was available at sowing (and hence rainfed cropping was considered as a potential land-use), optimal strategies in the higher rainfall environments (Gunnedah and Goondiwindi) were generally irrigation + rainfed strategies that utilised irrigation water across a wider area (e.g. S+1/R and S+2/R). These results in the higher rainfall environments were similar to those observed by Gaydon et al. (2011) in an area of southern Australia with similar growing season rainfall to Gunnedah, who found that maximum farm profitability under limited water situations was obtained by spreading irrigation water over a wider area in winter cereal crops.

This contrasted slightly with results for the lowest rainfall environment (Emerald) where both rainfed and fallow strategies were either ranked similarly, or strategies including fallow land were considered the most risk-efficient in the EWP analyses. The most risk-efficient farm-management strategy also varied between environments when zero soil water was available at sowing, with a small area of full irrigation being the most risk-efficient strategy in the driest environment, but not in either of the wetter environments.

The identification of different optimal strategies between environments was unsurprising, given the relationship already identified between soil water and risk-efficient deficit irrigation strategies (section 5.4.2.3) that is logically extended to variable precipitation between environments. Oweis and Hachum (2006) also identified alternative optimum deficit irrigation strategies for different wheat growing environments in Syria with varying rainfall.

It is also important to note that the risk-efficiency of the different irrigation strategies is a long term average generated from multi-year simulations. In individual seasons with markedly higher rainfall than the mean, strategies spreading irrigation water across a wider area will be more profitable than the strategy that is most risk efficient across all years. Conversely in low rainfall years, strategies that have increased irrigation frequency on a smaller crop area are likely to have increased profitability compared to the most risk-efficient strategies from the long term analyses. While it is possible that the use of seasonal climate forecasts could improve the probability of selecting a better strategy for the particular season (e.g. Hammer et al., 1996), evaluation of the value of seasonal forecasting in improving the selection of deficit irrigation strategies is beyond the scope of the present study.

5.5. Conclusions

The APSIM farming systems model was successfully used to predict seasonal soil water fluctuations for three irrigation treatments at a single location. However as was observed in Chapter 3, APSIM was initially unable to simulate soil water or grain yield in a treatment that experienced a severe vegetative N stress while being grown using the canopy management technique of in-crop N application. APSIM did satisfactorily simulate the treatment when in-crop N was applied at an earlier crop stage in the simulation than occurred in the field. Further work is necessary to isolate and better understand the specific crop growth functions that are preventing the accurate simulation of biomass development in an irrigated environment after a severe vegetative N stress has been relieved.

The results of the simulation study into whole-farm water productivity in a limited water situation demonstrated that applying deficit irrigation strategies across larger areas of wheat were generally more profitable and risk-efficient (on average across seasons) than fully irrigating smaller areas. The optimal deficit irrigation strategies typically involved using one-third to one-half of the farm area to grow partially irrigated wheat, while the remaining area was sown to rainfed wheat.

Increased access to non-irrigation water (i.e. in higher rainfall environments or through greater stored soil water at sowing) altered the relative risk-efficiency of irrigation strategies and meant that larger areas of deficit irrigated cropping (with decreased frequency of irrigation across the area) became more risk-efficient. However in a low rainfall environment where water was expensive and soil water was given the same economic value as irrigation water, fully irrigated wheat in conjunction with fallow land was the most risk-efficient strategy. The importance of evaluating farm-management strategies using EWP instead of CWP was also evident in this study, as re-ranking of the risk/return profile occurred between these alternative methods of calculating whole-farm WP.

Accounting for the intrinsic value of stored soil water and precipitation was also identified as fundamental when assessing the benefits of deficit irrigation strategies in water limited situations, given that the larger land area utilised by deficit irrigation strategies accessed much larger absolute volumes of soil water and precipitation. The use of rainfed crops in the whole-farm simulation analyses demonstrated the intrinsic value of this additional water, and altered the choice of optimum farm-management strategy. Re-ranking of farm-management strategies was also observed when applying an economic value for soil water remaining at the end of the cropping season. Future evaluations of deficit irrigation strategies must begin to account for such considerations.

Chapter 6 - General discussion and conclusions

6.1. General discussion

The overarching objective of this study was to determine the agronomic practices required for achieving maximum water productivity in the northern grains production region of Australia, through the specific investigation of two hypotheses:

(1) *that 'lodging' constrains irrigated wheat yields in the northern grains region, and agronomic techniques can be utilised to control lodging.*
(2) *that when irrigation water availability is limited, maximum whole-farm crop water productivity for wheat is achieved by partially irrigating a larger crop area rather than fully irrigating a smaller area.*

The findings of this study demonstrate that lodging is closely associated with reduced grain yield in irrigated wheat crops, and that agronomic techniques including in-crop N application, reduced plant population and choosing lodging resistant cultivars are able to substantially reduce lodging without reducing potential yield. The study has also demonstrated that under economic scenarios currently relevant to commercial wheat growers in the northern grains region, maximum water productivity is generally obtained by partially irrigating larger areas of wheat, although an exception was identified in a low rainfall environment when water was assigned a high economic value.

6.1.1. Implications for researchers and limitations of the study

6.1.1.1. Applicability of the APSIM model to irrigated wheat production systems.

This study has demonstrated the suitability of APSIM for simulating irrigated wheat production in the northern grains region, reinforcing previous studies that demonstrated the ability of APSIM to simulate grain production in high yielding environments (Asseng et al., 1998; Chenu et al., 2011; Peake et al., 2011), and identify optimum rainfed and irrigated cropping strategies (e.g. Carberry et al., 2009; Power et al., 2011; Gaydon et al., 2012).

However in order to simulate furrow irrigated fields it was necessary to use modified light interception parameters to account for the 'furrow gaps' that reduce light interception in furrow irrigated wheat fields. While this adjustment satisfactorily accounted for observed differences in grain yield between different furrow configurations in field trials (Appendix B), these calibration trials were conducted only on north-south configured beds. The adjusted parameters therefore represent a maximum reduction in light interception that may not apply in east-west configured beds, which logically intercept more light during the cropping season due to the low position of the sun in the northern sky during late winter and early spring. Further investigation is required to establish the extent of light interception differences between different bed alignments, and determine whether such differences alter yield potential of irrigated wheat crops grown on different bed orientations.

APSIM was also unable to simulate the rapid recovery of wheat from severe vegetative N stress under water non-limiting conditions. This did not prevent the simulation of irrigated wheat production systems, as N non-limiting simulations were found to satisfactorily represent the grain yield and water use of crops grown using such N regimes. However, further work is necessary to isolate and better understand the specific crop growth functions preventing the accurate simulation of biomass development in an irrigated environment after a severe vegetative N stress has been relieved.

While the use of a validated simulation model allows rapid examination of research questions across multiple soil types and environments, there are some limitations associated with their use. Model outputs represent the best case outcome for each season × environment × management combination, and the incidence of crop disease or disorders not simulated by the model (including lodging) could mean that the optimal strategies identified in the simulation studies may not provide the optimal result ‘on-farm’. For example, French and Schultz (1984a) demonstrated that well grown crops possessed a maximum transpiration efficiency of 20 kg^{-1} mm^{-1} ha^{-1} of grain for crop water use over and above evaporative losses, which matched the known theoretical limit at the time (Passioura, 1976). However they also demonstrated that many of the commercial crops monitored had CWP substantially lower than represented by the line of maximum response. Hochman et al. (2009) have more recently demonstrated that the same issues still exist in rainfed cropping.

Accordingly, irrigated growers in the region have been advised to trial new irrigated wheat growing techniques on a small scale initially, in order to ensure that the results from this study can be repeated in conjunction with the specific management techniques and environmental conditions found on individual farms (Peake et al., 2014a). The use of in-season crop simulation tools such as Yield Prophet (Hochman et al., 2009) should also allow growers to benchmark their production fields to determine whether they are achieving production levels close to the water-limited yield potential, or whether other factors such as disease or nutrient deficiencies are limiting their crop water productivity.

6.1.1.2. Prediction of potential yield by the APSIM model.

Questions were also raised during the study regarding the accuracy of prediction of potential yield by the APSIM model (Chapter 3). Observed grain yields for several fields in 2009 were greater than that simulated by APSIM, due to under-prediction of both grain number and kernel weight. Subsequently, long term simulations for potential yield were adjusted to account for the increased maximum kernel weight observed in field experiments. However it is possible that the yield potential of the cultivar Kennedy could still be greater than that simulated in the present study, as it was decided not to simultaneously re-parameterise grain number determination routines in APSIM. This decision was taken due to the preliminary nature of the ‘skip-row-factor’ parameterisation developed for this study, and the possibility that inaccuracy in its development could have been related to the under-estimation of grain number.

It is also uncertain whether the larger kernel weights were caused by (a) the more modern cultivar Kennedy having a greater inherent yield potential than the cultivar Hartog, which was used in APSIM parameterisation experiments, or (b) the use of the canopy management technique of in-crop N application. Further work is necessary to address these questions, which could be conducted by comparing biomass development, grain yield and yield components of Kennedy and Hartog in field experiments across multiple N timing treatments. It is recommended that such experiments should use support netting to prevent lodging from influencing experimental results.

Although data presented in this study were limited (Chapter 3), questions were also raised as to whether long-season cultivars may have higher potential yields than those simulated herein for Kennedy, a quick maturing cultivar. While the large over-prediction of grain yield for the long-season cultivars Strzelecki and Gregory in the current study was at least partially related to the extensive lodging observed in these cultivars, it is also possible that the predicted grain yield for these cultivars was inaccurate. Preliminary simulations conducted concurrently to the present study (Peake and Angus, 2009) suggest that Strzelecki (a long-season cultivar) has yield potential of approximately 2 t ha^{-1} greater than Kennedy in the region, however it remains to be seen whether the simulated increase in potential yield associated with longer season cultivars can be achieved in the field in the absence of lodging. Recent field work and simulation studies in rainfed production systems of southern Australia have demonstrated yield increases associated with sowing longer season germplasm (Kirkegaard and Hunt, 2010; Hunt et al., 2012; Kirkegaard et al., 2014). However, this yield advantage may be due to improved crop and whole-farm adaptation to water limited environments through traits such as deeper root systems, and the ability to sow more of the farm area in an optimum sowing window (Kirkegaard et al., 2014), which are not necessarily applicable to the current irrigated study.

The identification and/or development of lodging resistant long-season cultivars would be required in order for commercial growers to take advantage of any increased yield potential associated with longer season germplasm in irrigated production fields. But it could be beneficial to first determine whether long-season cultivars actually possess greater yield potential than quick maturing cultivars under water and nutrient non-limiting conditions, an experiment that could also be carried out with the use of support netting to eliminate lodging.

It is interesting to note that other simulation studies of potential yield in sub-tropical spring wheat have not identified lodging as a constraint to grain yield during model validation (e.g. Aggarwal et al., 1994; Andarzian et al., 2008). This may have occurred for a number of reasons: (1) agronomic management (particularly in-crop N application or the use of lodging-resistant genotypes) may have reduced lodging to negligible levels, (2) lodged plots may have been eliminated from datasets and not discussed, (3) measured yields may not have reached true yield potential due to under-supply of water or N, or (4) harvesting methods in labour-intensive farming systems may have eliminated some lodging-related yield losses that occur in broad-scale, mechanized harvesting systems.

6.1.1.3. Evaluation of agronomic techniques for reducing lodging risk

The field study of agronomic techniques (Chapter 4) demonstrated a clear link between canopy development in the vegetative growth phase and the severity of grainfill lodging, which extended the findings of previous research into links between shading during vegetative growth and lodging (Sparkes and King, 2007; Sparkes et al., 2008). Potentially, these relationships could be utilised in developing tools for the in-season detection of lodging risk, although the relationship varied between cultivars in 2011, possibly due to the effect of genotype × environment interaction on the development of lodging.

However, numerous plant characteristics influence lodging risk, many of which develop after the vegetative growth phase e.g. stem height, stem centre of gravity, and stem wall thickness (Baker et al., 1998; Berry et al., 2003). Consequently, environmental conditions during later growth stages (e.g. stem elongation, anthesis and grain filling) may mitigate or exacerbate the level of lodging risk that has developed during tillering. Further investigation is therefore required to determine the relative importance of environmental conditions during later crop stages to the development of lodging risk.

Furthermore, soil moisture status, structure and strength are additional variables that interact with rainfall intensity and infiltration, and create the physical conditions around crop surface root systems that contribute to lodging (Berry et al., 2003). These factors have not been investigated in the current study, yet are potentially significant in irrigated production systems where soil moisture status can be monitored and manipulated to increase or reduce lodging risk. This was frequently evident during the field monitoring study in Chapter 3, where irrigation applications were observed to trigger lodging events in both furrow and overhead irrigated fields. The water falling from overhead irrigation systems was also considered to add to the weight of the crop canopy and contribute to lodging in one of the monitored fields. Thus, additional research is also necessary to better understand the role that soil type and soil moisture status, as well as irrigation method, frequency and volume have in contributing to lodging events.

While a range of agronomic treatments were demonstrated to reduce lodging risk while maintaining yield potential, the experiments were only carried out at a single location on two cultivars and require further testing across the region to confirm applicability across cultivars, soil types, irrigation systems and environments. Additionally, the irrigation method used in the agronomic field study (frequent overhead irrigation) probably enhanced N availability in low N treatments. Therefore, these results may not be directly applicable to furrow irrigated fields (the predominant irrigation infrastructure throughout the region) which are irrigated less frequently and therefore have less capacity to maintain high soil moisture during the vegetative growth phase. Further study is therefore required to determine the importance of early-season irrigation in maintaining N availability (and potential yield) in canopy managed fields, in subtropical regions.

It should also be remembered that plant breeding has previously been instrumental in reducing lodging risk through the introduction of dwarfing genes (Reitz and Salmon, 1968; Pinthus, 1973). Further genetic gains may be possible in germplasm relevant to the northern grains region, which has historically been developed for low-yielding, drought stressed environments. Evaluation of the 30+ commercial cultivars currently recommended for northern region growers may also lead to identification of additional cultivars with high levels of lodging resistance.

Lodging risk increases as a crop progresses through grainfilling (Berry et al., 2004), which is logical given that the increased weight of grain in the wheat head alters the centre of gravity of wheat plants. Therefore when comparing the lodging susceptibility of different genotypes it is important to ensure that weather events (which cause lodging events and also influence the development of grain yield) are experienced at similar growth stages. Germplasm evaluation experiments for lodging risk are therefore advised to use variable sowing dates between cultivars of different maturity groups in order to achieve this objective. Unfortunately, rain during the sowing period prevented the use of the recommended methods in the present study. While the quick maturing cultivar Kennedy was suggested to be more lodging susceptible than the longer season cultivar Gregory, further assessment is recommended to confirm this trend under conditions where anthesis can be synchronised.

6.1.1.4. Evaluation of deficit irrigation

The findings of the simulation study into whole-farm water productivity when water availability is limited (Chapter 5) showed similar results to recent deficit irrigation evaluations in maize (Rodrigues et al., 2013; Paredes et al., 2014) which found re-ranking of optimal strategies depending on whether crop water productivity (CWP) or economic water productivity (EWP) measures were used. This emphasised the importance of using EWP rather than CWP in identifying the most profitable and/or risk-efficient deficit irrigation strategies. Additionally, the present study reinforced existing studies in irrigated spring wheat (e.g. Zhang and Oweis, 1999; Ali et al., 2007) by demonstrating the increased profitability associated with deficit irrigation over larger areas.

The importance of assessing the entire farm water balance associated with deficit irrigation strategies was also demonstrated. This was achieved through the novel techniques of simulating rainfed cropping and assigning an economic value to net soil water usage, to explicitly assess the value of precipitation and stored soil water across the arable area. Given the significant consequences this had on the modelling of whole-farm EWP, future studies in deficit irrigation should begin to account for the value of stored soil water and precipitation that is associated with the fallow land or rainfed crop intended for the unirrigated portion of the farm, along with the soil water stored at maturity under a fully irrigated crop.

However it should be remembered that assigning an economic value to the net usage of stored soil water through the season is ultimately an arbitrary measure. Further investigation would be beneficial to more precisely determine the value of soil water remaining at the end of the season. Such investigation could involve the simulation of subsequent cropping seasons, and assessment of the impact of this stored water on the profitability of the subsequent crop.

6.1.2. Implications for irrigated wheat producers

6.1.2.1. Understanding potential yield and the impact of lodging in irrigated wheat production fields

One of the primary implications of this research is the improved knowledge available to irrigated wheat producers in the northern grain production region of eastern Australia. Previously, little information was available on the production potential and water-use of irrigated wheat in the region for use in benchmarking irrigated wheat against more commonly irrigated crops such as cotton.

By determining the potential yield and water use requirements of irrigated wheat crops it is now possible for irrigated growers to understand how much water is required to produce a high yielding wheat crop, and the potential grain yield (and hence economic return) that is possible in response to irrigation. Comparisons can thus be made to other irrigated crop options such as cotton to determine the most cost-effective use of water at the beginning of the wheat growing season. Whether to irrigate wheat or to retain the water for a subsequent cotton crop is a decision that will also be influenced by the expected price of the respective commodities at the time of decision making.

Additionally, the disorder known as lodging had rarely been observed in the region prior to 2008, and little knowledge existed as to the potential for severe grain yield losses. While the mean lodging-related yield-gap identified for lodged fields was 1.6 t ha^{-1}, the worst lodged individual field yielded 5.5 t ha^{-1} less than the potential grain yield for this field. Such yield losses provide a powerful incentive for growers to use the agronomic techniques identified in Chapter 4 to reduce the risk of lodging, as altered cultivars, plant populations and N regimes can be implemented with little additional cost to the irrigated grower.

6.1.2.2. Irrigation scheduling for maximising profitability when irrigation water is limited

The study of whole-farm EWP (Chapter 5) provides irrigated wheat producers in the region with improved knowledge of deficit irrigation strategies that will optimise profitability in limited water situations, for different environmental conditions and years. Irrigated growers in higher rainfall environments would be advised to consider spreading their water across a wider area, particular if there is stored soil water at sowing in the order of 100mm, and the climate outlook indicates average to above average rainfall for the wheat growing season. However in lower rainfall environments (particularly when sowing soil water is low or the seasonal climate outlook indicates below average rainfall) irrigated growers would be best advised to concentrate their irrigation water on smaller area of irrigated wheat.

Interestingly, irrigation strategies that involve growing a larger area of wheat may also have additional benefits to cotton growers, as it means larger areas of their farm would receive the disease-break rotational benefits of wheat in subsequent cotton crops.

It is also pertinent to note that that APSIM simulations do not predict the incidence of lodging, or its related yield losses. Successful implementation of the optimum irrigation strategies identified herein is therefore dependant on management of the crop to avoid lodging through the use of the agronomic techniques described in Chapter 4. It should also be remembered that the economic analyses assumed that all irrigation strategies achieved the same grain quality (and hence price), reflecting the lack of importance placed on grain protein concentration by local growers during the period encompassed by this study. This was due to the small price differences available for higher quality grades that gave little incentive to achieve specific grain protein and end-user quality requirements, partially caused by the impact of feedlot grain demand within the region. The applicability of these results into the future may change if a large price differential exists between different protein levels for wheat produced within the region.

6.1.2.3. Managing lodging risk through improved agronomy

The agronomic study discussed in Chapter 4 gives irrigated growers an improved understanding of the agronomic changes required to minimise lodging risk. Seed rates and N regimes identified in this study for minimising lodging risk while maintaining yield potential are lower than those recommended for irrigated wheat growing in temperate climates of southern Australia (Lacy and Giblin, 2006).

Unfortunately the soil mineral N content at the beginning of the 2008 season was already high in many fields (Chapter 3), as they had been prepared for cotton crops that were ultimately not sown. It is therefore important for the management of lodging to include pre-season testing for soil mineral N, as a prerequisite to developing a management strategy that will minimise lodging risk. Growers and advisors from the northern grains region are therefore advised to be cautious in the application of alternative agronomic techniques (including those discussed herein). As evidenced in 2008, agronomic techniques may not always have their intended effect in different environments or seasons.

Irrigation farms such as those in the limited water situation investigated in Chapter 5 are most likely to require the use of lodging reduction techniques if the preferred irrigation strategy is to apply two ‘in-crop’ irrigations following a sowing irrigation. In this case growers would be advised to use the agronomic techniques identified in Chapter 4 (reduced plant populations, choosing lodging resistant cultivars and in-crop N application) in the event that a wet season is experienced, leading to higher yield expectations and increased lodging risk. These techniques also have relevance to irrigators in the northern region for whom land area rather than water availability is the limiting factor to production. This situation is generally found within the region in smaller, isolated irrigation fields under overhead irrigation systems, often utilising small irrigation water allocations from a bore or nearby river.

Irrigation farms in water limited situations are less likely to require the use of lodging reduction techniques if the preferred irrigation strategy is to apply irrigation water across the maximum area possible. In these cases, water non-limited yield potential is unlikely to be reached and lodging risk is generally low. Growers in this situation should therefore consider the full range of cultivars available to rainfed cropping systems in order to select a cultivar with resistance to pests or diseases that are prevalent in their particular environment, and be less concerned with the lodging susceptibility of individual cultivars.

6.1.2.4. Implementation of research

The relevance of this work to irrigated growers in the northern grains region has entailed a need for regular communication to irrigated growers and advisors during the course of the study (Peake and Angus, 2009; Peake, 2010; Peake et al., 2012; Peake et al., 2014a). Through these regular communication events, as well as advertised field days at experimental locations and regular visits to individual fields across the region, the farming community has a greater understanding of the research findings. For instance, prior to the 2014 wheat season a minor river flow allowed growers to capture a small volume of water that was not considered sufficient to hold over for the 2014/2015 cotton season. A number of enquiries were made by agronomists and growers throughout the region to determine the most recent research results from this study. As a result, lodging-resistant quick maturing cultivars were sown at appropriate seed rates in most production fields, and N was applied during the cropping season where this was feasible.

Unfortunately, some advisors and growers are still not fully aware of the pitfalls of irrigated wheat growing. During the course of the 2014 season several lodged fields of a quick maturing cultivar (Crusader) were visited on one farm in southern Queensland. Enquiries as to the agronomic management of the fields revealed that an exceptionally high plant population had been established (by sowing approximately 300 seeds m^{-2}) in combination with high levels of sowing N (>200 kg N ha^{-1}) in the two worst lodged fields, and that both fields had been irrigated heavily during tillering due to the low soil moisture status of the dry subsoil. Farms in the same region that had established plant populations of approximately 100 plants m^{-2} and used in-crop N application experienced no lodging despite using the same cultivar and similar irrigation regimes. Clearly, there is a need for ongoing education to ensure the research findings are more widely disseminated throughout the region.

The economic benefits of this research are difficult to quantify. While irrigated wheat growing is increasing in popularity, it is still a relatively small industry in comparison to irrigated cotton growing, and production data are unavailable for the specific regions of interest. Such data are generally collated for the entire Murray-Darling Basin (MDB) which is not representative of the region of interest in this study, because it encompasses extensive irrigation districts in southern Australia where irrigation of cereals is more common than in northern areas of the MDB.

An estimate of $20 million was made for lost revenue due to lodging in 2008 (Peake and Angus, 2009) but was considered conservative. This estimate was based on an area of lodged crop of approximately 70,000 hectares (at 1.5 t ha^{-1} and $200 per tonne of lost grain). However the total irrigable area in the region is over 500,000 hectares and the price of wheat at the beginning of 2008 was extremely high in historical terms (over $400 per tonne). Combined with good water availability and the need for cash flow after several successive poor seasons, it is possible that the irrigated wheat area in such a favourable wheat growing season may have been even larger. Complete prevention of lodging in similar circumstances would therefore be of substantial economic benefit to the irrigated cropping community.

6.2. Conclusions

The results of this study support the first null hypothesis that lodging constrains irrigated wheat production in the northern grains production region of eastern Australia, and that agronomic techniques can be utilised to control it. In Chapter 3, yield-gap analysis was used to demonstrate that the degree to which lodging constrained yield in the 2008 season was 1.6 t ha^{-1} on average across lodged fields, while the worst lodged field may have lost up to 5.5 t ha^{-1} of grain yield due to the disorder. In Chapter 4, a number of agronomic methods were demonstrated to reduce lodging while maintaining or even increasing grain yield. These included ‘in-crop’ N application, the establishment of low plant populations comparable to those used in rainfed cropping, and the use of a more lodging resistant, quicker maturing cultivar.

The study also supported the second null hypothesis that maximum whole-farm water productivity was achieved by partially irrigating an increased area of wheat under water limited conditions. Chapter 5 demonstrated that the most risk efficient irrigation strategies (which also generally had the greatest absolute profitability) typically involved using one-third to one-half of the farm area to grow partially irrigated wheat, while the remaining area was sown to rainfed wheat. However, full irrigation of a smaller area was identified as the most risk efficient strategy in a low rainfall environment when residual soil water was assigned the same economic value as irrigation water, when the price of water was high. The benefits of using economic water productivity rather than crop water productivity in evaluating deficit irrigation strategies were also demonstrated in Chapter 5, along with the importance of accounting for the intrinsic value of stored soil water and precipitation across the entire farm. Future evaluation of deficit irrigation strategies must begin to account for such considerations.

In establishing these findings, the APSIM farming systems model was evaluated for its suitability to simulate irrigated wheat production systems. APSIM required adjustment to predict the performance of furrow irrigated fields, which have gaps between irrigation beds that reduce light interception and potential yield. It also initially under-predicted the grain yield of crops that experienced severe vegetative N stress, but satisfactorily simulated these crops by using non-limiting N simulations or by altering the date of N application in the simulations, and increasing the maximum kernel weight to match those observed in the field. APSIM satisfactorily predicted the performance of a quick maturing cultivar (Kennedy) that experienced low levels of lodging, however the results of the irrigation scheduling study assume that lodging is avoided through the use of in-crop N application, low seeding rates and lodging resistant cultivars, as recommended in Chapter 4.

Additional research is required on a number of questions raised in the study that would further benefit irrigated grain producers in the region, including:

- Improving the ability of APSIM to predict irrigated wheat production in canopy managed fields that experience severe N stress in the vegetative phase, and understanding the importance of early season water availability in maintaining yield potential on low sowing N fields.

- Determining whether potential yield in the region could be higher than the levels identified herein due to (a) inherent advantages present in modern cultivars over the cultivar used in the construction of APSIM, (b) use of the canopy management technique of in-crop N application, or (c) the identification of suitable (lodging resistant) long-season germplasm.

- Determining the relative importance of environmental conditions (including soil conditions and irrigation management variables) during different crop stages in the development of lodging risk.

- Re-assessment of the value of stored soil water at the end of the irrigated wheat season, by assessing its value to subsequent crops.

Additional research is underway in order to begin answering these research questions.

While the 2008 irrigated wheat growing season was disappointing for a large number of irrigation producers in the northern grains region, it may ultimately be seen as a watershed for transformation of the irrigated crop mix in the region. Predictions of worsening irrigation water shortages and sustained high grain prices have fuelled increasing interest in irrigated wheat production, which is becoming a water-efficient and profitable alternative to irrigated cotton growing. Continued application of the results of this study and the subsequent ongoing research will be integral to the continuation of this transformation.

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Appendix A - Development of a rapid method for estimating the plant available water capacity of Vertosols

A.1. Introduction

Cropping systems simulation models such as APSIM (Keating et al., 2003) are increasingly used to conduct virtual experiments that assess the impact of management changes on environmental and economic outcomes in farming systems. APSIM is also being used by commercial growers as a decision support tool for in-season crop management via the Yield Prophet® online management tool (Hochman et al., 2009).

In order to use APSIM or Yield Prophet® to conduct on-farm crop simulations, it is necessary to measure the Drained Upper Limit (DUL) and Crop Lower Limit (CLL) (Dalgliesh and Foale, 1998) for the soil of the field in question. DUL and CLL represent the maximum and minimum soil water content available to a specific crop on a given soil. Together they are used to define the Plant Available Water Capacity (PAWC) of the soil, an important determinant of crop yield, and fundamental to the use of APSIM and Yield Prophet®. While the importance of understanding field PAWC is widely known, growers, consultants and researchers alike find it difficult to characterise soil PAWC due to lack of labour resources or difficulty in accessing appropriate soil sampling equipment. It is also a slow process as it takes an entire season to obtain the first set of CLL measurements, and several seasons of CLL data to generate a precise measure of CLL for single crop. An accurate method for rapid estimation of PAWC would therefore facilitate the use of crop models for on-farm management.

While pedotransfer functions have been increasingly used worldwide to predict a range of soil physical properties including wilting point and field capacity (e.g. Minasny et al., 1999; McBratney et al., 2002), only limited development of such functions has occurred on soils relevant to the northern region, and little development has occurred in relation to the interaction of the root system with soil physical properties. Some progress has previously been made in estimating CLL from DUL (Hochman et al., 2001) for specific soil types, and in estimating CLL in the presence of subsoil constraints (Hochman et al., 2007). The APSOIL database (Dalgliesh et al., 2006) uses these functions to estimate CLL values where no other data are available. However, matching a soil to one of the many available in the database is difficult without some knowledge of the soil's characteristics. This study reports on a rapid method for selecting appropriate soil characterisations from the APSOIL database, based on a hand assay of plant available water content obtained from pre-season soil samples, in conjunction with gravimetric moisture content data. An improved relationship between DUL and CLL for northern region Vertosols is also described, which was derived as part of the process of developing the rapid soil characterisation method.

A.2. Materials and methods

Rapid soil characterisation was developed through four stages: (1) development of updated relationships between DUL and CLL on Vertosols in the northern region, (2) using the updated DUL/CLL relationships to create a set of 11 'Typical Vertosol' soil types for easy selection of an appropriate soil, (3) development of a simple hand-assay for approximating plant available water (PAW), and (4) demonstration of the use of the hand assay in conjunction with gravimetric soil water data and the 'Typical Vertosols' to rapidly identify shrink-swell soils, using information gained from a single set of soil cores (typically taken prior to sowing). The use of this protocol is termed 'Rapid Soil Characterisation'.

A.2.1. Revisiting the relationship between DUL and CLL on Vertosols

While the relationship between DUL and CLL has previously been described for various crops grown on black and grey Vertosols (Hochman et al., 2001), it was decided to revisit the analysis with the now substantially larger soil data set available, and establish the relationship between DUL and CLL across the entire range of Vertosols in the APSOIL database.

Vertosols from Queensland and northern NSW (101 in total) with measured DUL and CLL for wheat, sorghum or cotton were extracted from the APSOIL database. The wheat CLL was measured in 77 of the 101 soils, but soils with CLL measured for cotton (17 soils) or sorghum (7 soils) were also included in the analysis as CLL in the top 150 cm is similar for these crops (Hochman et al., 2001). Gravimetric water content (grams of water per gram of dry soil) at DUL and CLL (i.e. DUL $_{g\ g^{-1}}$ and CLL $_{g\ g^{-1}}$) was back-calculated for each soil, by dividing the APSOIL volumetric measures of DUL and CLL (i.e. DUL $_{mm^3\ mm^{-3}}$ and CLL $_{mm^3\ mm^{-3}}$) by bulk density. (DUL and CLL for each APSOIL entry is field measured as gravimetric moisture content, but the data are stored in the database at volumetric water content, hence back-calculation was necessary to regenerate the original gravimetric data). Linear regressions between CLL $_{g\ g^{-1}}$ and DUL $_{g\ g^{-1}}$ were then conducted for each individual depth layer. Depth layers used for each soil characterisation were the standard APSOIL configuration of 0-15, 15-30, 30-60, 60-90, 90-120, 120-150 and 150-180 cm below the soil surface.

A.2.2. Consolidation of data into 11 'typical' soil types

The large number of soil types in APSOIL makes it difficult to sort through and identify the best soil type to use in an individual field crop simulation. A range of 'typical' Vertosols was generated from the APSOIL database and ranked from highest to lowest PAWC, simplifying the selection of an appropriate soil for 'one-off' or pre-characterisation simulations. The 104 soils were sorted according to DUL $_{g\ g^{-1}}$ of the 0-15 cm depth layer. Soils with similar DUL $_{g\ g^{-1}}$ were grouped and the mean of DUL $_{g\ g^{-1}}$ was calculated across each group for individual depth layers thus creating eleven DUL $_{g\ g^{-1}}$ soil profiles. Each group of soils had a range of less than 0.033 $_{g\ g^{-1}}$ for DUL $_{g\ g^{-1}}$, and soils were grouped such that the PAWC of one typical soil differed from the next typical soil in the sequence, by 10-20 mm.

CLL $_{g\ g^{-1}}$ for each typical soil was then generated using the linear relationships between DUL $_{g\ g^{-1}}$ and CLL $_{g\ g^{-1}}$ for individual soil layers (section A.2.1.). Bulk density of each layer was derived from the existing relationship described by Gardner (1985) and also used by Dalgiesh and Foale (1988), using the air-filled porosity of 0.05 of Gardner (1985) which applies to a greater range of Vertosols.

A.2.3. The development of a hand assay to assess plant available water and match gravimetric data to the most appropriate 'Typical Vertosol'.

The use of APSIM or Yield Prophet® to simulate production from a field requires sampling at (or near) sowing to measure soil water content and soil mineral N status. The use of a simple hand assay at this time to rate the soil moisture content of the soil gives additional information that can be used to identify an appropriate soil type from the APSOIL database.

A gravimetric measurement of sowing soil water (measured across multiple depth layers) may be dry (close to CLL), wet (close to DUL) or intermediate. If this relative wetness is unknown, the same gravimetric moisture content data may logically fall close to DUL on a low PAWC soil, or close to CLL on a high PAWC soil, depending on the bulk density of the soil. However, by estimating whether the soil is wet, intermediate or dry using the hand assay, the gravimetric soil water data can be matched to a Typical Vertosol. This is done by comparing the results of the hand assay with the relative position of volumetric soil water data (determined by multiplying the gravimetric data with bulk density of the Typical Vertosol under consideration) on PAWC graphs for a range of Typical Vertosols (e.g. Figure A.2.). Through trial and error, a hand assay was developed for use when taking soil cores for starting soil water (Table A.1). While it is only designed for use on clay soils, different rules could potentially be developed for different soil textures.

Table A.1. Rules for estimating soil moisture status of vertosols using a hand assay.

Estimated soil moisture (volumetric water content)	Soil properties during hand assay
0% (at, or below CLL)	Soil core is very hard, barely able to create thumbnail imprint
25%	Soil core can be broken easily with one hand into pieces but doesn't crumble easily
50%	Soil core is crumbly – when compressed with one hand it Crumbles easily and feels moist
75%	Soil core is malleable and adhesive – when compressed it forms a ribbon rather than crumbling
100% (at, or above DUL)	Soil core is very malleable and feels sticky or 'squishy'

A.3. Results and discussion

High correlations were observed between CLL $_{g\,g^{-1}}$ and DUL $_{g\,g^{-1}}$ for individual depth layers across the 101 soils in the database (Table A.2, Figure A.1). However, in some soils, particularly in the 120-150 and 150-180 cm depth layers, measured CLL $_{g\,g^{-1}}$ was frequently equal to DUL $_{g\,g^{-1}}$ (data not shown). It is also probable that in shallower layers, measurement error has skewed the CLL measurement in the direction of DUL in some soils due to delays in installation of rain-out tents, poor crop nutrition, or runoff infiltrating under the rain-out tents prior to sampling. As

Table A.2. Regression equation and r^2 value for the relationship between CLL $_{g\,g^{-1}}$ and DUL $_{g\,g^{-1}}$

Depth Layer	Regression equation	r^2
0-15 cm	= 0.4601*DUL + 0.0186	0.85
15-30 cm	= 0.5116*DUL + 0.0103	0.84
30-60 cm	= 0.5869*DUL + 0.0008	0.85
60-90 cm	= 0.5804*DUL + 0.0206	0.86
90-120 cm	= 0.6532*DUL + 0.0328	0.81
120-150 cm	= 0.6899*DUL + 0.0427	0.87
150-180 cm	= 0.8532*DUL + 0.0244	0.89

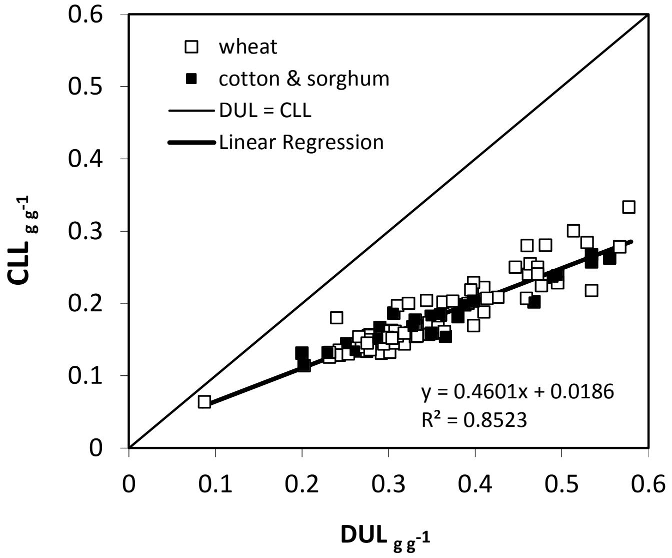

Figure A.1. CLL $_{g\,g^{-1}}$ vs. DUL $_{g\,g^{-1}}$ for the 0-15cm layer

such, the regression line may not represent the lowest (or boundary) CLL applicable across a range of soil textures, particularly in the deeper layers. Further work is necessary to develop a CLL 'boundary' function, and a predicted CLL response to subsoil constraints similar to that developed by Hochman et al. (2007).

Using the Typical Vertosols greatly simplifies the identification of appropriate soils for use in situations where a full soil characterisation is not available. Figure A.2 demonstrates the use of rapid soil characterisation to match sowing soil water content with typical PAWC graphs for two soil types. Sowing soil water data and a matched Typical Vertosol PAWC are displayed along with the CLL measured for the field.

The measured CLLs show greater variability between depth layers than the typical CLLs, as seen in Figure A.2. Accurate determination of CLL requires measurements to be made over multiple seasons, as the pattern of water extraction down the soil profile can vary with the variable seasonal rainfall patterns. It is possible that where the Typical Vertosol differs from CLL measured in a single season, the Typical Vertosol values may actually provide a better estimate of the underlying soil characteristics.

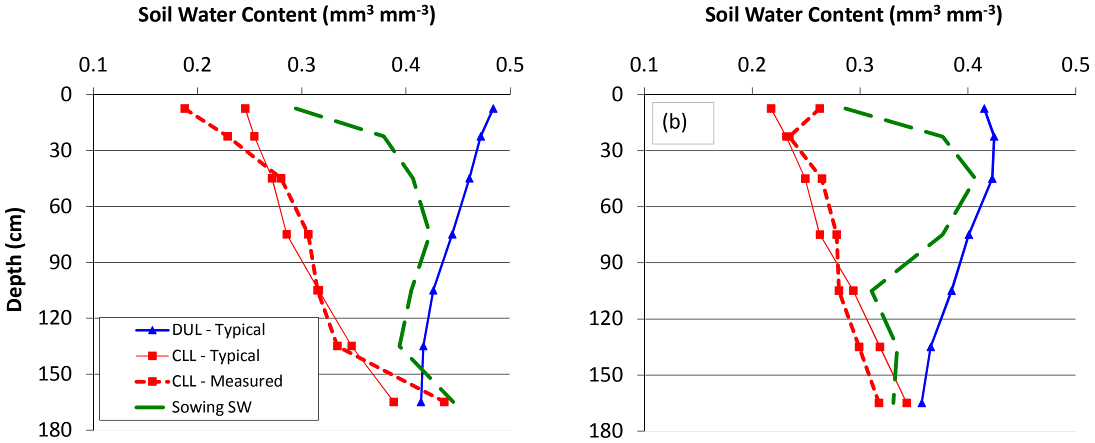

Figure A.2. Typical PAWC graphs matched to sowing soil water content and measured CLL using Rapid Soil Characterisation at (a) Brookstead and (b) Collarenebri.

Assessment across 4 soil types where hand assessments of starting soil water were conducted and CLLs were measured, showed good agreement between predicted and estimated plant available water at sowing (PAW) with a 1 mm, 7 mm and 20 mm difference between estimated and measured PAW in three of the soils. In the fourth soil a 44 mm difference between estimated and measured PAW was observed, however 34 mm of this difference occurred in layers deeper than 90 cm and in the presence of a subsoil constraint (data not shown).

A.4. Conclusions

Accurate new relationships have been developed that allow the prediction of CLL from measured DUL across a wide range of Vertosols in the northern region. Where soil characterisations are unavailable, a hand assay coupled with gravimetric water content can be used to match any Vertosol with one of 11 Typical Vertosols for use in APSIM simulations, a process termed ‘Rapid Soil Characterisation’. Further work is necessary to (1) test the use of this method more widely with inexperienced operators, and (2) to add a subsoil constraints adjustment to CLL. This is pertinent particularly in deeper soil layers where the CLL-DUL regression line of best fit (e.g. Fig. A.1) currently represents the average relationship for soils both with and without subsoil constraints, rather than CLL in the absence of subsoil constraints.

A.5. Appendix A - References

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Appendix B – Parameterising APSIM simulations to account for reduced light interception in furrow irrigated fields.

B.1. Introduction

While recent irrigation efficiency initiatives have prompted more growers from the northern grains region to install centre-pivot or lateral-move (CPLM) irrigation systems for increased water productivity, the majority of the irrigated cropping area in the northern grains region has been developed as furrow irrigated fields.

Typically, the use of furrow irrigation requires that the furrow between raised beds remains unplanted to a wheat crop, to allow the unrestricted flow of water down the furrows. This was observed in distinct furrow gaps (Section 3.2.3, Figure 3.1) in 11 of the 13 furrow irrigated fields monitored in 2008 and 2009 (Table 3.1a) that meant these crops did not intercept all of the solar radiation available during the cropping season.

Solar radiation is more likely to be the limiting factor to crop yield in irrigated fields compared to rainfed fields, given the abundant supply of water and fertiliser in irrigated crop production. Hence, it was important to have a capacity in the APSIM simulations to reduce light interception in furrow irrigated fields.

It was beyond the scope of this dissertation to measure skip row light interception in each field and develop a new APSIM routine for modelling light interception in response to varying canopy archictecture of furrow irrigated wheat. Field latitude, furrow alignment (in relation to the suns trajectory over the north-south axis), and the precise width of the furrow gap were all variables that differed between fields, that together create a complex interaction beyond the scope of this dissertation to model.

Thus it was decided to (1) confirm whether increased furrow gap area was associated with decreased grain yield, and (2) approximate the effect of reduced light interception on the fields using a pre-existing APSIM function that was originally developed for ultra-wide row sorghum (Whish et al., 2005).

B.2. Background: The APSIM 'skip_row_factor' parameter

In APSIM, the standard formula for estimating light interception is as follows:

$$\text{Cover\_green} = 1 - e^{-kl}$$

where

Cover_green = the proportion of ground area 'covered' by green (photosynthetically active) leaf, which is equal to the proportion of solar radiation intercepted on a given day in the APSIM simulation.

e = Euler's constant, the base of the natural logarithm

k = the extinction coefficient (constant)

l = LAI = the Leaf Area Index of the crop

This formula for calculating light intercepted by the crop assumes that leaf area is randomly horizontally distributed, an assumption which does not hold in a skip-row sorghum crop or furrow irrigated wheat crop where some of the light intercepts the ground between rows.

The function originally developed for sorghum (Whish et al., 2005) modifies the equation to:

$$\text{Cover\_green} = (1 - e^{-kls})/s$$

where the new variable 's' is the 'SKIPROW' factor from the APSIM sorghum module. The SKIPROW factor ranges between 1 (when no skip-row effect is modelled), and 2 for a 'double-skip' sorghum crop (where 2 adjacent rows are sown, and the next two adjacent row positions are not sown). The effect of the variable 's' is two fold:

(1) as the denominator of the equation it reduces the asymptote of the curve such that maximum light interception can be no greater than 1/s, and

(2) it modifies the shape of the exponential curve (determined by the LAI and extinction coefficient) to account for the reduced ground area covered by the crop, i.e. the increased concentration of plants on a smaller ground area means the light interception within that area will increase more rapidly.

In the APSIM 'plant' module that is used when conducting wheat simulations, the parameter 'skip_row_factor' is implemented slightly differently to the 'SKIPROW' factor in the sorghum module, in that the user specified value is transformed by adding 2, then dividing by 2. This requires the user to set the value for 'no effect' at zero (equivalent to setting the sorghum 'skip_row_factor' equal to one).

B.3. Materials and Methods

B.3.1. Overview

The 'skip_row_factor' parameters for this study were developed in a three stage process. In the first stage, experiments were run comparing the grain yield of two metre beds, one metre beds, and crop area with no furrow gaps to determine the decrease in grain yield that could be related to increased furrow gap area.

In the second stage, reduced light interception due to the furrow gaps in these fields was calculated and combined with observed hourly solar radiation data measured at Gatton in a previous experiment, to calculate the proportion of daily solar radiation lost during the midday hours when the sun was reaching the ground in the furrow gap. The final stage involved the calibration of 'skip_row_factor' parameters so that they reduced light interception by the amounts calculated in stage one, and testing that these reductions caused an appropriate reduction in grain yield in the calibration fields.

B.3.2. Determining the effect of increased furrow gap area on grain yield

Two experiments were used to demonstrate the amount of grain yield lost to increased furrow gap area. The first was from Field 17b, which was the low sowing N (canopy managed) experiment that used the cultivar Kennedy at Gatton in 2009 (Table 3.1). This experiment (briefly discussed in Chapter 3 and described in detail in Chapter 4) included a comparison between one metre and two metre beds. Only the canopy managed (low sowing N) Kennedy field was used from the 2009 experiments, as it was the cultivar × N regime combination where the comparison between one metre and two metre beds was least likely to have been affected by lodging. As discussed in section 4.2.1., the plot configuration in this experiment consisted of 7 rows sown over a distance of 1.4 m, with 60 cm 'furrow' gaps

The second experiment was a nitrogen (N) × cultivar experiment conducted at Gatton in 2012 on a similar soil to the 2009 experiment, which has not been discussed elsewhere in this dissertation. This experiment was sown to four cultivars and two fertiliser N regimes (in-crop N application vs. N applied at sowing), with both N regimes receiving a total of 265 kg ha^{-1} of N prior to anthesis. Plot configuration was slightly different to the 2009 experiment, with 7 rows sown over a distance of 1.5 m with 50 cm furrow gaps, and 14 m long plots to allow for larger biomass samples to be taken. The experiment was fully irrigated, and was managed to be disease and water non-limiting. Plots were two metres wide and thus mimicked a 2 m irrigated bed configuration. Biomass cuts were taken at harvest such that one metre lengths of the three rows in the middle of the plot were harvested separately to one metre lengths of the two outside rows on either side of the plot. The grain yield of the three centre rows was first measured separately, then combined with the grain yield from the outside rows to also allow measurement of yield across the entire plot (incorporating the effect of furrow gap). Thus the grain yield of the three centre rows was equivalent to a solid (or gap-free) crop row configuration (such as those used under CPLM irrigation), while grain yield from the entire quadrat was equivalent to a two metre bed configuration.

The 2012 experiment was aligned identically to the 2009 experiment, slightly askew (5 degrees) from a north-south alignment, ensuring that sunlight penetrated the furrow gaps during the middle of the day.

B.3.3. Calculation of reduced light interception for north-south aligned furrow gaps

B.3.3.1. Trigonometric calculation of ground area intercepting solar radiation.

Crop height observations and the measured width of the furrow gap were used in combination with the calculated position of the sun to determine (1) the time of day that sunlight would first reach the soil surface in the furrow gaps, and (2) the amount of the furrow gap remaining in shade at the end of each hour.

Observations taken from the 'simulated' raised beds at Gatton, 2009, indicated an average crop height of 60 cm between floral initiation and anthesis. While the actual furrow gap (the distance between the outside crop rows of adjacent beds at ground level) was 60 cm, the 'effective' furrow gap was determined as 50 cm after adjustment for the crop tillers that leaned into the actual furrow gap. Day-length was approximately 12 hours throughout the critical stem elongation phase during winter, meaning that the sun angle changed 15 degrees each hour of the day. This resulted in incomplete light interception in the furrow gap for approximately 2.5 hours each side of the sun’s zenith (Table B.1) for north-south configured beds.

Table B.1. Calculation equations used to develop reference times for the movement of shaded zones within furrow gaps prior to the suns zenith, for north-south configured beds.

Time	Equations
Beginning of shadow recedence: equates to 9.21am	Tan *x* = 60 cm / 50 cm =50.2° (50.2° / 90° * 6 = 3.34 hrs after sunrise)
10am equates to 34.6 cm of shadow = 15.4 cm of sunlight intercepting the ground within the furrow gap.	4 / 6 hrs since sunrise = 0.666* 90° = 60° sun angle = Tan 60 = 60 / *x* = 34.6 cm
11am equates to 16.1 cm of shadow = 33.9 cm of sunlight intercepting the ground within the furrow gap.	5 / 6 hrs since sunrise = 0.8333* 90° = 75° sun angle = Tan 75 = 60 / *x* = 16.1 cm
12pm equates to 50 cm of sunlight intercepting the 50 cm furrow gap	

Calculations conducted for the 2012 experiment (not shown) used the same average crop height of 60 cm, but a narrower effective furrow width of 40 cm to correspond with the actual (ground level) furrow gap of 50 cm.

B.3.3.2. Calculation of hourly and daily solar radiation interception

The total solar radiation lost to the crop was calculated for a 40 and 50 cm effective furrow gap in both a one metre and two metre bed system.

Hourly solar radiation data were obtained from a previous experiment at Gatton in winter 2006 (Peake et al., 2008). Data from Table B.1 were used to determine what proportion of solar radiation was lost to the furrow gap on an hourly time step, by linearly reducing the solar radiation recorded for each hour of the day by the average amount of ground within the furrow exposed to sunlight within that hour. For example, between 10 and 11am, each 50 cm effective furrow gap was calculated to be in 25 cm of shadow (the average of 34.6 and 16.1 from Table B.1). Therefore the amount of radiation not intercepted by a 2m bed configuration during this hour is 25 cm / 200 cm (or 12.5% of the ground area). Thus solar radiation intercepted by the crop between 10 and 11am was calculated to decrease by 12.5% in response to the 50 cm effective furrow gap. The same decrease was also applied to the solar radiation received between 1pm and 2pm.

B.3.4. Calibration of ‘skip_row_factor’ for reducing light interception

APSIM runs for the 2009 and 2012 experiments were used to calibrate the skip_row_factor to achieve the calculated reductions in light interception. Average simulated light interception from APSIM Growth Stage 25 (tillering) to 65 (anthesis) was used as the calibration metric, as the period between these growth stages is the critical growth stage for stem biomass accumulation, which determines maximum grain number (and hence maximum grain yield) in APSIM.

B.4. Results and discussion

B.4.1. The effect of increased furrow gap area on grain yield

As discussed in Chapter 4, the one metre beds in the canopy managed experiment had 6% less grain yield than the two metre beds on average across cultivars and management regimes. However when the Kennedy low sowing N field was considered separately to avoid the influence of lodging that was more prevalent in the other experiments, one metre beds yielded 9% (0.6 t ha^{-1}) less than two metre beds, with water, nutrients and lodging not considered limiting to crop yield. This grain yield increase was entirely due to the significant ($p<0.05$) decrease in grain number (also 9%) in the one metre beds, as kernel weight was not significantly different ($p>0.05$) between bed configurations. The one metre bed configuration lost twice as much ground area to furrow gaps (1.2 m) than the two metre bed configuration (0.6 m).

In the 2012 experiment, the middle three rows (uninfluenced by furrow gaps) had a significantly ($p<0.05$) higher grain yield than the whole quadrat yield that was influenced by furrow gaps on both sides. Grain yield was 8% higher in the three centre rows, on average across cultivars and N regimes (Table B.2).

Table B.2. Grain yield of centre rows vs. entire quadrats (incorporating furrow gaps) for four genotypes and two N application regimes at Gatton, 2012.

	Agronomic strategy	
Genotype	Low sowing N grain yield (t ha^{-1})	High sowing N grain yield (t ha^{-1})
Crusader		
Entire quadrat	6.85	6.64
Centre rows	7.34*	7.30*
SB155		
Entire quadrat	8.17	8.10
Centre rows	8.79*	8.42
Ellison		
Entire quadrat	6.17	5.71
Centre rows	6.82*	6.10*
Kennedy		
Entire quadrat	7.65	6.89
Centre rows	8.10	7.80*

*Significantly different ($p<0.05$)

B.4.2. Calculation of reduced light interception in north-south aligned furrow gaps

The reduction to the observed hourly solar radiation data were summed for each day from July to September. Ground-level furrow gaps 60 cm wide were calculated to reduce daily solar radiation interception by 20% and 10% in one and two metre bed fields respectively (Table B.3). When the ground-level furrow gap was reduced to 50 cm, intercepted solar radiation was calculated to be reduced by 14% and 7% respectively for the one and two metre beds (Table B.3).

Table B.3. Calculated light interception by crops grown under one metre and two metre bed configurations for a north-south configured wheat crop at Gatton, 2006.

Furrow gap size, month	Measured daily solar radiation	Calculated solar radiation intercepted $MJ\ m^{-2}$ and (% of Daily)	
	$MJ\ m^{-2}$	1m Bed	2m Bed
60 cm ground-level furrow gaps[A]			
July	14.2	11.1 (78.1%)	12.7 (89.4%)
August	14.4	11.5 (79.9%)	12.9 (89.6%)
September	19.9	16.0 (80.4%)	17.9 (89.9%)
50 cm ground-level furrow gaps[A]			
July	14.2	12.1 (85.8%)	13.2 (92.9%)
August	14.4	12.5 (86.4%)	13.4 (93.2%)
September	19.9	17.3 (86.7%)	18.6 (93.4%)

[A] The furrow gap was measured as the distance between the outside rows of two adjacent beds, at ground level.

B.4.3. Calibration of 'skip_row_factor' for reducing light interception

In order to decrease light interception in 60 cm furrow gaps (i.e. 50 cm effective furrow gaps) by 10 and 20%, a 'skip_row_factor' of 0.3 and 0.68 were required, respectively. To achieve light interception reductions of 7 and 14% (for narrower furrow gaps such as those from Gatton in 2012) a 'skip_row_factor' of 0.2 and 0.44 respectively was required. Grain yield was reduced by an almost identical percentage to the reduction in light interception in each simulation. This meant that the simulated grain yield reductions (10% and 7%) were very similar to those observed in the field: 9% for the comparison between one and two metre beds in 2009, and 8% for the comparison between solid configuration and two metre beds in 2012 when the furrow gap was slightly narrower.

B.4.4. General discussion

The results of field trials comparing different bed configurations indicated that as expected, the inclusion of north-south aligned furrow gaps of 50-60 cm was associated with reduced grain yield in irrigated wheat. The slight difference in yield reduction between years is logically attributed to a change in configuration of the research planter, which decreased the furrow gap at ground level to 50 cm in 2012. It is important to remember however, that the effect of furrow gaps on grain yield remain untested in east-west configured fields where sunlight penetrates into the furrow gap to a lesser degree in the middle of the day, due to the low position of the sun in the northern sky during late winter and early spring.

At similar latitudes to those encountered herein, Fischer et al. (2005) measured a 7% decrease in intercepted PAR in the 30 days prior to anthesis on 0.7 m beds (two rows of wheat 20 cm apart between 50 cm wide furrow gaps) compared to wheat grown without furrow-gaps, and simultaneously observed a yield decline of 12% associated with the furrow gaps. In other experiments with slightly wider furrow gaps (54 or 55 cm) on a 0.8 m bed configuration, they found grain yield differences of between 5% and 12%. These results were similar to those observed in the present study, where a 6–9% yield decline was associated with one-metre beds that had a 60 cm wide ground-level furrow gap.

Calibrated values for the APSIM ‘skip_row_factor’ function were successfully used to reduce simulated light interception and grain yield to levels comparable to those calculated and measured in field experiments in 2009 and 2011. The ‘skip_row_factor’ parameters developed for fields with a 60 cm ground-level furrow gap were ultimately used to simulate the field experiments and commercial fields from 2008 and 2009 (Chapter 3), as this furrow gap was used in most of the production fields.

B.5. Conclusion

The calibration of the APSIM parameter ‘skip_row_factor’ for reduced light interception in furrow irrigated wheat allowed the accurate simulation of observed yield reductions due to furrow gaps, without the need for a complex canopy modelling that is beyond the scope of this dissertation. However as these calibrations have been performed only on north-south configured beds, they should be considered as a maximum furrow gap effect. Further investigation is required to determine if east-west configured beds could yield more than north-south beds with an identical furrow gap due to better light interception from the low winter sun.

B.6. Appendix B – References

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