Cotton Catchment Communities CRC

FINAL REPORT

Part 1 - Summary Details

Cotton CRC Project Number: 1.04.18

Project Title: Dynamic deficits - matching irrigation to plant requirements in a variable climate

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Cotton CRC Program: The Farm

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Part 3 – Final Report Guide (due at 31st May 2012)

Background

This project focussed on developing and evaluating the concept of 'dynamic deficits' to help cotton producers improve the efficiency of use of irrigation water.

Development of new approaches to increase irrigation water use efficiency (IWUE) is critical given the increased attention to water use in Australia and predicted climate change – higher temperatures and more variable rainfall. Current irrigation strategies rely strongly on information from soil moisture probes or on schedules based on what has worked in the past for a particular field. In many instances the decision to irrigate is based on average climatic conditions to prevent plant stress and does not take into account the actual or future level of plant stress.

Climatic factors such as relative humidity and temperature can influence the demand for moisture by the crop to enable effective cooling (evaporative demand). Different levels of demand can change the water potential of the plant at the same level of soil moisture deficit. In fact, under high evaporative demand the cotton plant can experience short periods of moisture stress even when the water in the soil is close to field capacity (maximum level), because it is unable to match the rate of transpiration required to maintain effective cooling. This may create problems when pre-determined deficits are used for irrigation scheduling as they may not reliably match the plant's water requirements. Conceivably under high levels of soil moisture with high evaporative demand, plants could still experience stress which will impact on growth and ultimately yield. Hence, to maximise yield and irrigation water use efficiency, the 'deficit' for irrigation may need to be dynamic and vary with climatic conditions and soil moisture content.

A dynamic deficit approach would aim to improve irrigation efficiency by taking into account the current crop stress, the current soil moisture, and how the weather forecast affects crop stress. For example, it is common in the cotton industry in clay soils to irrigate at a deficit of 80 mm. Under average summer evaporative demand of 8 mm per day, this deficit would lead to a 10 day irrigation cycle. Under low evaporative demand of 5 mm per day, 80 mm would last for 16 days before irrigation was required. With dynamic deficits, under low evaporative demand the irrigation interval could potentially be more than 16 days and save considerable irrigation water in more humid areas and seasons, avoid waterlogging and appear as increased IWUE. A dynamic deficit approach could apply to all methods of irrigation: flood, spray and drip.

This project built on the outcomes of two previous CRC projects (1.02.05 and 1.04.08) by investigating whether the plant stress response to soil water availability changed in response to differences in evaporative demand. This required detailed studies into the interaction between soil type, soil moisture content, evaporative demand and plant stress. The confirmation of the relationship found in preliminary data from previous projects that changes in climatic conditions affect the level of stress a plant regardless of the level of soil moisture, will support the hypothesis that there is an opportunity for the deficit for optimum yield and IWUE to be dynamic.

This project developed rules for irrigation scheduling taking into account the forecasted climate and tested the validity and practicality of dynamic deficits in the field. Understanding when and by how much to vary deficits and in what regions or situations the greatest benefits of a dynamic deficit approach would be realised is important in refine irrigation scheduling and improving commercial practice for both short-term gains in irrigation water use efficiency and variability in water use in the long term.

Objectives

This project aimed to improve cotton irrigation WUE using dynamic deficits to (i) avoid plant stress and maximize yield and (ii) make the most effective use of in-crop rainfall. The final project objectives to achieve these aims were:

1. Establish rules for dynamic deficits from experiments with dynamic deficits across different sites and seasons
2. Complete climate analyses to determine the relevance of dynamic deficits in different seasons and regions to determine where a dynamic deficit approach could improve irrigated water use efficiency
3. Test and validate the concept of a dynamic deficit irrigation approach and the impact on yield and irrigated water use efficiency.
4. Collaborate with other researchers in detailed physiological studies to improve synergy in agronomy and physiology research outcomes
5. Extension of results to industry in collaboration with the Delivery and Development team

Methods

OBJECTIVE 1:

To investigate the effect of vapour pressure and evaporative demand on cotton plant moisture stress response experiments were established in four different cotton growing regions. In St George and Bourke, the experiment had two different sowing times, in Narrabri the experiment had three different sowing times to provide a wider range of soil moisture profiles at different crop stages and environmental conditions at this site. An experiment in Breeza was in collaboration with Cotton Seed Distributors.

In order to accurately capture the relationship between soil water, climate and plant stress required intensive data collection across all sites during the crop growing period. Frequent measurements of plant functions during flowering were made including plant water status (leaf water potential and stomatal conductance) and soil water; details of measurements are outlined in Objective 3. Climatic data was obtained from the Silo patch point data set for the weather station nearest to the experimental site (Bureau of Meteorology).

OBJECTIVE 2:

Detailed climate analyses to establish the relevance of dynamic deficits in different seasons and regions were completed using the SILO patched point data set (Bureau of Meteorology), Cottassist Climate Analysis Tool (CSIRO) and the cotton simulation model OZCOT (CSIRO).

OBJECTIVE 3:
The most detailed component of this project was completed at ACRI with the Dynamic Deficit experiments focusing on the plants' physiological response to irrigation treatments applied at different deficits in response to the 4-day forecast.

Two large scale field experiments were completed to determine whether applying our knowledge about the interaction between the plant, soil and climate could enable irrigation timings to be more "dynamic" based on soil water measurements and using weather forecasts of either future short term periods of high or low periods of evapotranspiration (ETo). Irrigation treatments were designed to evaluate irrigating earlier in response to high ETo, delaying irrigation timing in response to low ETo and no response to forecast for the whole season.

Two field experiments were conducted in 2009-10 and 2010-11 in Narrabri. Four treatments were applied to enable evaluation of: Control - no response to forecast for the whole season, irrigating at earlier in response to high ETo, and delaying irrigation timing in response to low ETo. The cultivar Sicot 71BRF was used in both experiments. A randomised complete block with three replicates was used. Plots were 60 m long by 16 m wide. Standard on-farm sowing and crop management practices were used.

To determine the implications of using a dynamic deficits approach, detailed measurements were taken in all three experiments including crop growth, soil moisture, plant stress and yield.

Measurements

Soil water measurements

Frequent measurements of soil water were made using neutron moisture meters and capacitance probes to calculate fraction of transpirable soil water (FTSW). Soil water was measured at approximately weekly intervals and the day prior and two days following an irrigation and following rainfall. Two access tubes were located in each plot and measurements taken at 0.20, 0.30, 0.40, 0.50, 0.60, 0.90, 1.0 and 1.2 m depths. The moisture content of the top 0.15 m of soil was determined by a calibrated impedance probe (ThetaProbe, Delta-T Devices, Cambridge UK). The depth of extraction was determined over time to be when the next layer down in the soil profile had been depleted by 5% the roots were determined to be extracting water from that layer.

Soil moisture contents obtained using the neutron probe, have been normalized using the fraction of transpirable soil moisture content (FTSW). FTSW expresses plant available soil moisture as a percentage from 0 to 100.

Plant stress measurements

Leaf water potential is the resistance to water movement within the plant, and the demands for transpiration imposed by the environment (heat load, humidity, wind, etc.). Measurement of leaf water potential (LWP) was made using a PMS model 600 pressure chamber with compression gland using the method described by Turner (1987). Pressure chamber readings were taken around solar noon approximately weekly from flowering to cut-out, on the same day as a neutron probe measurement.

Readings were conducted on the first fully expanded leaf (third from the terminal) and 2 readings per plot were conducted at each measurement.

Biomass accumulation, fruit development and retention
Starting just before first square, plant samples (aboveground) were collected from each plot approximately every 10 days. Plants were harvested from two x 1 m^2 quadrants in each plot. Total fresh biomass was measured and a sub-sample of four plants taken for partitioning and dry matter measurements. The sub-samples were partitioned into laminae, stems (including petioles), squares, green bolls (flowers and non-open bolls) and open bolls (two or more sutures on the boll dehisced). The number of each fruit type and the number of aborted fruit was recorded to calculate fruit retention. Samples were dried in an oven at 70ºC for at least 48 hours and weighed. At least seven harvests were taken over the season. The first biomass harvest was taken when squaring started (between 61 and 88 days after sowing (DAS) depending on the year) and the last after all bolls had opened (between 145-152 DAS).

Maturity, yield and yield components
Maturity (Days after sowing to 60% open bolls) was measured by hand picking all open bolls in a 2 m^2 area in all plots. The number of bolls was recorded and the seed cotton samples ginned in a 10-saw gin (Continental Eagle Corp, Prattville, AL, USA). The measurement row in each plot was machine picked and seed cotton yield, lint yields (bales/ha), gin turnout (%) and average boll size, lint per boll, (g/boll) were calculated.

Results and Outcomes
The results and outcomes relating to each objective in the project are summarised below:

OBJECTIVE ONE:
Preliminary analyses by Neilsen in a previous CRC project identified that the plant stress response to soil moisture was related to changes in atmospheric vapour pressure. To determine whether atmospheric vapour pressure (VP) can alter the plant stress response at the same soil moisture content we compiled a large data set of soil water x plant stress (using leaf water potential (LWP) as a measure) x climate experienced by the crop. This analysis includes six experiments from three previous projects (Neilsen/Brodrick and Yeates) and three further experiments from the current project. There was no data collected during the period of measurement from the field experiment in Bourke or Breeza and limited data from St George as there was no access to the field experiments in Bourke and Breeza during the measurement period and access to St George was limited due to prolonged flooding in 2010-11.

The wide variability in LWP at the same FSTW across nine experiments (Fig 1) indicated that climatic conditions were likely to be having a large influence on the level of plant stress even under the same soil water conditions. A correlation analysis of the climatic variables in these experiments showed the highest linear correlation with afternoon leaf water potential (LWP) was FSTW (0.6435), other, fairly high correlations with LWP, were Vapour Pressure (0.-.186), Vapour Pressure Deficit (-0.266), ETo (-0.258), Maximum Temperature (-0.2102), Maximum Relative Humidity

(0.266) . Those variables were also highly correlated with each other (i.e. correlations between 0.77 and 0.99), suggesting they all accounted for the same variability in LWP and one only could/should be used in the regression model. To determine whether VP could account for climatic influence on the relationship between plant stress and FTSW, VP was used in the multiple regression analysis. Accounting for changes in vapour pressure significantly improved the relationship between LWP and FTSW indicating that taking into account climate is important in understanding the relationship between soil water and plant stress.

Vapour pressure is a simple function of humidity and temperature. In meteorology, VP is used almost exclusively to denote the partial pressure of water vapour in the atmosphere. Vapour pressure is a measurement of the amount of water vapour in a volume of air and increases as the amount of water vapour increases. The water VP is directly related to the number of water vapour molecules in the air. Humans experience the sensation of 'humidity' when the vapour pressure reaches around 18 to 20 hPa, allowing for individual tolerances and acclimatisation to local conditions. The air can feel 'humid' despite the fact that the *relative humidity* doesn't convey it. For example, at 3 pm on an average January day in Broome, the relative humidity would be about 66%, but the VP would be around 30 hPa. Conversely, on a cool, foggy morning in Hobart with a temperature of 5°C, the relative humidity will be 100% but the VP would only be around 9 hPa.

To determine if there was a critical level of plant stress that we could use as a simple rule of thumb to adjust the irrigation deficit based on forecast VP we grouped data into high and normal VP. There were not enough data points to allow a low VP category to be tested. The results of this analysis found that generally, when crops experienced high VP (greater than 20 hPa) during flowering in both seasons crops were more stressed compared when they experienced normal VP (lower than 20 hPa) during flowering (Fig 1). The results also showed that only when soil moisture levels were near to field capacity there was little affect of vapour pressure.

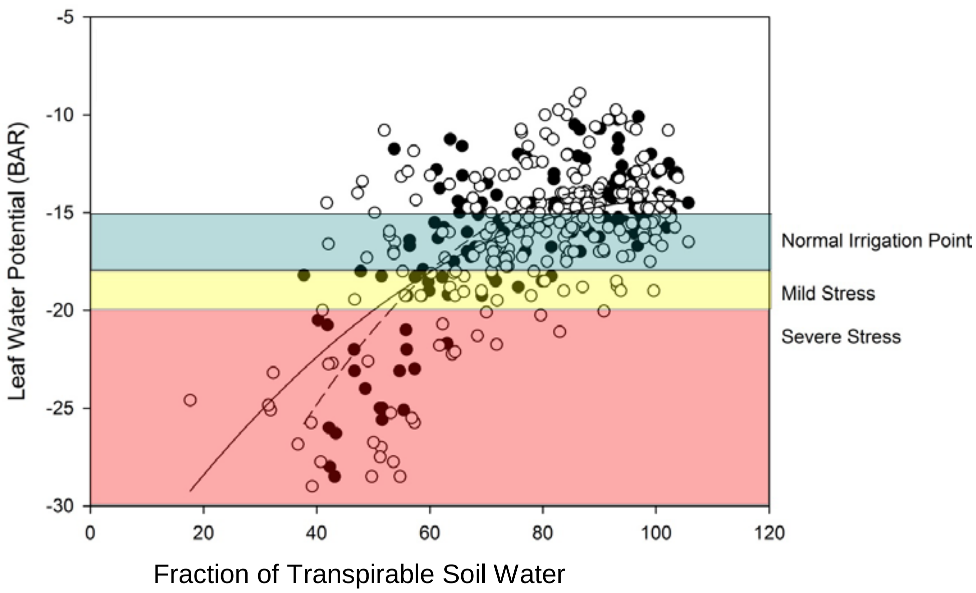

Figure 1. The effect of vapour pressure on the relationship between plant stress (leaf water potential) and fraction of transpirable soil water. LWP less than -20 indicates the plant is suffering stress. Data is grouped into high VP (VP > 20 hPa; solid circles and solid line) and normal VP (VP < 20 hPa; open circles and dashed line).

The initial relationship (using 61 data points from two experiments) by Yeates/Neilsen found the highest correlation to VP; however the collation of all the data (699 data points from 9 experiments) found that ETo and VPD had much higher correlations with FTSW and LWP. Under extremely humid or extremely dry conditions vapour pressure does not accurately reflect the evaporative demand on the plant. The Bureau of Meteorology has recently added evapotranspiration (ETo) to the 4 day forecast and has announced plans to make these forecasts freely available. Prior to these forecasts being available using ETo was not possible. ETo may be a better climatic variable to use in predicting crop stress as it incorporates a number of climatic variables including vapour pressure, temperature, wind speed and radiation and is more closely linked physiologically to crop water use as it is the combined process of both evaporation from soil and plant surfaces and transpiration through the plant. To determine whether ETo could be used instead of vapour pressure to predict crop stress we reanalysed the data using ETo in the multiple regression analysis.

Accounting for changes in ETo also significantly improved the relationship between LWP and FTSW ($p<0.015$; $r2 = 0.479$). To determine if a simple rule of thumb of "high ETo" and "low ETo" days could be used to determine the stress response, these data were grouped into high (ETo > 7 mm/day) and normal (ETo < 7 mm/day); however, there were not enough data points to allow a low (ETo < 5 mm/day) category to be tested. A simple linear regression with groups showed that LWP measured on "High ETo" days experienced greater stress at the same level of FTSW compared with "Normal ETo" days (Fig 2).

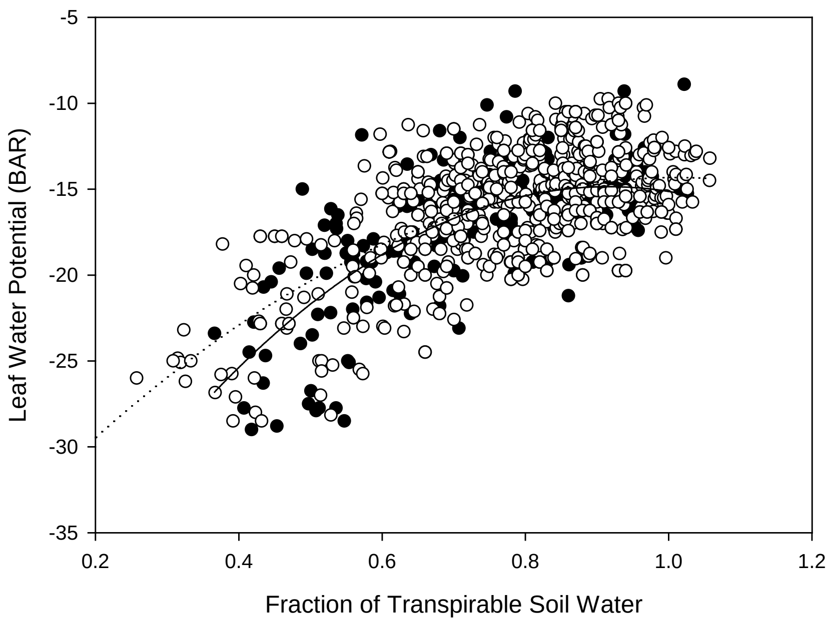

Figure 2. The effect of evapotranspiration (ETo) on the relationship between plant stress (leaf water potential) and fraction of transpirable soil water. LWP less than -20 indicates the plant is suffering stress. Data is grouped into high ETo (ETo>7mm/day; solid circles and solid line) and normal ETo (ETo<7 mm/day; open circles and dashed line).

The results of these analyses suggest that short-term forecasts of ETo may provide an indicator of potential triggers for a dynamic deficit scheduling approach. As changes in VP or evapotranspiration (ETo) affected the level of stress a plant regardless of the level of soil moisture, there is an opportunity for the deficit for optimum yield and IWUE to be dynamic, e.g. increase under mild conditions and decrease in hot/humid conditions.

OBJECTIVE 2:
A detailed analysis of historical climate data was undertaken to determine the range in vapour pressure (VP) and evapotranspiration (ETo) across cotton seasons, and how this differs across cotton growing regions. These analyses were important in determining the opportunities for applying dynamic deficits using either VP or ETo in different regions. Understanding how often a "High VP or ETo" or "Low VP or ETo" event would impact on irrigation decision making is important as taking into account the forecasted conditions is only relevant leading up to an irrigation event. To evaluate how often a high or low VP rule would be implemented across different seasons and regions we also ran a number of different scenarios using the OZCOT crop simulation model where a High or Low or completely dynamic (responding to both high and low future VP) rule was applied to enable assessment of how often a dynamic deficit approach taking into account the four day forecast would impact on decision making and how this would impact on yield and water use.

Vapour Pressure Climate Analysis
The highest average vapour pressure occurs in each cotton growing region in January and February (Fig 3 shows the monthly average across a number of cotton growing regions). As would be expected this varies significantly between years with some areas such as Bourke having some years (shown in Fig 4 as in weekly averages) where vapour pressure is much higher than the long term averages. In fact on average Bourke only has an average of 7 days in January where vapour pressure exceeds 20 hPa.

However, our analysis showed that monthly average and weekly averages did not appropriately capture the differences in vapour pressure in different cotton regions and did not allow comparison with the frequency of high or low pressure days adequately. When the frequency of days with VP >20 hPa in a summer month is calculated from historical records, the average number of days between regions differ greatly (Fig 5).

To assist in the completion of the analysis of the large historical data set, Loretta Clancy modified the CottASSIST Climate Analysis tool to include vapour pressure in the outputs of the reports. The report now returns average VP and has the functionality to set and evaluate the frequency of different levels of VP and evapotranspiration (ETo). This functionality enabled quick and detailed analysis of the number of days in weeks or months of varying levels of high or low VP to be conducted for all cotton growing regions. This will allow quick analysis of the opportunity to apply account for crop stress in the future as we refine rules for either VP or ETo thresholds.

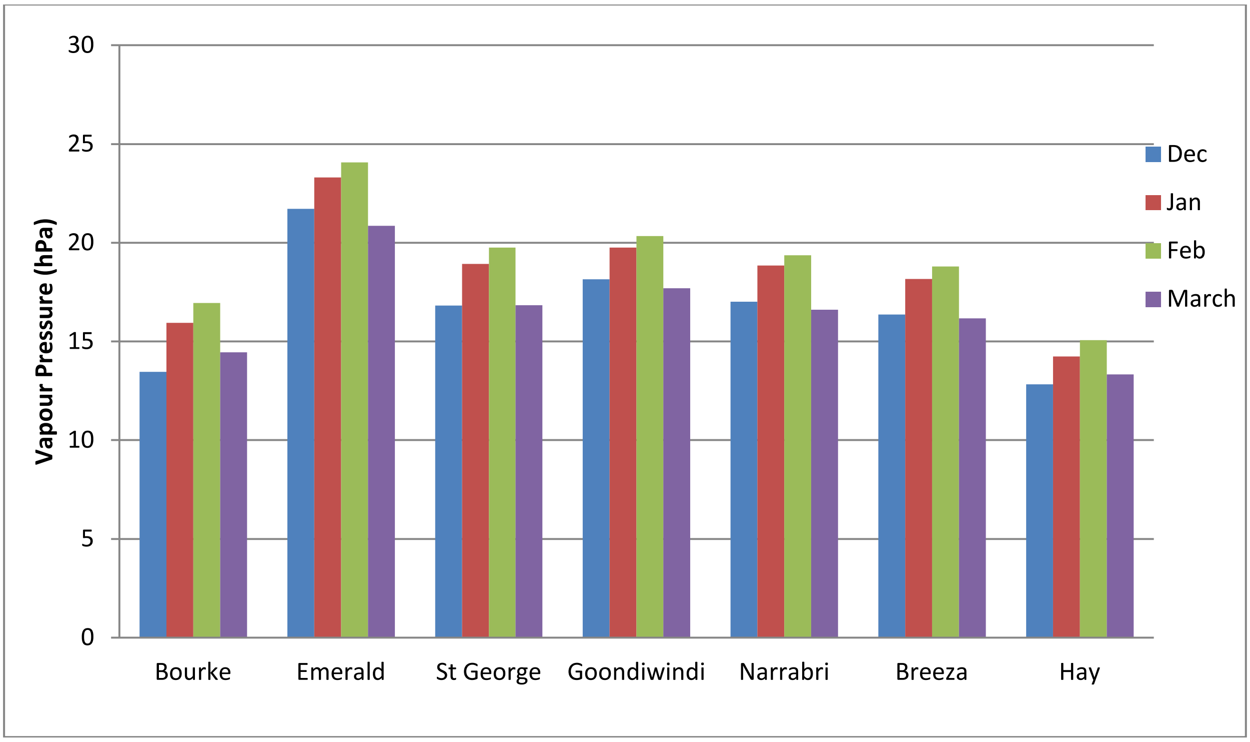

Figure 3. Monthly average vapour pressure across different cotton growing regions Dec-March 1957-2011.

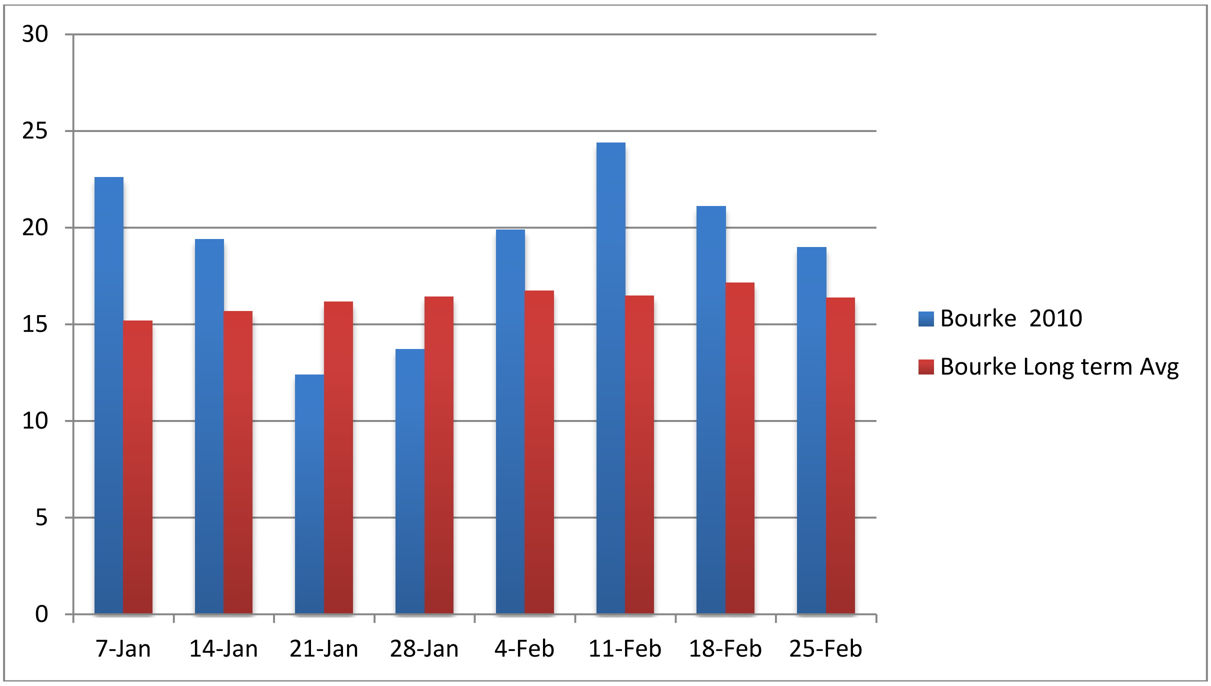

Figure 4. Weekly average vapour pressure for Bourke in 2010, and long term weekly average vapour pressure for 1957-2010.

Analysis of the long term averages of different regions showed that in all regions January and February were the months that had the highest number of days with "High VP" (days where the VP was > 20 hPa) (Fig 5). Emerald, St George, Narrabri and Goondiwindi had more than 10 days exceeding the "High VP" rule in both January and February. The number of "Low VP" days varied between regions with Bourke and Hay averaging greater than 10 days in January and February whereas warmer regions averaged 4 to 5 "Low VP" (days where the VP was <15 hPa) days in the same months (Fig 6). This analysis suggests that using a high vapour pressure rule may not accurately capture extremes in climatic variables that result in plant stress in areas which are extremely dry as vapour pressure is a measure of how humid the air is and very low humidity results in a lower vapour pressure. Bourke and Hay had very low frequency of high vapour pressure days. In fact on average Bourke has only average of 7 days in January where vapour pressure exceeds 20 hPa. Emerald had an extremely high number of "High VP" days, suggesting that in environments with high humidity a "High VP" may not accurately capture extremes leading to plant stress as because high humidity results in a high VP and does not reflect evaporative demand in these conditions.

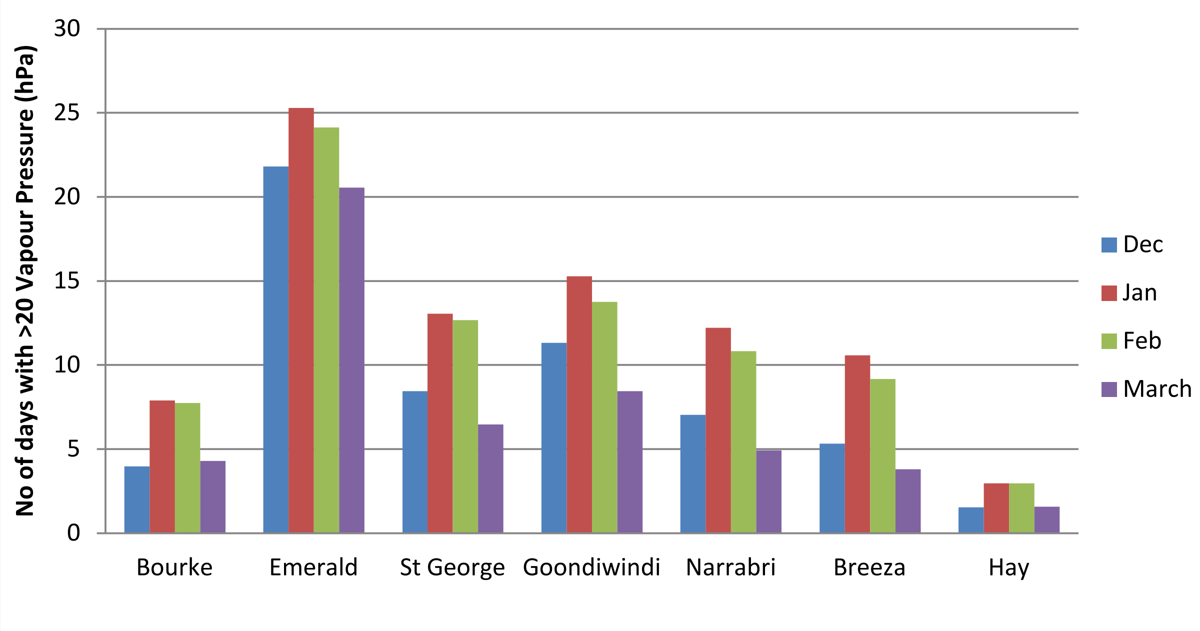

Figure 5. Frequency of days in December, January, February and March where vapour pressure exceeded 20 hPa across different cotton growing regions 1957-2011.

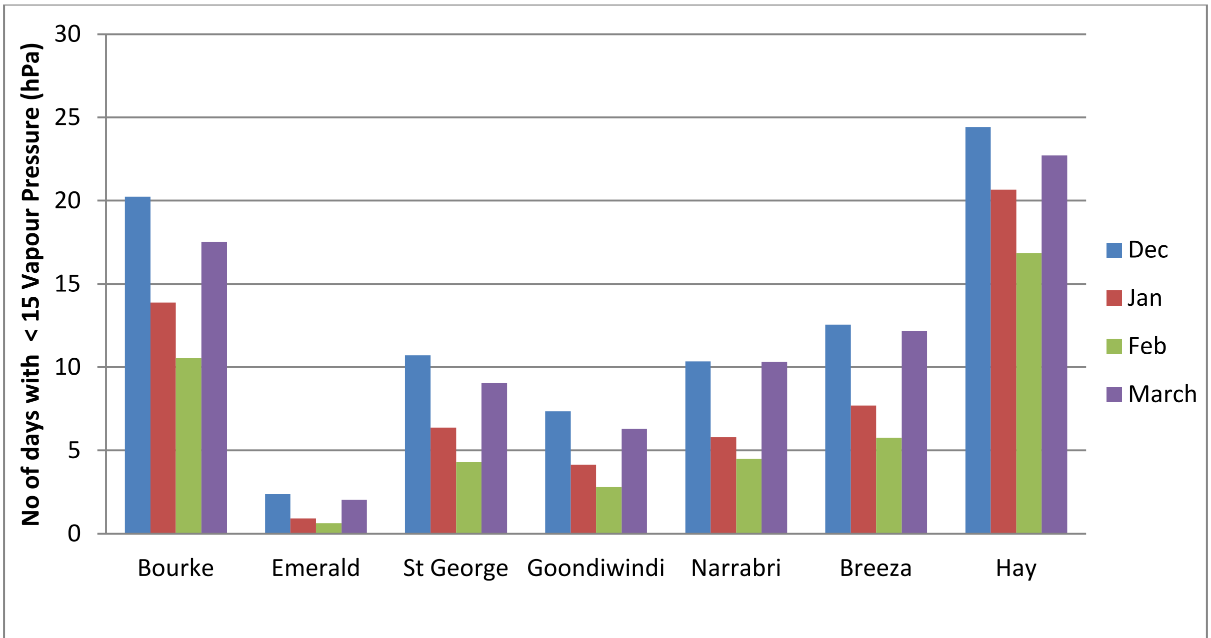

Figure 6. Frequency of days in December, January, February and March where vapour pressure was less than 20 hPa across different cotton growing regions 1957-2011.

Applying Vapour Pressure Rules with the OZCOT simulation models

The analysis of the historical climate data identified that across all cotton growing regions there is an opportunity to refine our irrigation scheduling in response to either “High VP” or “Low VP” or both. Understanding how often a “High VP” or “Low VP” event would impact on irrigation decision making is important as taking into account the forecasted conditions is only relevant leading up to an irrigation event.

To evaluate how often a high or low VP rule would be implemented across different seasons and regions we ran a number of different scenarios using the OZCOT crop simulation model where a High or Low or completely dynamic (responding to both high and low future VP) rule was applied to enable assessment of how often a dynamic deficit approach taking into account the four day forecast would impact on decision making and how this would impact on yield and water use. Regions chosen to run the simulations were those that were found to have a significant number of “High” or “Low” VP days. Bourke, Emerald and Hay were not included in the analysis as the climate analysis suggested that high vapour pressure may not accurately reflect conditions leading to plant stress in those regions.

OZCOT was modified to handle six new input parameters via its agronomy file. Critical values were specified for high and/or low VP values that represent the accumulated VP values over a four day forecast, or the average of the four day forecast values. Inputs are limited to either ‘sum’ (accumulated) values or alternatively ‘average’ values for any given simulation. Both high and low critical values were defined for a single simulation, or applied separately. If the forecast VP values exceeded the corresponding high VP critical value specified, or the VP forecast values fall below the corresponding low VP critical value, then the high or low VP adjustment factor was applied within the irrigation decision rule. Irrigations were determined within OZCOT on a daily basis when using the soil water deficit rules. The modifications to the model involved assessing if the high or low VP critical value had been exceeded and then adjusting the ‘deficit to irrigate at’ value by applying the appropriate defined adjustment factor. An adjustment factor of greater than 1 results in the ‘deficit to irrigate at’ value increasing, and so potentially delaying an irrigation. Conversely, for an adjustment factor of less than 1, the ‘deficit to irrigate at’ is reduced, and so an irrigation may be brought forward. OZCOT was modified to apply these modified rules and report instances when the rules applied altered the irrigation schedule.

These simulations allowed us to identify how often a high or low VP forecasted event was likely to coincide with an irrigation decision across different regions and using the historical data set for 50 seasons.

The outcomes of the simulations found that are more opportunities to apply a “Low VP” rule across different regions compared with responding to “High VP” (Fig 7). The highest average number of irrigations altered from the control (normal deficit) by the different scenarios were an average of 1.6 times per season in St George in response to High VP, an average of 2.9 times per season at Myall Vale (Namoi) in the fully “Dynamic” simulation where irrigations were both earlier or later in response to either high or low VP forecasts and an average 4.6 times per season in Breeza in response to low VP.

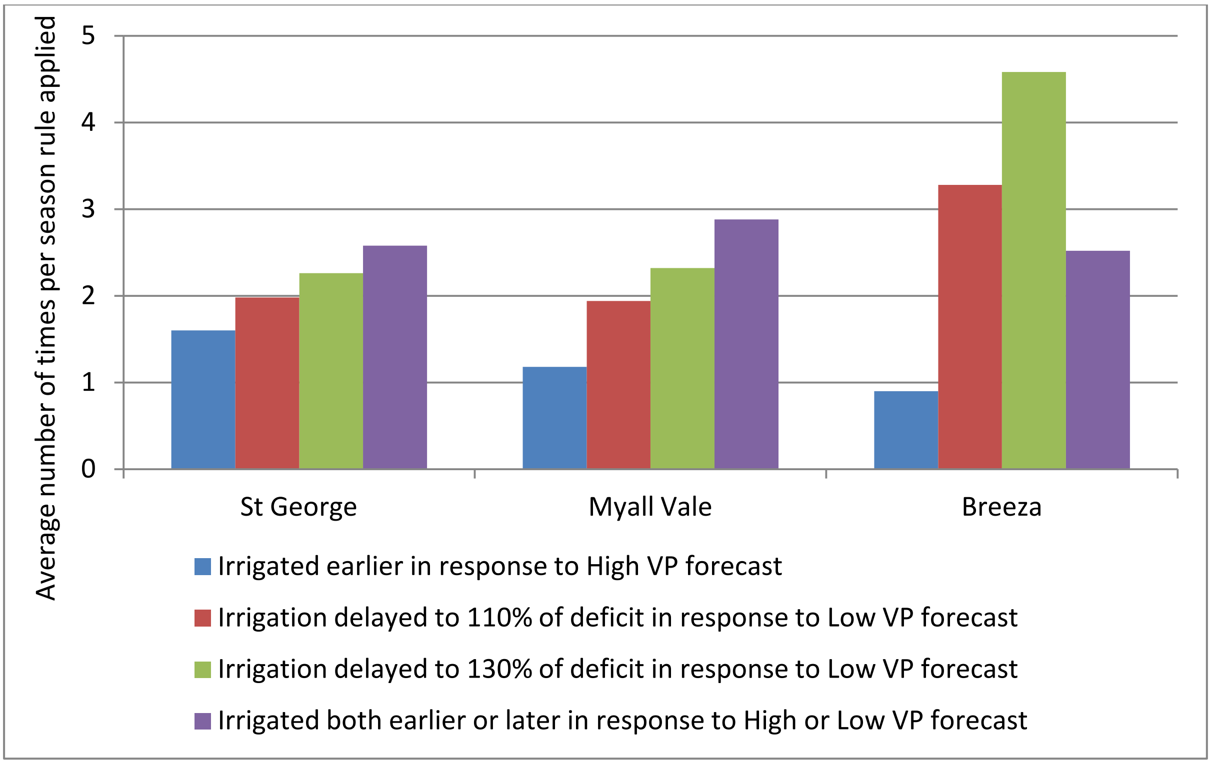

Figure 7. Average number of times per season an irrigation rule was changed in response to forecasted high or low vapour pressure (VP) using the OZCOT Model for 1960-2010.

These simulations also allowed an evaluation of how applying these rules would affect yield and water use across different cotton growing regions and seasons. For example, in St George there was not a great effect on yield in response to a dynamic deficit approach (Fig 8). There were few differences in yield to a high VP (>20 hPa) forecast or a low VP (<15 hPa) forecast. The number of irrigations was slightly higher in the High VP scenario but there were no great differences in total water use efficiency. Most seasons the control had slightly better IWUE and captured more rainfall than the High VP scenario and was not different from the Low VP

In Myall Vale, there was no yield response to either the High or Low VP rule; with only slightly higher irrigation water use efficiency when an irrigation was delayed until the deficit reached 130% of the normal deficit in response to a low VP forecast (Fig 9). This was likely due to increase rainfall capture. This analysis indicates that there are few significant responses in yield or irrigated water use efficiency when applying an irrigation rule based on a vapour pressure rule.

A sensitivity analysis of the VP threshold was completed comparing different VP thresholds. Increasing the "High VP" threshold of 20 to 25 hPa found that an irrigation would only be altered in 9 of the 50 yrs in St George; 1 year in Myall Vale and 2 years in Breeza.

Increasing the "Low VP" threshold so that irrigations were delayed if the four day forecast was for a VP <20 hPa found significant decreases in lint yield and water use efficiency (Fig 8 and 9). This result highlights the importance of taking into account the impact the climate has on plant stress when delaying irrigations.
scenario.

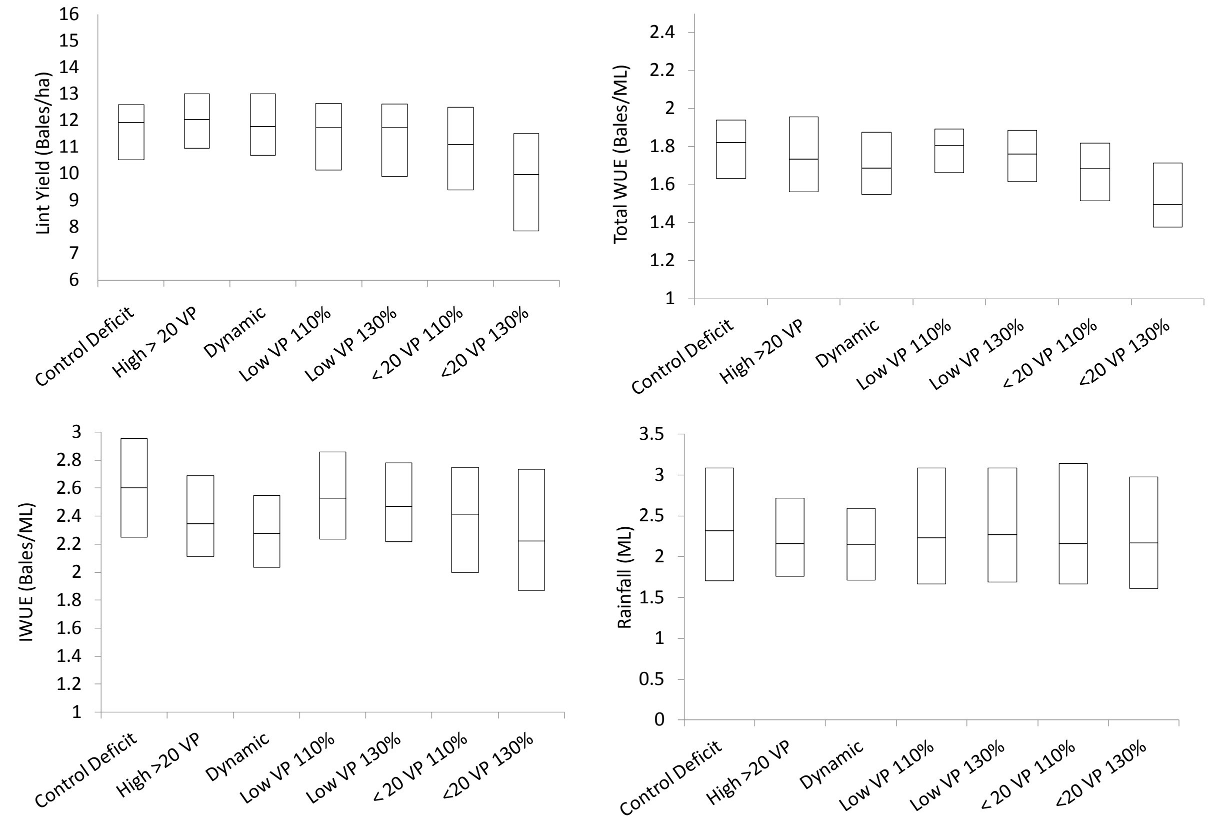

Figure 8. Box plots of lint yield, total water use efficiency (WUE), irrigated WUE and effective rainfall in response to different irrigation scheduling simulations by the OZCOT model in St. George. The control used the normal irrigation deficit (55% PAWC) for that soil type; High > 20 VP was irrigated earlier at 80% of the normal irrigation deficit for that soil type when the four day forecast was for daily average VP greater than 20 hPa ; Low VP and < 20 VP , irrigated later at 110%, and 130% of the normal irrigation deficit for that soil type when the four day forecast was for daily average VP less than 15 hPa (Low VP) or less than 20 hPa (<20 VP); Dynamic, irrigated both earlier and later in response to the four-day forecast. The horizontal line within the box indicates the median, boundaries of the box indicate the 25th and 75th percentile.

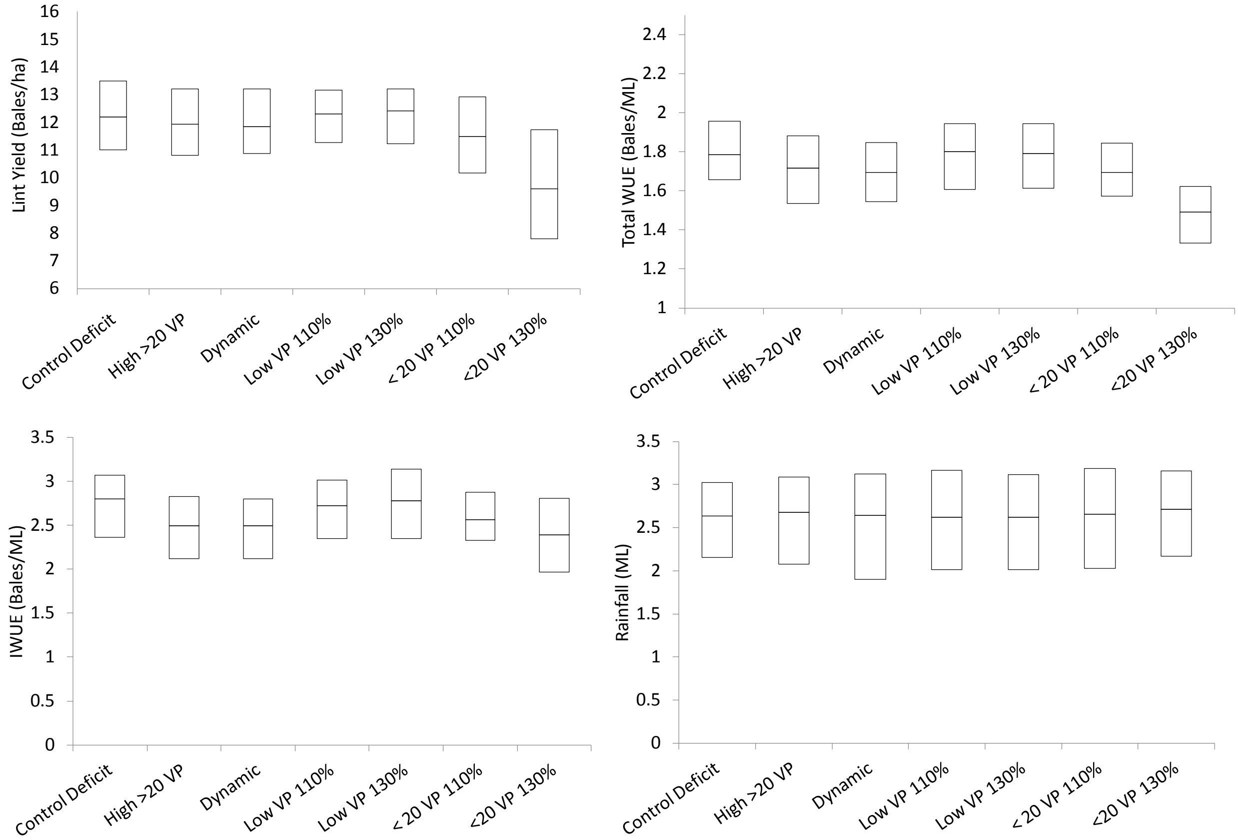

Figure 9. Box plots of lint yield, total water use efficiency (WUE), irrigated WUE and effective rainfall in response to different irrigation scheduling simulations by the OZCOT model at Myall Vale. The control used the normal irrigation deficit (55% PAWC) for that soil type; High > 20 VP was irrigated earlier at 80% of the normal irrigation deficit for that soil type when the four day forecast was for daily average VP greater than 20 hPa ; Low VP and < 20 VP , irrigated later at 110%, and 130% of the normal irrigation deficit for that soil type when the four day forecast was for daily average VP less than 15 hPa (Low VP) or less than 20 hPa (<20 VP); Dynamic, irrigated both earlier and later in response to the four-day forecast. The horizontal line within the box indicates the median, boundaries of the box indicate the 25th and 75th percentile.

Evapotranspiration Climate Analysis

The analysis of ETo found that average ETo is highest in the summer months from December to February (Fig 10). Conversely to VP, average ETo was highest in Bourke and Hay, indicating that it is more appropriate for reflecting the evaporative demand on the crop in drier environments.

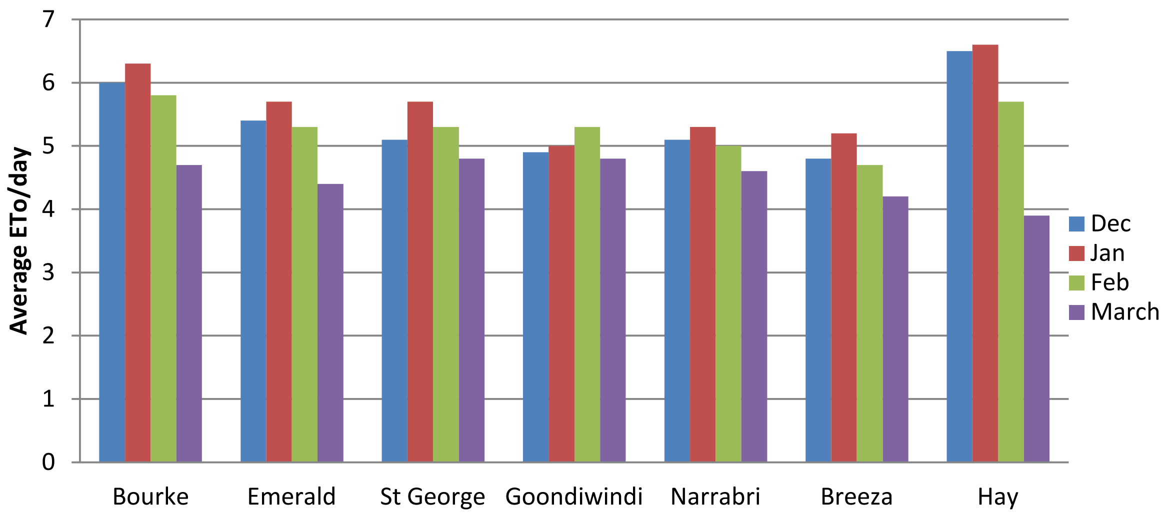

Figure 10. Monthly average evapotranspiration (ETo) across different cotton growing regions Dec-March 1957-2011.

Monthly and weekly averages masked the extremes in ETo across the different regions and seasons. Comparing the frequency of high ETo days (> 7mm ETo/day) between regions identified that there were on average at least 10 "High ETo" days in all regions except Breeza in December (Fig 11). St George, Bourke and Hay had the highest number of "High ETo" days in January and most regions had fewer "High ETo" days in February ranging from an average of two in Breeza and Emerald up to 11 in Bourke.

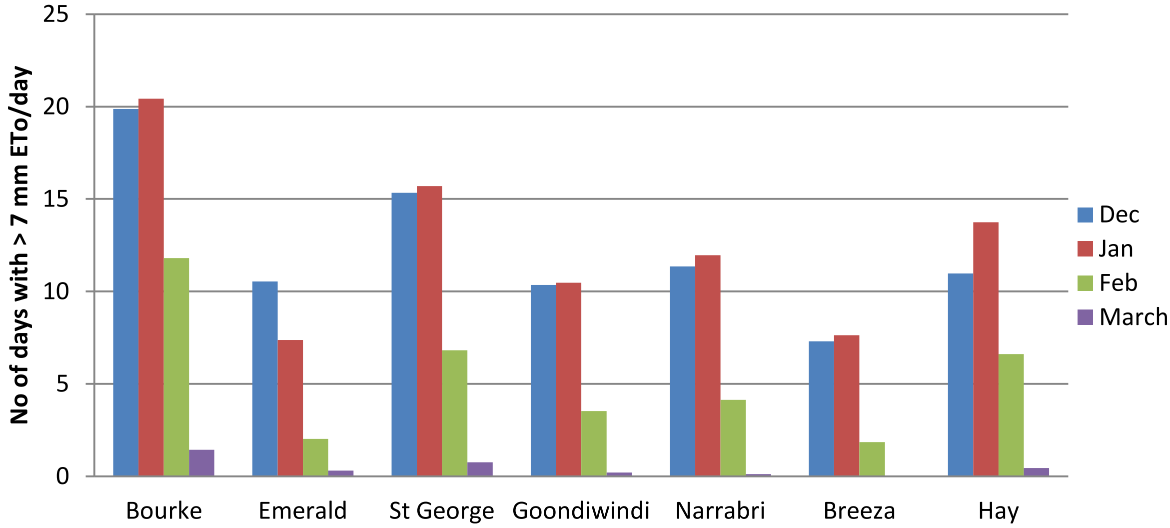

Figure 11. Frequency of days in December, January, February and March where evapotranspiration (ETo) exceeded 7 mm/day across different cotton growing regions 1957-2011.

The number of "Low ETo" days (ETo < 5mm ETo/day) was highest in Emerald and Breeza in January and February and most regions except Bourke and Hay had an average of at least 5 low VP days in those months (Fig 12).

This analysis identified that over the historical record in January and February there is likely to be an opportunity to apply either a "High ETo" or a "Low ETo" rule to irrigation decision making in most cotton growing regions. Adjusting irrigation timing in response to a "High ETo" is likely to occur more often in Bourke and Hay. Emerald and Breeza are the regions with the highest likelihood of a "Low ETo" rule being applied.

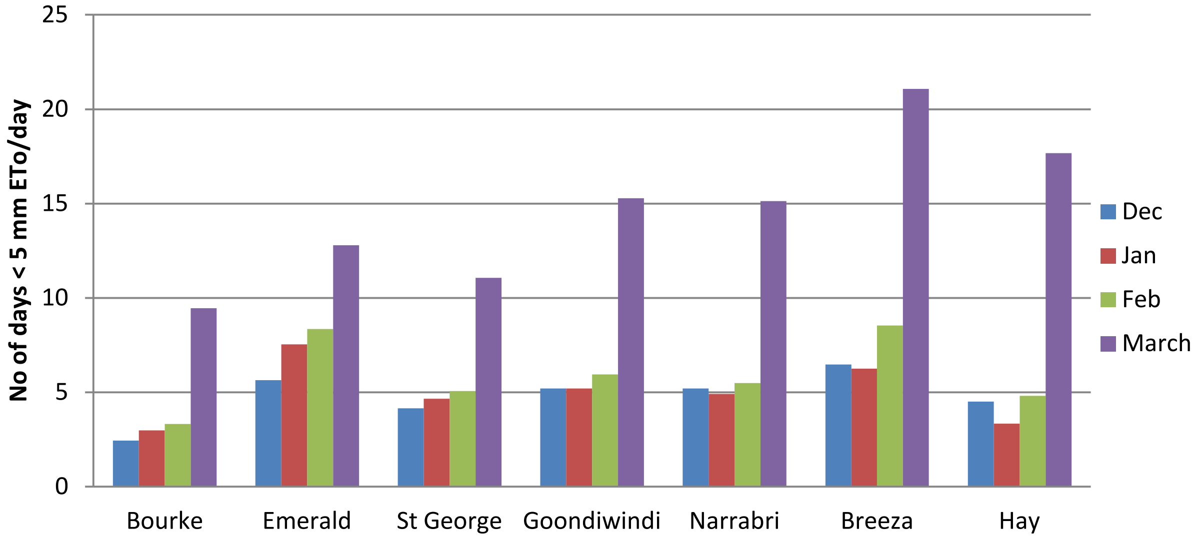

Figure 12. Frequency of days in December, January, February and March where evapotranspiration (ETo) was less than 5 mm/day across different cotton growing regions 1957-2011.

Understanding how often a “High ETo” or “Low ETo” event would impact on irrigation decision making is important as taking into account the forecasted conditions is only relevant leading up to an irrigation event. To determine what effect taking into account forecasted ETo instead of VP would have on the frequency and magnitude of changes to water use and yield as predicted by the OZCOT model, requires evaluation of whether forecasted ETo should be calculated from the SILO climate data as a input in the model or using ETo calculated by the model itself. ETo is not currently enabled in the climate input files as these have only recently become widely available in the historical climate data. An in-depth analysis using ETo and simulating different scenarios with the OZCOT model will form part of new research following on from the outcomes of this project.

OBJECTIVE 3:

Two large scale field experiments were completed to determine whether applying this knowledge could enable irrigation decisions to be more "dynamic" in optimising irrigation timings based on soil water measurements and using weather forecasts of either future short term periods of high or low periods of evapotranspiration (ETo). Irrigation treatments were designed to enable evaluation of: Control - no response to forecast for the whole season, irrigating at earlier in response to forecasted high ETo, and delaying irrigation timing in response to low ETo. A third experiment was sown in 2011/12 but flooding and frequent rainfall during flowering meant that no irrigations were applied during the measurement period. All three experiments had detailed measurements of crop growth, soil moisture, plant stress and yield to determine the implications of employing a dynamic deficits approach compared to a traditional fixed soil water deficit approach to irrigation scheduling.

Results of two years of deficit experiments

Yield and water use and plant Stress

To undertake experiments a simple rule of thumb was determined using the response of plant stress, soil water and ETo described in the results for Objective 1. Using this rule we planned to implement a total of four treatments during the course of the season. Dynamic irrigation timing was only implemented between flowering and cut-out as previous research had already determined that this is the most critical period for precise irrigation timing. Treatment 1 – was the control treatment, with irrigations scheduled at the normal 65-75 mm deficit for that soil type. Treatment 2 – was irrigated earlier than the control at a smaller deficit in response to forecasted high ETo. Treatment 3 – was irrigated later than the control at a larger deficit in response to forecasted low ETo conditions. Treatment 4 – was dynamic, with irrigations scheduled either earlier or later in response to forecasted high or low ETo conditions.

The 2009/10 season was characterised by long periods of low evaporative demand, so the season provided excellent opportunity to evaluate the impact of delayed irrigation using a low ETo forecast. In the 2009/10 experiment four treatments were applied and the dynamic treatment (4) was irrigated later than the control on two occasions (Table 1). Frequent and detailed measurements of plant water status, soil water plant growth were taken. The experiment was harvested in May and achieved high yields (experiment average of 13 b/ha) (Table 2).

There were no significant differences in yield, water use or efficiency (Table 2). While irrigations were delayed this did not equate to improvements in yield, total water use or water use efficiency (bales/ML). Irrigations were delayed up to deficits of 105 mm during late flowering compared to 78 mm, with no impact on yield (Table 1).

Table 1. Summary of irrigation treatments in the 2009/10 and 2010/11 Dynamic Deficit experiments. Plant stress (leaf water potential) is considered not stressed above -18 BAR (×) and stressed when less than -18 BAR (✓). Stress is considered mild between -18 and -20 BAR and severe when less than -20 BAR.

Treatment	Deficit control	Deficit Treatment	Early High ETo	Delayed Low ETo	Stressed in Control before irrigation	Stressed in Treatment before irrigation	Rainfall after Control and before treatment irrigation
2009/10							
2	62	51	3 days		✓ -20.2 BAR	× -16.8 BAR	
3	74	64		6 days	Too late in season for measurement of LWP		15 mm
4	78	105		3 days	✓ -19.8 BAR	✓ -22.8 BAR	
4	74	62		6 days	Too late in season for measurement of LWP		15 mm
20010/11							
2	60	45	3 days		× -16.1 BAR	× -15.4 BAR	
3	61	54		8 days	× -16.1 BAR	✓ -19.0 BAR	33 mm

The 2010/11 season provided different conditions to the previous experiment, in that irrigations did not start until January due to above average rainfall; however, the remainder of the season had very little rainfall with some distinct periods of very high and low evaporative demand. The dynamic deficit experiment in 2010/11 in Narrabri had a total of three irrigation treatments applied during the course of the season. Treatments 1 to 3 were the same as in the 2009/10 experiment. As there were fewer irrigations between flowering and cut-out in 2010/11 the "dynamic" treatment had one delayed irrigation which was the same as treatment 3.

In treatment 2, an irrigation was applied at a smaller deficit (45 mm) compared with the control in response to a high ETo forecast (Table 1). In treatment 3 in response to forecasted low ETo, irrigation was delayed 4 days to a planned deficit of 90 mm, and in that period there was 33 mm of rain which further delayed the irrigation another 4 days. This resulted in this treatment receiving one less irrigation over the season translating into irrigation water savings of approximately 0.8 ML/ha compared to the control (Table 1).

The experiment was harvested in May and again achieved high yields (experiment average of 12 b/ha) (Table 2). Statistical analysis of the results of this experiment also found that there were no differences in yield or total water use efficiency, (Table 1). The plant based measurements showed that the control treatments were more stressed compared with the earlier irrigation treatment but still remained greater than a LWP of -20 bar in the control. Importantly, the plant stress measurements in the delayed irrigation treatment showed that despite the delay of 4 days, the crop was still not showing stress (LWP of -16 bar compared with -15 bar in the control).

Neither irrigating earlier or later resulted in any yield penalty in either year. Irrigating early to maintain a higher soil moisture content during periods of high vapour pressure did result in a lower leaf water potential and hence less stress, however this did not translate into differences in crop yield. The control irrigation (normal deficit) in this experiments generally maintained the crop below a severe stress threshold (LWP > -20 bar).

Table 2. Lint yield and estimated water use for 2009/10 and 2010/11 Dynamic Deficit Experiments. Significant differences indicated by * 95% significance level; ** 99% significance level.

Treatments	Average Lint Yield (bales/ha)	Irrigation Water Applied (ML)	Effective Rainfall (ML)	Total Water (mm)	Bales/ML total water	Bales/ML applied
2009/10						
1 Control	13.0	3.26	3.19	680.8	1.9	4.0
2 Smaller Deficit (High ETo)	14.2	3.24	3.20	678.2	2.1	4.4
3 Larger Deficit (Low ETo)	13.7	3.28	3.20	679.2	2.0	4.2
4 Dynamic	14.5	3.66	3.20	725.8	2.0	4.0
L.S.D	2.5	***0.30**	0.09	41.4	0.4	0.9
2010/11						
1 Control	12.7	3.92	2.84	735.9	1.73	3.3
2 Smaller Deficit (High ETo)	12.1	3.65	2.88	731.2	1.65	3.3
3 Larger Deficit (Low ETo)	11.5	3.11	2.90	682.1	1.68	3.7
L.S.D	1.8	****0.34**	0.06	***43.15**	0.2	****0.2**

Biomass accumulation, fruit development and retention

There were few differences in biomass accumulation, fruit development and retention in 2009/20010 dynamic deficit experiment in response to altering the deficit in response to forecasted ETo. The only statistically significant differences found was lower peak LAI and fruit numbers (fewer squares) in the dynamic treatment (irrigations delayed twice during the measurement period in response to forecast low ETo), final node number was lower and the treatment reached 60% open bolls (maturity) 7 days earlier than the control treatment (Fig 13). The leaf water potential measurements indicated that the plants in that treatment were experiencing severe stress prior to the first delayed irrigation (-22.83 BAR) (Table 1). Fruit numbers recovered in the dynamic treatment after the next irrigation and final yield was not significantly different to the control. Similarly, where the irrigation was applied earlier in response forecasted high ETo and the control experienced mild stress before irrigation that irrigation treatment had higher peak fruit numbers but the control compensated for this difference within a week after the control was irrigated. This loss of squares mostly likely contributed to higher micronaire found in treatment 4 as fewer immature fruit would have been harvested. There were no other differences in fibre quality found in the 2009/10 experiment.

There were no differences in biomass accumulation, fruit development and retention in 2010/11 dynamic deficit experiment in response to altering the deficit in response to forecast despite delaying the irrigation in Treatment 3 nine days. The leaf water potential measurements before this irrigation remained > -20 BAR indicating that the 33 mm of rain in the interval between the control irrigation and the treatment being irrigated was sufficient to prevent crop reaching the severe stress threshold that was reached in the 2009/10 experiment (Table 1). There were no differences in any fibre quality parameters measured in the 2010/11 experiment.

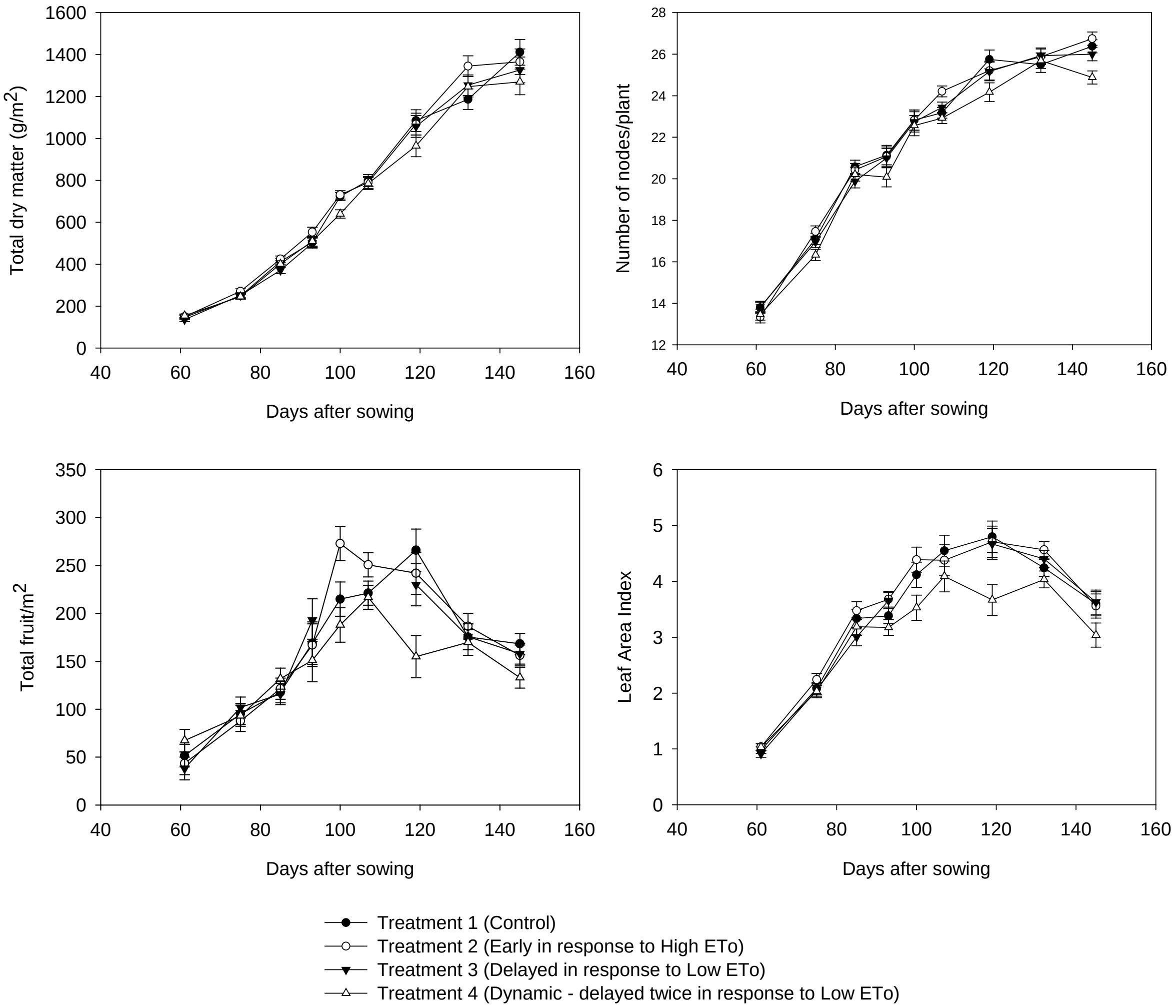

Figure 13. Total dry matter, node numbers, fruit numbers and leaf area index in response to different treatments in the Dynamic Deficit experiment 2009-2010.

The lack of a response to the high ETo, earlier irrigation treatment, needs further investigation, as does the high variability in the response of LWP to soil water. One of the difficulties in using leaf water potential as an indicator of plant stress is that it is still an average, discrete method of sampling, and there is a need for continuous monitoring of plant stress to determine whether accounting for current and future crop stress in irrigation scheduling can bring greater savings in water use. Continuous monitoring would allow monitoring of the timing and duration of stress, the level of stress and identification of any acclimation to stress by the crop. Future research will be focussed on continuous monitoring of crop stress to develop our understanding in greater detail of the affect of different scheduling approaches on the crop. This will enable us to develop and refine a relationship to predict crop stress in response to the forecasted climatic conditions.

Evaluating OZCOT's ability to model the Dynamic Deficit experiments

To evaluate the ability of OZCOT to simulate yield, total water use efficiency and irrigated water use efficiency in response to changes in irrigation scheduling based on the rules of High or Low ETo, the models outputs were compared with the results of the dynamic deficit experiments in 2009/10 and 2010/11 (Fig 14). When comparing simulated seasonal water use, water use efficiency, and lint yield using OZCOT with measured data from the Narrabri experiments, the model provided a reasonable estimate of lint yield except for the dynamic treatment in 2009/10 where it under-estimated lint yield, however it tended to over-estimate water use, in 2009/10 the model overestimated irrigated water use and in 2010/11 both irrigated water use and effective rainfall were over estimated. As a result of over estimating effective rainfall and total and irrigated water use efficiency were under-estimated but similar patterns in irrigated water use efficiency in response to the different irrigations treatments were simulated.

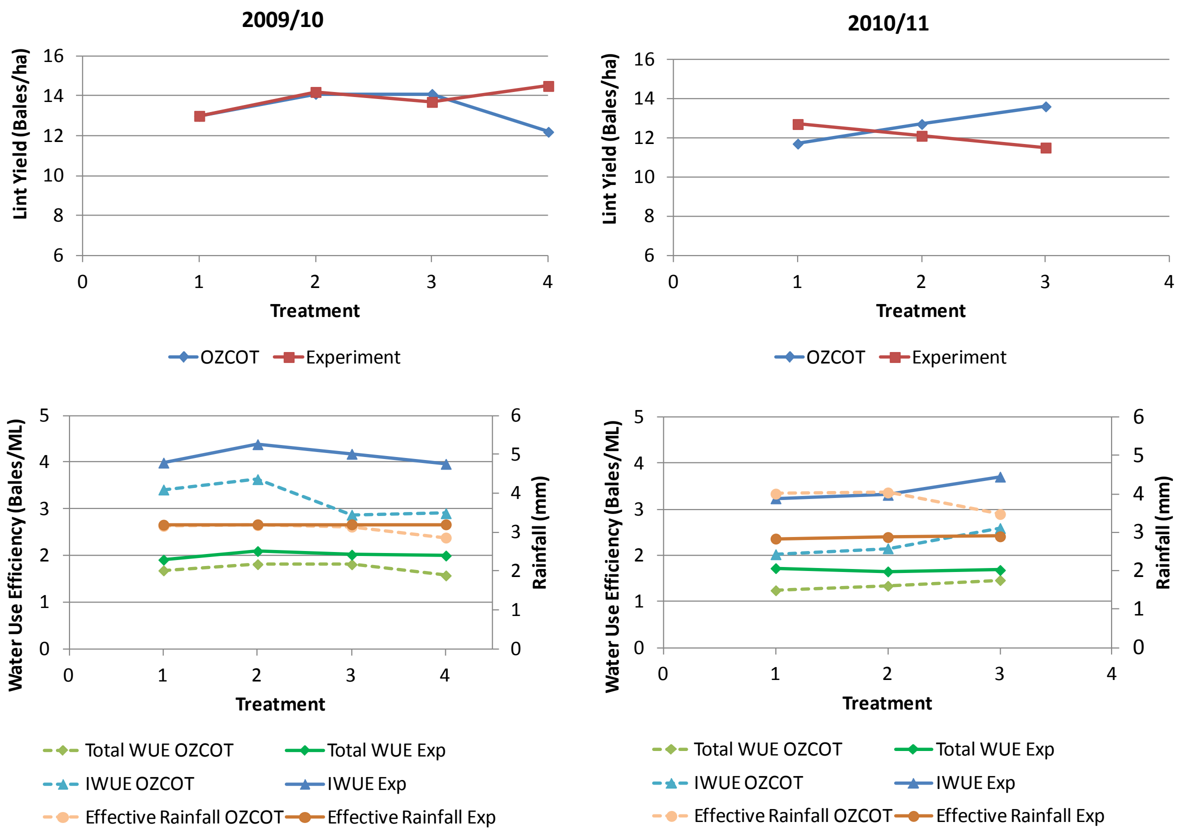

Figure 14. Comparison between predicted and measured lint yield (kg/ha), seasonal total and irrigated water use efficiency and effective rainfall for the 2009/10 and 2010/11 Dynamic Deficit experiments.

OZCOT's ability to simulate changes in response to different irrigation scheduling scenarios will enable future research to evaluate and benchmark cotton's response to different irrigation scheduling based on future forecasts of ETo in different cotton growing regions.

OBJECTIVE 4:

There was significant collaboration in this project with other CRC scientists in the agronomy/physiology team to coordinate resource use to ensure experimental outcomes (e.g. regional sowing time experiments designed with M. Braunack to investigate resource use efficiency and climate x soil water x plant stress interactions and row spacing experiments with M. Bange investigating water use and fibre quality).

The collaboration developed with the USDA in developing new research techniques using of novel technologies will be critical in assisting in developing a predictor of plant stress to assist with water management in both fully irrigated and limited water situations.

We have also developed collaborations with scientists at the University of Queensland to initiate research to develop expertise and a fundamental understanding of cotton root morphological and physiological responses to different environmental conditions.

Significant collaboration with industry and growers using a participatory research approach has enabled achievement of both scientific outcomes and industry ownership and impact (e.g. sowing time experiments and limited water experiment in collaboration with growers, the Gwydir Valley Irrigators Association, NSW DPI and Cotton Seed Distributors).

OBJECTIVE 5:

In addition to the experiments completed in Narrabri and St George, a large scale experiment in collaboration with the Gwydir Valley Irrigators Association, NSW DPI and Australian Food and Fibre was completed in 2010/11. This experiment compared fully irrigated, partially irrigated and limited irrigation treatments with three different row spacings. Few broad conclusions about using partially irrigated approaches can be drawn from one season's data, however the difficulties in using traditional approaches to irrigation scheduling and soil water measurement were apparent throughout the planning and execution of the experiment. This experiment highlighted the need for detailed and intensive research into these systems because of the breadth and complexity of the issues in managing a partially or limited irrigation system. A second experiment in 2012/13 is planned for the same site to continue to evaluate these systems in collaboration with the GVIA and AFF.

Extension of the results of this project included presentations at 7 industry field days, the Cotton CRC Forum, UNR cotton production course, interviews with ABC Radio and ABC TVs Landline program and presentations to visiting groups to the Australian Cotton Research Institute (e.g. AusAid, Rotary Youth Agricultural Group, CRC Board) during the 3 yr duration of this project. The results of the experimental outcomes from this project have been published in a cotton grower article, and submitted for publication in a conference paper for the Australian Agronomy Conference and an article for the Cotton Water Story Publication. Updates by R. Brodrick to 4 chapters of WaterPAK in June 2012 will incorporate outcomes of this project and 3 previous CRC projects.

Conclusion

The outcomes of this project determined that there is an opportunity to refine irrigation scheduling by dynamically changing the soil water deficits to improve growth by avoiding plant stress during periods of high evaporative demand (lower deficits) and improve water use efficiency by reducing the need for irrigation during periods of low evaporative demand (larger deficits). Measurements of plant stress using leaf water potential showed that the plant stress response to soil water availability changed in response to differences in ETo.

The results of the two years of dynamic deficit experiments showed that there may be considerable utility in delaying irrigation timing and extending opportunities to capture rainfall when ETo is low. This allows for more flexibility in cotton systems that require a significant number of fields to be irrigated at a point in time, and potential irrigation water savings. In both years there was no detrimental effect on yield or water use efficiency. In 2009/10 there was no difference despite considerable delays (up to 6 days) in one irrigation, and in 2010/11 the forecasted low ETo period also allowed an opportunity to capture rainfall event resulting in an irrigated water saving of 0.8 ML over the season in one treatment. Periods of low ETo are often associated with a depression or low pressure weather front which may bring an opportunity to capture rainfall. Delaying irrigations during flowering without taking into account ETo can have significant impacts on yield with Steve Yeates reporting a yield loss of 2.7% for every day that an irrigation was delayed in his experiments.

Importantly, this approach still focussed on using a measure of soil water, in this case a deficit approach, as the primary measure for irrigation scheduling. The relationship developed uses an average response of soil water, plant stress and ETo. Using leaf water potential as a measure of plant stress showed that in some instances irrigations may have been scheduled earlier or later in the dynamic treatments if we were able to identify future plant stress. Even when there were instances of high ETo, crops are not as stressed as would be expected based on current understanding.

The results of this project have identified a need for a measure of plant stress used with soil water measurement to assist with developing a truly dynamic deficit irrigation approach. Without an improved measure of plant stress we could continue to approach further analysis of the dynamic deficit approach by changing the deficit and accounting for crop stage, crop size, and boll load. This was similar to the approach used by HydroLOGIC to assist timing of irrigation.

However, given that there is also an opportunity to continually and directly measure plant stress directly using canopy temperature easily, being able to couple this with both continuous soil water measurements and forecast ETo would allow better evaluation of the value/risk of bringing forward and delaying irrigation.

Research will continue to develop a framework to provide a method to identify plant stress (based on a continuous measure) which, coupled with current and future soil water deficits and with short term ETo forecast, would allow the dynamic deficit approach to be used confidently and accommodate local conditions.

New initiatives will follow on from this project investigating dynamic deficits to optimise water use in a variable climate. A future project planned to commence in July 2012 incorporates the outcomes of current project and new research needed in the area of improving understanding of plant water stress to optimise irrigation management in both fully irrigated and limited water conditions for better yield, quality and water use efficiency. Future research will also involve collaboration with a project using canopy temperature sensors to specifically schedule irrigations (joint CSIRO/CRDC/USDA) to develop new science that links canopy temperature with plant stress in furrow irrigated environments. We will attempt to relate LWP to canopy temperature so that we can fully utilise all the data already collected in the current project.

Extension Opportunities

Detail a plan for the activities or other steps that may be taken:

A paper and poster for the Australia Cotton Conference is being prepared for publication and presentation at the 2012 Conference.

Updates to WaterPAK incorporating the outcomes of the experiments in this project are expected to be completed by June 2012.

Publications

A. Publications relevant to this project.

Peer reviewed articles / books

Brodrick R, Neilsen J, Bange M, Hodgson, D and Mundey, L (2012) Dynamic Deficits for irrigated cotton – matching the soil water to plant requirements. In: Proceedings of the 16th Australian Agronomy Conference, 14-18 October 2012, Armidale, New South Wales. (submitted, under review)

Non-peered reviewed articles

Brodrick, R (2012) Understanding and matching irrigation to plant requirements in a variable climate. Cotton Water Story (in press)

Brodrick R, Quinn J, Farrell Z, Jackson R, Montgomery J, Stone M, Young A, Fox R and Robinson J. (2011) Less crop but more drops? The Australian Cottongrower: 32: 16-20

Presentations (conference, field days, workshops etc)

Invited to speak at 7 field days
Co-ordinated (with Phil Firth) two nutrition workshops as a member of the Lower Namoi Cotton Growers Association Research and Development Committee (2011)
Interviewed by ABC Radio (2011)
Interviewed for a cotton segment for ABC TV's Landline Program (2011)
Presented at the 15th Australian Agronomy Conference (2011)
Guest Lecturer for UNE Cotton Production Course - Irrigation Scheduling and Plant Water Relations (2010 and 2011)
Presented at the Fibre to Fabric Course for Schools (2010)

Presented at the CRC Science Forum (2012)
Presented to various visiting groups at ACRI e.g. AusAid, Rotary Youth Agricultural Group, CRC Board.
Presented at two CSIRO Cotton Theme Meetings

B. All other publications by project team during this period.

Peer reviewed articles / books
Brodrick R, Bange MP, Milroy SP, Hammer GL (2012) Physiological determinants of high yielding ultra-narrow cotton: canopy development and radiation use efficiency. *Field Crops Research* (in press)

Brodrick R, Bange MP, Milroy SP, Hammer GL (2012) Physiological determinants of high yielding ultra-narrow cotton: biomass accumulation and partitioning. *Field Crops Research* (in press)

Brodrick R, Bange MP, Milroy SP, Hammer GL (2010) Yield and maturity of ultra-narrow row cotton in high input production systems. *Agronomy Journal* **103**, 843-848.

Brodrick R and Bange M (2010). Determining physiological cut-out in ultra narrow row cotton systems. In: Proceedings of the 15th Australian Agronomy Conference, 15-18 November 2010. Lincoln, New Zealand. http://www.regional.org.au/au/asa/2010/crop-production/plant-density/6970_brodrickr.htm#TopOfPage

Non-peered reviewed articles
Brodrick R and Bange M (2010) *Overview of recent research into ultra-narrow row cotton in Australia*, CSIRO Plant Industry, Canberra 8pp

Bange M and Brodrick R (2010) Do sowing rules change for Bollgard II cotton? *The Australian Cottongrower*. 31: 11-14

A publication plan has been developed with three papers planned for publication. One focusing on the calibration of AM vs. PM Leaf Water Potential measurements (previous CRC project); a second paper which discusses the effect of climatic variables on the relationship between Leaf Water Potential and Soil Water, and a third presenting the outcomes of the two Dynamic Deficit experiments.

Part 4 – Final Report Executive Summary

This project aimed to improve cotton irrigation WUE using dynamic deficits to (i) avoid plant stress and maximize yield and (ii) make the most effective use of in-crop rainfall.

Our analysis of a large data set of soil water x plant stress (using leaf water potential (LWP) as a measure) x climate experienced by the crop confirmed that atmospheric vapour pressure or evapotranspiration (ETo) can alter the plant stress response at the same soil moisture content. That is, if ETo is high a plant will may experience higher stress at higher soil moisture levels, and conversely if ETo is low a plant might not be stressed despite lower soil moisture availability. This analysis includes six experiments from three previous projects and three further experiments from the current project.

Two years of large scale field experiments have found that there is considerable utility in delaying irrigation timing and extending opportunities to capture rainfall when ETo was low. This allows for more flexibility in cotton systems that require a significant number of fields to be irrigated at a point in time, and potential irrigation water savings. In both years there was no detrimental effect on yield or water use efficiency. In 2009/10 there was no difference despite considerable delays (up to 6 days) in one irrigation, and in 2010/11 the forecasted low ETo period also allowed an opportunity to capture rainfall event resulting in water savings of 0.8 ML over the season in one treatment. Periods of low ETo are often associated with a depression or low pressure weather front which may bring an opportunity to capture rainfall. Yeates found that delaying irrigations without taking into account ETo during flowering could have significant impacts on yield with a yield loss of 2.7% for every day that an irrigation was delayed.

Results from the past two experiments have indicated the need for a measure of plant stress used with soil water measurement to assist with a dynamic deficit irrigation approach. The results are showing that even when there are instances of high ETo, crops are not as stressed based on current understanding. We could continue to approach further analysis of the dynamic deficit approach without a measure of plant stress, changing the deficit accounting for crop stage, crop size, and boll load. This was similar to the approach used by HydroLOGIC to assist timing of irrigation.

The outcomes of the experiments in this project showed that there was considerable utility in delaying irrigation timing and extending opportunities to capture rainfall when ETo was low. This allows for more flexibility in cotton systems that require a significant number of fields to be irrigated at a point in time, and potential irrigation water savings.

The continuation of the research will involve determining a framework to provide a method to predict plant stress (based on a continuous measure) which couples current and future soil water with short term ETo forecast along with crop stage. This would allow the dynamic deficit approach to be used confidently and will accommodate local conditions. The approach used presently uses an average response of soil water, plant stress and ETo. There is also an opportunity to continually and directly measure plant stress directly using canopy temperature easily and being able to couple this with both soil water and forecast ETo would establish the value/risk of bringing forward and delaying irrigation.

Dynamic Deficits for Irrigated Cotton – matching the soil water to plant requirements.

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Abstract

Current irrigation strategies for cotton rely strongly on irrigation scheduling based on soil moisture content using fixed whole season deficits. There may be an opportunity to refine irrigation scheduling by dynamically changing the soil water deficits to improve growth by avoiding plant stress during periods of high evaporative demand (lower deficits) and improve water use efficiency by reducing the need for irrigation during periods of low evaporative demand (larger deficits). Measurements of plant stress using leaf water potential showed that the plant stress response to soil water availability changed in response to differences in evaporative demand (ETo). One field experiment tested the concept of a dynamic deficit where irrigation timing was based on soil water measurements and weather forecasts of short term periods of high or low ETo. Three irrigation treatments were applied to the experiment; a control treatment, with irrigations scheduled at the normal 65-75 mm deficit for that soil type; a high ETo treatment which was irrigated earlier than the control at a smaller deficit in response to forecasted ETo; and a low ETo treatment which was irrigated later than the control at a larger deficit in response to forecasted low ETo conditions. There was no difference in yield between irrigation treatments, however, delaying the irrigation in response to forecasted low ETo enabled more rainfall to be captured than the other treatments leading to 0.8 ML/ha saving in irrigation water. These results indicate there is flexibility in irrigating cotton in response to future forecasts potentially saving water, however this study has highlighted the need for a definitive measure of plant stress to assist irrigation decisions to match plant requirements.

Introduction

With increased attention to water use in Australia it is critical to develop new scientific approaches to increase irrigation water use efficiency (IWUE). Current irrigation strategies rely strongly on assessment of soil moisture by soil moisture probes, or use irrigation schedules that are aligned to fixed soil water deficits based on measurements on previous experiences for particular fields. In many instances however the irrigation point (deficit) is based on average climatic conditions to prevent plant stress and does not take into account the current or future level of plant stress. Denmead and Shaw (1962) showed that the impact of a given water deficit on plant function is greater when the evaporative demand is high. To improve water use and efficiency a flexible or ‘dynamic’ soil deficit may need to be employed in irrigation scheduling by more effectively accommodating the current crop stress, the current soil water, and whether the short-term forecast of evapotranspiration will increase or decrease future crop stress. This is important as most of Australia’s cotton experiences significant in-crop climatic variation.

This study aimed to:

(1) establish that variation in ETo at different plant available water contents (PAWC) changes how a crop responds to PAWC; and
(2) test the concept of dynamic deficits on crop production and IWUE.

Methods

Two field experiments were monitored to measure plant stress response to evaporative demand under varying soil water conditions in Narrabri (30.318S, 149.788E), Australia in the 2003-04 (Exp. 1) and 2004-05 (Exp. 2) seasons. Each experiment was sown with the cultivar Sicot 289BR developed by CSIRO Australia. The experiment was sown at two sites with soils of different water holding capacities (self-mulching vertosols, with a plant available water content of 130 mm in one site; and 200 mm in the second site). Plots were 50 m long and 20 m wide with four replicates.

A third field experiment (Exp. 3) was sown into moisture using the cultivar Sicot 71BRF on 14 October 2010 in Narrabri, Australia. Yield and water use were measured to determine the response to different irrigation treatments. Treatments were designed to enable comparison of a control - scheduled according to normal irrigation point for that soil, equivalent to 55% FTSW, to treatment irrigations which were scheduled dynamically between flowering and cutout. Treatment 1 had one irrigation treatment applied earlier compared with the control when the forecasted 72 hr ETo exceeded 7 mm/day and Treatment 2 had one irrigation applied later than the control where the forecasted ETo was for <5 mm/day. A randomised complete block with three replicates was used. Plots were 60 m long by 16 m wide.

All three experiments were sown using a commercial row crop planter, and grown using high input management and insect control, typical of commercial practice, as described in Hearn and Fitt (1992).

In Exps. 1 and 2 measurement of leaf water potential (LWP) was made using a PMS model 600 pressure chamber with compression gland using the method described by Turner (1987). Pressure chamber readings were taken around solar noon approximately weekly from flowering to cutout. Readings were conducted on the first fully expanded leaf (third from the terminal) and 2 readings per plot were conducted at each measurement.

In Exps. 1 and 2 soil water was measured at approximately weekly intervals on the same days as leaf water potential.

In Exp. 3, soil water was measured at approximately weekly intervals and the day prior and two days following an irrigation and following rainfall. At the end of the season, yield was determined by machine picking of the measurement row in each plot. The soil moisture deficit was calculated as the difference between the plant available water content of the soil on the day of measurement and the maximum plant available water content of those layers of soil that the roots were extracting moisture from.

In all three experiments, two access tubes were located in each plot and measurements taken at 0.20, 0.30, 0.40, 0.50, 0.60, 0.90, 1.0 and 1.2 m depths. The moisture content of the top 0.15 m of soil was determined by a calibrated impedance probe (ThetaProbe, Delta-T Devices, Cambridge UK). The depth of extraction was determined over time to be when the next layer down in the soil profile had been depleted by 5% the roots were determined to be extracting water from that layer.

Soil moisture contents obtained using the neutron probe, have been normalized using the fraction of transpirable soil moisture content (FTSW). The amount of water available in the soil is expressed as a percentage which normalises the water holding capacity of the soil.

Meteorological data for the experimental period in all experiments was measured by a nearby weather station. 72 hr meteogram forecasts of ETo were accessed under subscription from the Bureau of Meteorology.

Results and Discussion

Plant Stress Response to Evaporative Demand

The wide variability in LWP at the same FTSW in Exps. 1 and 2 (Figure 1) indicated that climatic conditions were likely to be having a large influence on the level of plant stress even under the same soil water conditions. To account for climatic influence on LWP in Exps. 1 and 2, ETo and FTSW were used in the multiple regression analysis. Accounting for changes in ETo significantly improved the relationship between LWP and FTSW by 5.5% ($p<0.001$; $r^2 = 0.678$). To determine if our simple rule of thumb of "high ETo" and "low ETo" days could be used to determine the stress response, these data were grouped into high (ETo>7 mm/day) and normal (ETo<7 mm/day); however, there were not enough data points to allow a low (ETo<5 mm/day) category to be tested. A simple linear regression with groups showed that LWP measured on "High ETo" days experienced greater stress at the same level of FTSW compared with "Normal ETo" days (Figure 1).

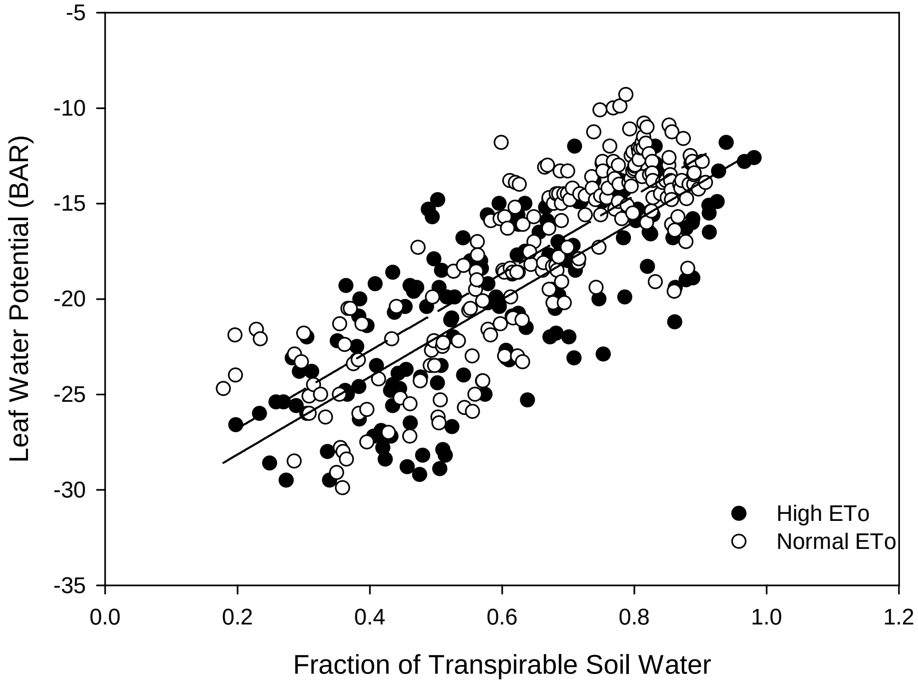

Figure 1. The effect of evapotranspiration (ETo) on the relationship between plant stress (leaf water potential) and fraction of transpirable soil water. LWP greater than -20 indicates the plant is suffering stress. Data from Exps. 1 and 2 is grouped into high ETo (ETo>7mm/day; solid circles and solid line) and normal ETo (ETo<7 mm/day; open circles and dashed line).

Although, more data is required to quantify this relationship, short-term forecasts of high or low ETo may provide an indicator of potential triggers for a dynamic deficit scheduling approach. As changes in evapotranspiration (ETo) affected the level of stress a plant regardless of the level of soil moisture, there is an opportunity for the deficit for optimum yield and IWUE to be dynamic, e.g. increase under cool humid conditions and decrease in hot dry conditions. For example, it is common in the cotton industry in clay soils to irrigate at a deficit of 80 mm. Under average summer evaporative demand of 8 mm per day, this deficit would lead to a 10 day irrigation cycle. Under low evaporative demand of 5 mm per day, 80 mm would last for 16 days before irrigation was required. With dynamic deficits, under low evaporative demand the irrigation interval could potentially be more than 16 days and save considerable irrigation water in more humid areas and seasons, avoid waterlogging and appear as increased IWUE. A dynamic deficit approach could apply to all methods of irrigation: flood, spray and drip.

Dynamic Deficit Experiment

To test the hypothesis of dynamic deficits in response to forecasted ETo, Exp. 3 had a total of three irrigation treatments applied during the course of the season. In treatment 2, an irrigation was applied at a smaller deficit (40 mm) compared with the control in response to a high ETo forecast. In the second treatment in response to forecasted low ETo, irrigation was delayed 4 days to a planned deficit of 90 mm, and in that period there was 33 mm of rain which further delayed the irrigation another 4 days. This resulted in this treatment receiving one less irrigation over the season translating into irrigation water savings of approximately 0.8 ML/ha compared to the control (Table 1).

Table 1. Lint yield and water use for Exp. 3. ns, no significant differences

Treatments	Average Lint Yield (kg/ha)	Irrigation Water Applied (ML/ha)	Effective Rainfall ML	Total Water (mm)	Total WUE (kg/mm)	Irrigation WUE (kg/mm applied)
Control	2892	3.92	2.84	736	3.92	7.38

Treatment 1 (High ETo)	2735	3.65	2.88	731	3.74	7.50
Treatment 2 (Low ETo)	2609	3.11	2.90	682	3.82	8.38
L.S.D (0.05)	323.8	0.34	ns	43.2	ns	0.02

There were no differences in yield or total water use efficiency in Exp. 3 (Table 1). Importantly, during the period of low ETo, despite the delay of 4 days in the irrigation for treatment 3 there was no impact on lint yield. Delaying irrigations during flowering without taking into ETo can have significant impacts on yield with previous research reporting a yield loss of 2.7% for every day that an irrigation was delayed (Yeates et al., 2010). The forecasted low ETo also allowed an opportunity to capture rainfall events resulting in irrigated water savings of 0.8 ML over the season in one treatment. Periods of low ETo are often associated with a depression or low pressure weather front which may bring an opportunity to capture rainfall.

The lack of a response to the high ETo, earlier irrigation treatment, needs further investigation, as does the high variability in the response of LWP to soil water. We are assessing in more detail when the crop was stressed and for how long it was under stress in the different irrigation treatments. One of the difficulties in using leaf water potential as an indicator of plant stress is that it is still an average, discrete method of sampling, and there is a need for continuous monitoring of plant stress to determine whether accounting for current and future crop stress in irrigation scheduling can bring greater savings in water use.

Conclusion

This preliminary study showed an opportunity to refine irrigation scheduling by dynamically changing the soil water deficits to improve growth by avoiding plant stress during periods of high evaporative demand (lower deficits) and improve water use efficiency by reducing the need for irrigation during periods of low evaporative demand (larger deficits). Measurements of plant stress using leaf water potential showed that the plant stress response to soil water availability changed in response to differences in evaporative demand (ETo). However, neither irrigating earlier or later in response to high or low forecasted ETo resulted in any yield penalty. We are currently investigating in more detail when the crop was stressed and for how long in these treatments to ascertain why irrigating earlier to prevent crop stress had little effect. The results of one field experiment showed that there may be considerable utility in delaying irrigation timing and extending opportunities to capture rainfall when ETo is low. This would allow for more flexibility in cotton farming systems that require a significant number of fields to be irrigated at a point in time, and potential irrigation water savings.

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Understanding and matching irrigations to plant requirements in a variable climate

Rose Brodrick, CSIRO Plant Industry, Narrabri

To improve water use and efficiency a flexible or 'dynamic' soil deficit may need to be employed in irrigation scheduling.

In brief:

- Irrigation scheduling can be improved by taking into account the current crop stress, the current soil moisture, and how the weather forecast (evapotranspiration) affects crop stress. This is called a 'dynamic deficit' approach.
- Large scale field experiments compared the 'dynamic deficit' approach with a more traditional approach to irrigation scheduling and found no significant differences in yield, water use or efficiency.
- When evapotranspiration is low, irrigations can be delayed which can extend the opportunity to capture rainfall and hence save on irrigation water.
- For the effective timing of irrigations based on a 'dynamic deficit' approach, it is important to combine a measure of plant stress with soil moisture and weather forecasts.
- Practical measurements of plant stress using canopy temperatures could be used to establish the value/risk of bringing forward and delaying irrigation.

Current irrigation strategies rely strongly on information from soil moisture probes or on schedules based on what has worked in the past for a particular field. In many instances the decision to irrigate is based on average climatic conditions to prevent plant stress and does not take into account the actual or future level of plant stress. An opportunity exists to improve irrigation efficiency by taking into account the current crop stress, the current soil moisture, and how the weather forecast affects crop stress. Our research showed that changes in evapotranspiration (ETo) affected the level of plant stress regardless of soil moisture, highlighting the need for irrigation scheduling to reflect both factors. The outcomes of field experiments that applyed a "dynamic deficit" approach supported our idea of refining irrigation scheduling to help reduce the effects of plant stress during periods of high evapotranspiration and to irrigate less during periods of low evapotranspiration. Periods of low evapotranspiration are often associated with a depression or low pressure weather front which may bring an opportunity to capture rainfall.

Climatic factors such as relative humidity and temperature can influence the demand for moisture by the crop to enable effective cooling (evaporative demand). Different levels of demand can change the water potential of the plant at the same level of soil moisture deficit. In fact, under high evaporative demand the cotton plant can experience short periods of moisture stress even when the water in the soil is close to field capacity (maximum level), because it is unable to match the rate of transpiration required to maintain effective cooling. This may create problems when pre-determined deficits are used for irrigation scheduling as they may not reliably match the plant's water requirements. Conceivably under high levels of soil moisture with high evaporative demand, plants could still experience stress which will impact on growth and ultimately yield. Hence, to maximise yield and irrigation water use efficiency, the 'deficit' for irrigation may need to be dynamic and vary with climatic conditions and soil moisture content.

Our analysis of a large data set of soil water, measurements of plant stress (using leaf water potential (LWP) as a measure) and climate experienced by the crop confirmed that evapotranspiration can alter the plant stress response at the same soil moisture content.

This analysis found that generally, when crops experienced high evapotranspiration (greater than 7 mm/day) during flowering they were more stressed compared to when they experienced lower evapotranspiration (less than 7 mm/day) during flowering (Figure 1). The results also showed that only when soil moisture levels were near to field capacity there was little affect of evapotranspiration.

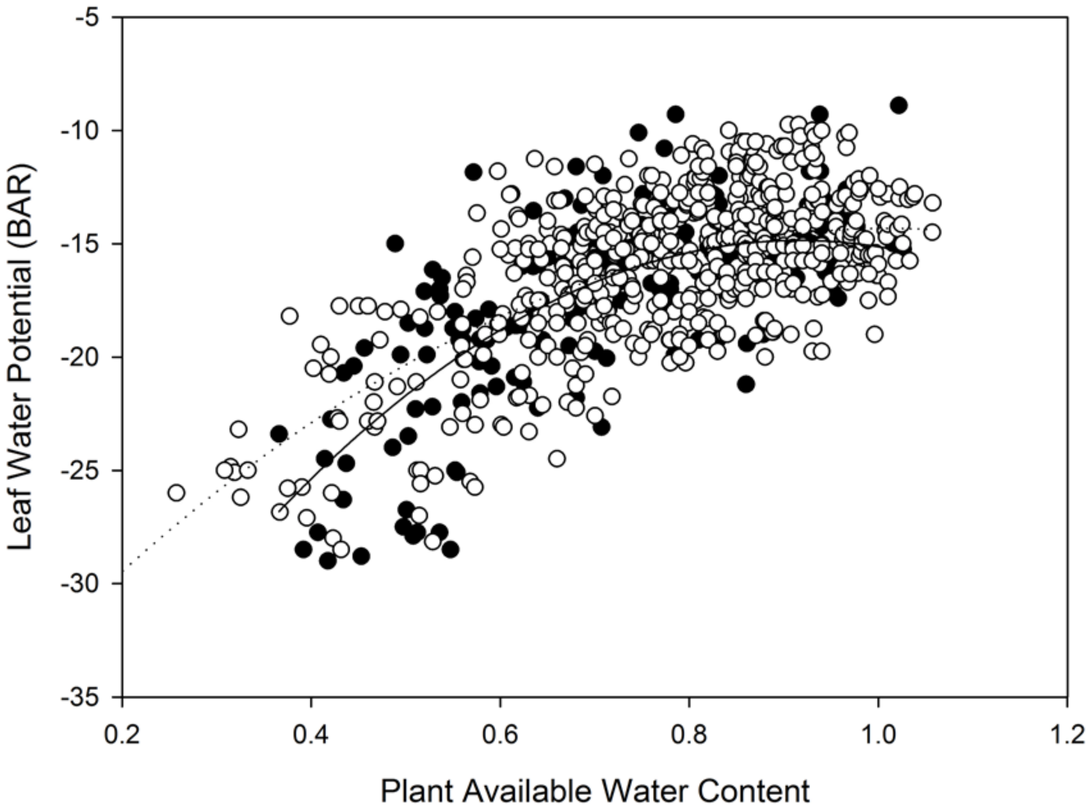


Figure 1. The effect of evapotranspiration (ETo) on the relationship between plant stress (leaf water potential) and fraction of transpirable soil water. LWP less than -20 indicates the plant is suffering stress. Data is grouped into high ETo (ETo>7mm/day; solid circles and solid line) and normal ETo (ETo<7 mm/day; open circles and dashed line).

Validating 'dynamic deficit' approach

Two large scale field experiments were completed to determine whether applying this knowledge could enable irrigation timings to be more "dynamic" based on soil water measurements and using weather forecasts of either future short term periods of high or low periods of evapotranspiration. Irrigation treatments were designed to evaluate irrigating earlier in response to high evapotranspiration, delaying irrigation timing in response to low evapotranspiration and no response to forecast for the whole season. To determine the implications of using a dynamic deficits approach, detailed measurements were taken in all three experiments including crop growth, soil moisture, plant stress and yield.

2009/10 Dynamic Deficit Experiment

The dynamic deficit experiment in 2010/11 in Narrabri had a total of four irrigation treatments applied during the course of the season. Treatment 1 – was the control treatment, with irrigations scheduled at the normal 65-75 mm deficit for that soil type. Treatment 2 – was irrigated earlier than the control at a smaller deficit in response to forecasted high evapotranspiration. Treatment 3 – was irrigated later than the control at a larger deficit in response to forecasted low evapotranspiration conditions. Treatment 4 – was dynamic, with irrigations scheduled either earlier or later in response to forecasted high or low evapotranspiration – in this experiment this treatment was irrigated with later than the control on two occasions. Dynamic irrigation timing was only implemented between flowering and cut-out as previous research had already determined that this is the most critical period for precise irrigation timing. The 2009/10 season was characterised by long periods of low evaporative demand, so the season provided excellent opportunity to evaluate the impact of delayed irrigation using a low evapotranspiration forecast.

There were no significant differences found in yield, water use or efficiency (see Table 1). While irrigations were delayed this did not equate to improvements in yield, total water use or water use efficiency (kg/ha/mm). Irrigations were delayed up to deficits of 103 mm during late flowering compared to 75 mm, with no impact on yield.

2010-2011 Dynamic Deficit Experiment

The dynamic deficit experiment in 2010/11 in Narrabri had a total of three irrigation treatments applied during the course of the season. Treatments 1 to 3 were the same as in the 2009/10 experiment. As there were fewer irrigations between flowering and cutout in 2010/11 the “dynamic” treatment had one delayed irrigation which was the same as treatment 3.

The season provided different conditions to the previous experiment, in that irrigations did not start until January due to above average rainfall; however, the remainder of the season had very little rainfall with some distinct periods of very high and low evaporative demand. In treatment 2, an irrigation was applied at a smaller deficit (40 mm) compared with the control in response to a high evapotranspiration forecast. In the second treatment in response to forecasted low evapotranspiration, irrigation was delayed 4 days to a planned deficit of 90 mm, and in that period there was 33 mm of rain which further delayed the irrigation another 4 days. This resulted in this treatment receiving one less irrigation over the season translating into irrigation water savings of approximately 0.8 ML/ha compared to the control (Table 1).

Once again there were no significant differences found in yield or total water use efficiency (Table 1). The plant based measurements showed that the control treatments were more stressed compared with the earlier irrigation treatment but still remained under a LWP of -20 bar in the control. Importantly, the plant stress measurements in the delayed irrigation treatment showed that despite the delay of 4 days, the crop was still not showing stress (LWP of -16 bar compared with -15 bar in the control).

Neither irrigating earlier or later resulted in any yield penalty in either year. Irrigating early to maintain higher soil moisture content during periods of high evapotranspiration did result in lower leaf water potential and hence less stress, however this did not translate into differences in crop yield. The control irrigation (normal deficit) in these experiments generally maintained the crop below a stress threshold (LWP < -20 bar). We are currently investigating in more detail when the crop was stressed and for how long in these treatments to ascertain why the earlier treatments had little effect.

Results from these experiments show that when evapotranspiration is low irrigations can be delayed which consequently extends the opportunity to capture rainfall. This could potentially save water and allows for more flexibility in cotton systems that require a large number of fields to be irrigated at in the same time. In both years there was no effect on yield or water use efficiency. In 2009/10 there was no difference despite considerable delays (up to 6 days) in one irrigation, and in 2010/11 the forecasted low evapotranspiration period also allowed an opportunity to capture a rainfall event resulting in water savings of 0.8 ML over the season in one treatment. Delaying irrigations during flowering without taking into account evapotranspiration can have significant impacts on yield with Steve Yeates reporting a yield loss of 2.7% (for Bt cotton) for every day that an irrigation was delayed in his experiments (See page X).

Table 1. Lint yield and estimated water use for 2009/10 and 2010/11 Dynamic Deficit Experiments. Significant differences indicated by * 95% significance level; ** 99% significance level.

Treatments	Average Lint Yield	Irrigation Water Applied	Effective Rainfall ML	Total Water (mm)	Bales/ML total water	Bales/ML applied
2009/10						
1 Control	13.0	3.26	3.19	680.8	1.9	4.0
2 Smaller Deficit (High ETo)	14.2	3.24	3.20	678.2	2.1	4.4
3 Larger Deficit (Low ETo)	13.7	3.28	3.20	679.2	2.0	4.2
4 Dynamic	14.5	3.66	3.20	725.8	2.0	4.0
L.S.D	2.5	***0.30**	0.09	41.4	0.4	0.9
2010/11						
1 Control	12.7	3.92	2.84	735.9	1.73	3.3
2 Smaller Deficit (High ETo)	12.1	3.65	2.88	731.2	1.65	3.3
3 Larger Deficit (Low ETo)	11.5	3.11	2.90	682.1	1.68	3.7
L.S.D	1.8	****0.34**	0.06	***43.15**	0.2	****0.2**

The results show that even when there are instances of high evapotranspiration, crops are not as stressed as they should be, based on our current understanding. This indicates the need for a measure of plant stress combined with soil water measurement and weather forecasts to assist with the dynamic deficit irrigation approach.

Practical measurements of plant stress using canopy temperatures could be used to establish the value/risk of bringing forward and delaying irrigation. Other opportunities involve determining a plant stress prediction model incorporating current and future soil moisture with short term evapotranspiration forecast as well as crop stage. Considering we presently use an average response of soil water, plant stress and evapotranspiration, this model would refine and improve the dynamic deficit approach.

In a potential project that continues to investigate the use of dynamic deficits and in collaboration with a project using canopy temperature sensors to schedule irrigations (See pages XX) we will develop science that links canopy temperature with plant stress in furrow irrigated environments. We will attempt to relate leaf water potential to canopy temperature so that we can fully utilise data already collected.

Less crop but more drops?

By Rose Brodrick (CSIRO), James Quinn (CSD), Zara Farrell (GVIA), Rod Jackson, Janelle Montgomery (NSW DPI), Michael Stone (ICMS), Alison Young, Ray Fox and Joe Robinson (AFF)

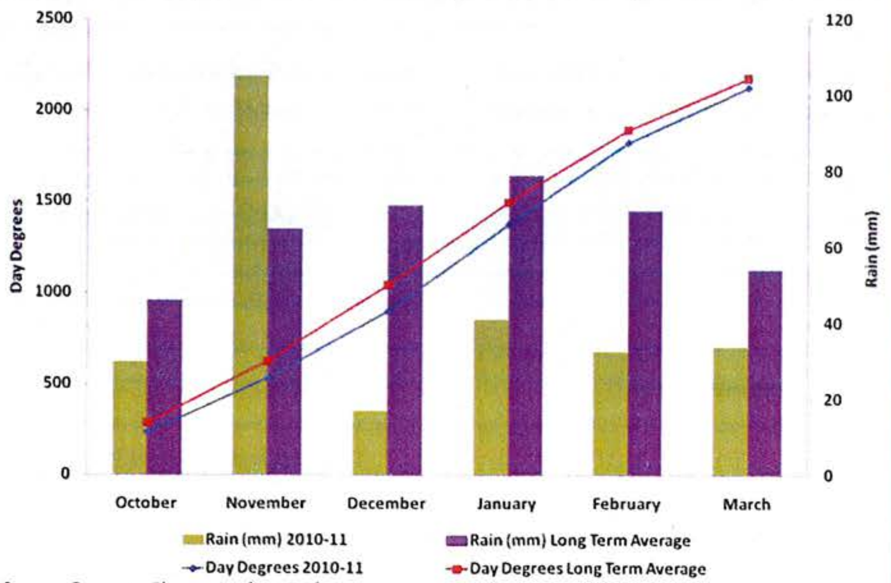
In 2010–11 a large scale irrigation experiment was established to determine whether alternative planting configurations such as single and double skip, generate more bales per megalitre in years where water is limited. Three water treatments (full, semi, limited) were implemented across the different plant configurations to establish the relationship between crop stress and yield.

Development of new approaches to increase crop water use efficiency is critical given the increased attention to water use in Australia and predicted climate change – higher temperatures and more variable rainfall. One of the key challenges growers have when they have water for a limited number of irrigations is confidently knowing when to use this water to optimise yield, quality and water use efficiency. Irrigation timing is critical in cotton to minimise negative impacts on yield and fibre quality.

In 2008 the Gwydir Valley Irrigators Association (GVIA) received funding from the Australian Government, as represented by the National Water Commission, to undertake a water efficiency project aimed at improving irrigation efficiency in the Australian cotton industry, primarily in north west NSW. The funding was provided to implement a series of irrigation comparison trials, designed and coordinated by growers for growers. A variation of the original project outline provided the opportunity to support the Water Regime and Row Configuration experiment at Redbank, Moree. The funding provided assisted the project steering group to better resource the experiment throughout the growing season.

The concept and implementation of the experiment was initiated by GVIA, Australian Food & Fibre Limited, ICMS Pty Ltd (Integrated Crop Management Services), Cotton Seed Distributors and CSIRO. Irrigation extension and technical support was also provided by NSW Department of Primary Industries. Funding from the National Water Commission and the generous donation of the Smart Crop sensors by Smart Field enabled the experiment to be fully instrumented and managed with a fully replicated trial design.

FIGURE 1: Day Degrees and Rainfall at Redbank Experiment 2010–11 compared with the long-term averages for Moree



Source: Cottassist Climate Analysis Tool.

HIGHLIGHTS...

- We compared the yield and water use of partially irrigated systems using solid, single-skip and double skip configurations to a fully irrigated solid crop
- Irrigations were scheduled using NAWF with the aim to keep the crop in the partially irrigated system flowering as long as possible to take advantage of any in-crop rainfall where three irrigations were available or to finish the crop off where only one was planned
- The season was characterised by a very wet start and dry finish, with less ability for the partially irrigated treatments to capture rainfall than in a more typical year
- The solid, fully irrigated crop yielded over 12.5 bales per hectare but the single-skip semi-irrigated had a respectable yield of 8.65 bales per hectare with better irrigation water use efficiency
- Difficult to make conclusions about these systems from one year's data and more research is needed to determine the potential of the single-skip semi-irrigated system (or others) in a partially irrigated production system.

METHODS

The experiment was planted on September 28, 2010 using Sicot 74BRF. Each plot was large enough (at least 24 rows wide) to allow separate irrigations to be applied to each plot and there were three replicates of each treatment. Row spacing treatments were solid (one metre spaced rows), single-skip (2 in, 1 out) and double skip (2 in, 2 out). The control treatment was solid with full irrigation according to normal farm scheduling and two partially irrigated treatments were applied to each row spacing.

The semi-irrigated treatment had three irrigations applied to each row spacing treatment and the limited-irrigated treatment had only one irrigation applied during the season. With the partially irrigated treatments the aim was to keep the crop growing during flowering to take advantage of any January or February rainfall so nodes about white flower were monitored and NAWF <7 considered a trigger point for irrigation in the semi-irrigated treatments. The last irrigation for the semi-irrigated treatment and the only irrigation for the limited treatments was applied approaching cutout (NAWF<5) with the aim to provide water to allow further growth meant that all the treatments had a full profile of soil moisture until late November and developed in relatively mild conditions in the first part of the growth period.

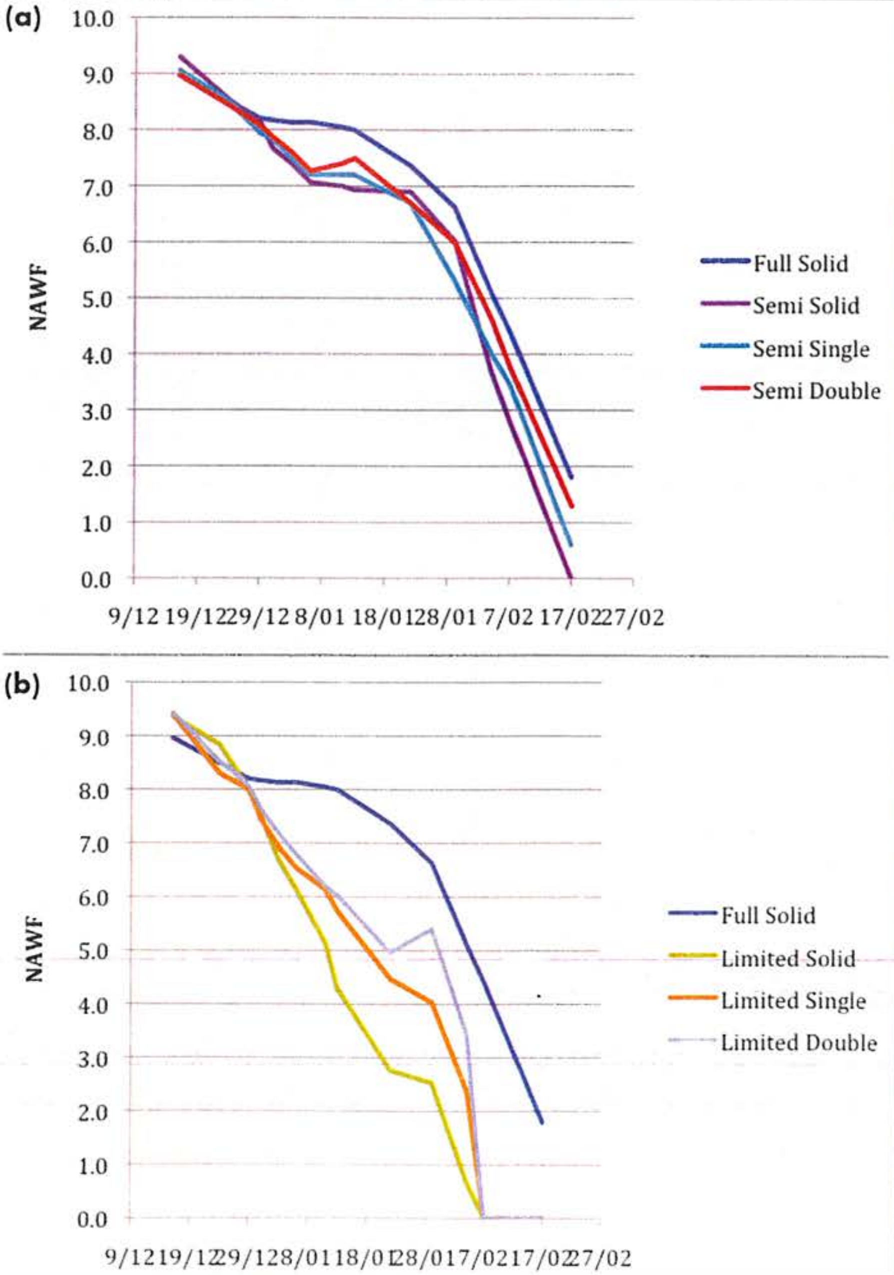
Irrigation scheduling

The first irrigation was applied to the solid, fully irrigated treatment on December 22 and this treatment was irrigated at around a 50–60 mm deficit a total of eight times during the season. The fully irrigated crop sustained NAWF above 8 until mid-January whereas the semi and limited water treatments rapidly declined from late December (Figure 2).

Irrigations were applied to all the semi-irrigated treatments on December 31 and to the solid treatment on January 14 and the single and double skip treatments on January 23 to prevent NAWF in the three row spacings from declining to <7 NAWF. The effect of the second irrigation led to an increase in NAWF in the semi-single skip and double skip treatments and delayed the solid declining further.

The limited treatment received an irrigation on January 14 when all row spacings had reached <5 NAWF to provide supplemental water at cutout to mature and maintain the fruit already set, but the double skip treatment had only just reach 5 NAWF and responded to the irrigation by putting on more nodes (Figure 2). The final irrigation on the solid, fully irrigated and the semi-irrigated treatments was applied on February 9. Real time water use measurements were difficult to calculate during the season, with no developed methodology for accounting for water use in the plant line and the skip.

FIGURE 2: Nodes above white flower at Redbank 2010–11 a) Solid, fully irrigated treatments compared to the semi-irrigated treatments b) Solid, fully irrigated treatments compared to the limited irrigated treatments



Fruit development

The impact of each irrigation treatment and row spacing was evident by tracking fruit development. Figure 3 shows fruit development in the plant line only (per linear metre so skip treatments need to be adjusted to account for the skipped rows on an area basis).

Early in the flowering period there were few differences, which is not surprising given that all the treatments had a full profile at the beginning of December. In terms of total fruit numbers there were few differences between the fully, semi and limited treatments until after the second irrigation when fruit numbers in the fully solid treatments became higher than the semi-irrigated treatments and the solid limited treatments had much lower fruit numbers.

In the linear metre, the semi-irrigated treatments and the single-skip and double skip limited treatments maintained reasonable fruit numbers until about three weeks after the second irrigation in the semi-irrigated treatments and the only irrigation in the limited treatment when fruit numbers began to decline. The double skip, semi-irrigated treatment was able to maintain those numbers longer, due to increased water availability in the skips.

All of the skip row spacings were able to maintain greater fruit numbers in the linear metre compared with either the solid, semi or solid, limited irrigation treatments. First position retention in the solid, fully irrigated treatment was over 60 per cent compared with 48 per cent for the single and double-skip semi-irrigated treatments.

First position retention was lowest in the solid, limited treatment with only 42 per cent of bolls retained. Boll distribution between the solid, fully irrigated treatments and the single-skip semi irrigated treatments was similar, but the double-skip had over 30 per cent of mature bolls on vegetative branches.

Yield and water use

Calibrated neutron moisture meters, c-probes and measurement of water applied at each irrigation provided a water balance

TABLE 1: Yield and water use in Redbank, Limited Water Experiment 2010–11

Treatments	Average yield bales per hectare	Estimated starting soil moisture 28/9/10	Irrigation water applied ML/Ha	Effective rainfall ML/Ha	Ending soil moisture at defoliation ML/Ha	Total available water ML/Ha	Bales/ML applied irrigation water	Bales/ML total water (irrigation, rainfall, and soil moisture reserves)	Estimated ETc
Solid – Full	12.54	2.20	4.15	2.28	1.15	7.48	3.02	1.68	7.35
Solid – Semi	7.08	2.20	3.20	1.87	0.56	6.71	2.21	1.06	6.87
Solid – Limited	6.67	2.20	1.43	1.94	0.00	5.57	4.66	1.20	5.82
Single – Semi	8.65	2.20	2.64	1.61	0.57	5.88	3.28	1.47	7.32
Single – Limited	6.26	2.20	1.11	1.69	0.11	4.89	5.65	1.28	6.39
Double – Semi	6.81	2.20	2.28	1.53	0.61	5.39	2.99	1.26	7.52
Double - Limited	5.09	2.20	0.89	1.60	0.11	4.58	5.72	1.11	6.79

and boll set and to retain and mature bolls already set in those treatments.

Comprehensive soil water and plant development measurements were collected throughout the season. Capacitance probes and neutron moisture probes were installed in both the plant line and skip rows to monitor soil water. Plant mapping, nodes above white flower, heights, nodes, light interception, canopy cover and maturity were monitored at least weekly to determine differences in crop growth and development.

Canopy temperature sensors (Smartcrop sensors) were installed above the crop to determine crop stress indicated by canopy temperature in each treatment and two plots were made large enough to be monitored by CSIRO's irriSAT system. The water balance was also calculated during the season using a calibrated canopy coefficient (Kc) approach by estimating canopy cover by using a 50 cm x 50 cm chequer board placed under the canopy with cover estimated by counting the proportion of visible squares compared with those covered by the canopy. James Quinn (CSD) has been using this approach to estimate crop water use in different systems where detailed soil moisture measurements are not available.

RESULTS

Climate

The 2010–11 season was cooler in terms of cumulative day degrees and characterised by above average rainfall up until Christmas followed by below average rainfall from January to March (Figure 1). This

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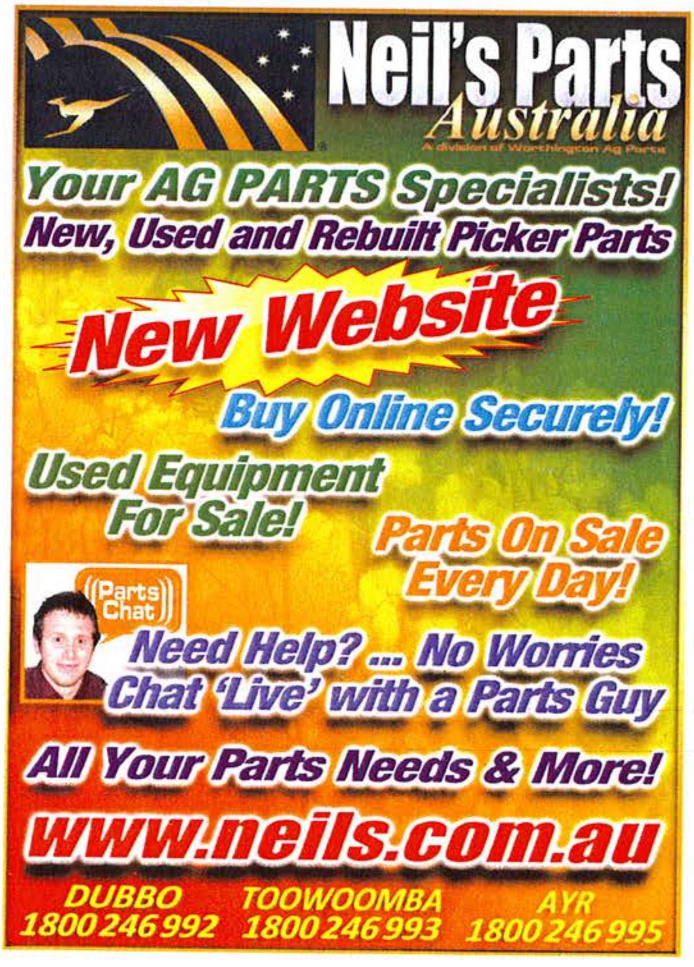


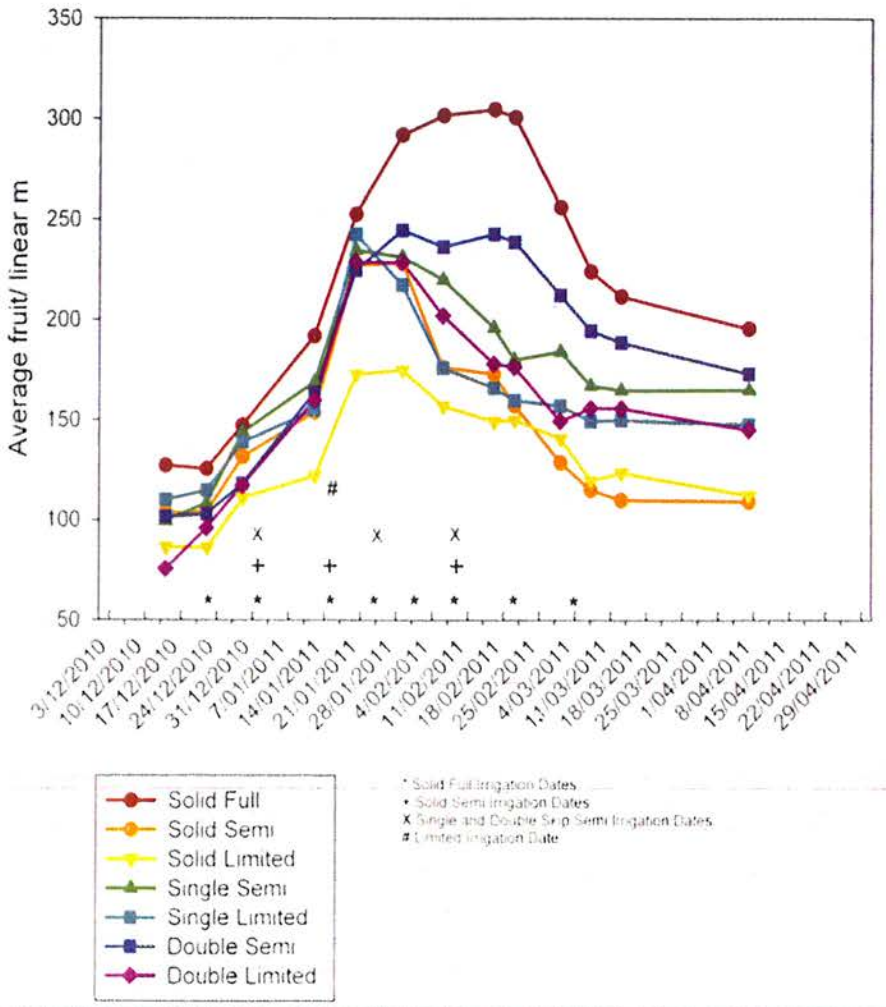
for each row spacing and irrigation treatment. Irrigations were applied to every second row as per normal farm irrigation practice. A single siphon was used in each treatment (except for the solid, limited irrigation treatment where double siphons were required to prevent overflow in the head ditch). Where the irrigation interval was greater than 21 days between irrigations, the irrigation took more than 15 hrs to complete compared to 10–11 hrs for the fully irrigated treatment.

Accounting for the skip proved to be a challenge in calculating plant available soil water. Patterns of extraction were followed and plant available soil water adjusted for both the depth of extraction in the plant line and skipped rows. As all different row spacings maintained a full profile until the end of November due to above average spring rainfall, extraction across the three row spacings remained similar with extraction within the plant line down to 60 cm at the time of the first irrigation in the solid, fully irrigated treatment.

By the end of December the skip row treatments had started to extract water from both the plant line and the skip, effectively giving the skip-row spacings access to more water than the solid treatments from that point on. By the end of the season, the semi and fully irrigated solid treatments were extracting moisture down to 100 cm, the limited solid treatment down to 120 cm, the single and double-skip semi irrigated treatments were extracting to 120 cm in the plant line and 100 cm in the skip. The single and double-skip limited irrigation treatments were extracting water from 120 cm in both the plant line and the skip by the end of the season.

Estimating crop evapotranspiration (ETc) using the chequer board method to calibrate it to the crop worked very well in the solid, fully irrigated and the semi-irrigated treatments, but this approach over-estimated water use in the limited irrigations and skip row treatments because it does not account for declines in crop water use due to plant stress and tended to over estimate the amount of water in the skip-rows (Table 1).

FIGURE 3: Average fruit counts in each treatment, irrigation dates are indicated on the figure



Yields were highest in the solid, fully irrigated treatment, followed by the single-skip, semi irrigated treatment and the solid, semi irrigated treatment (Table 1). Water use however was higher in the solid, fully irrigated and solid, semi irrigated treatment when compared to the single-skip semi-irrigated treatment, which had the highest irrigation water use efficiency and higher total water use efficiency than any of the other partially irrigated treatments.

The solid, fully irrigated treatments took longer to mature than the other treatments and rainfall in March led to the fully irrigated treatment having higher effective rainfall and more stored soil moisture remaining at the end of the season than the other treatments.

CONCLUSION

Evaluating these systems based on one season's data is not possible but the single-skip semi irrigated treatment had the highest irrigation water use efficiency and maintained reasonable yields. It is important to note that very little in-crop rainfall fell during the later part of the season and so the ability for the skip row treatments to capture more rainfall than the fully solid treatments was less than would be expected in a more typical season.

The semi-irrigated treatments required a significant amount of water in each of the three irrigations which needs to be considered when planning a partially-irrigated approach – three irrigations in a partially irrigated system is not necessarily equal to three in a fully-irrigated system.

In hindsight we may have scheduled the final irrigation earlier in the semi-irrigated treatments to maintain fruit numbers. Crop water use rapidly declined in the partially irrigated treatments before the final irrigation and the crop wasn't able to recover to fully utilise the final irrigation, evident by over 0.5 ML of stored soil moisture remaining in the profile in the semi-irrigated treatments.

Water use is difficult to calculate in real time in skip row systems and requires the development of new tools or technologies to accurately determine. The efficiency gain in the single-skip irrigated treatment indicates that it may have potential in a limited water situation, but more research is needed to develop irrigation strategies for limited water situations, across a range of environments to understand the consequences of the timing and amount of irrigation applied on plant stress, yield and quality.

Yield and Maturity of Ultra-Narrow Row Cotton in High Input Production Systems

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Cotton

ABSTRACT

Ultra-narrow row (UNR) cotton (*Gossypium hirsutum* L.), with rows spaced <40 cm apart, has the potential to reduce the time to maturity as UNR as fewer bolls per plant need to be produced to achieve comparable yields to 1 m spaced cotton crops. The objective of this study was to compare the maturity and yield of cotton grown under UNR spacing with conventionally spaced rows in high-yielding, high-input production systems (>1800 kg lint ha^{-1}). Six field experiments comparing UNR and 1 m spaced systems were conducted across a range of environments in Australia where yield on average was increased by 14.4% (P < 0.05) in UNR but the magnitude of this difference varied among experiments (3.7–38.8%). There were no differences in crop maturity (60% bolls open) between the systems. As expected, plants under the UNR system were smaller and produced fewer and smaller bolls. The higher yield under UNR was associated with a greater number of bolls per unit area. Although plants in the UNR crop had fewer fruiting branches and bolls per plant, these bolls did not mature earlier than those in the conventionally spaced crop. Lower boll retention was measured in the UNR crop and may be a key reason for the UNR crops maturing at the same time. The use of UNR may offer opportunities for growers to improve yields, but not for shortening the time of maturity in high yield high input systems. The use of the mepiquat chloride did not affect outcomes in this study.

Developing a cotton production system that reduces the time to crop maturity can lead to savings in production costs. In areas with shorter growing seasons, a shorter crop cycle can help in avoiding cool temperatures at the beginning and end of the season, which can be detrimental to yield and quality. The main drawback of earlier crop maturity in current production systems is that there is generally an associated penalty in lint yield (Bange and Milroy, 2004; Niles and Feaster, 1984; Stiller et al., 2004).

Ultra-narrow row systems were initially conceived for low-input production systems on marginal soils where plant growth was limited and yield might be improved by increasing plant density to compensate for the smaller plant size (Lewis, 1971; Kerby et al., 1996). In addition, UNR cotton has been proposed as a system for earlier maturity without substantial yield loss (Low and McMahon, 1973). The term UNR refers to cotton production systems with rows spaced <40 cm apart, compared with systems with conventionally spaced rows, which are usually 1 m apart (Nichols et al., 2003). The rationale for UNR production being earlier maturing than conventionally spaced cotton is relatively simple and based on general plant competition theory (Yoda et al., 1963). Plants grown in a high population should be smaller and set fewer fruit (bolls) per plant (Lewis, 1971). However, yield should be maintained as a higher plant population compensates for smaller plants having fewer bolls per plant. A smaller plant, with fewer bolls should mature earlier than a larger, more vegetative plant as the bolls are set earlier on the lower parts of the plant (Lewis, 1971). The closely spaced cotton closes the canopy faster than conventionally spaced cotton, leading to greater light interception by the crop earlier in the season (Kerby et al., 1996; Kreig, 1996).

Recently, UNR has been considered for high yielding (>1800 kg lint ha^{-1}), high-input cotton production systems in areas with a shorter growing season in Australia. Research into UNR in Australian cotton production systems has been limited to past studies (Low and McMahon, 1973; Hearn and Hughes, 1975; Constable, 1977a, 1977b), and means that UNR needs to be reexamined. Current production systems include improved insect management with integrated pest management (Wilson et al., 2004), and the use of high-yielding cultivars (particularly those with transgenic traits for insect control and herbicide tolerance). The availability of these transgenic herbicide-resistant cotton varieties has also reduced weed control problems in UNR cotton production that were encountered in the past, and has been a major influence of renewed interest in UNR cotton production (Atwell et al., 1996; Gerik et al., 1999; Bader and Culpepper, 2002).

The objective of this study was to investigate the maturity and yield of cotton grown under UNR spacing with conventionally spaced rows in high-yielding (>1800 kg lint ha^{-1}), high-input production systems, and compare these results with literature on UNR performance. Experiments were in three different seasons and in three distinct climatic regions.

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Abbreviations: UNR, ultra-narrow row.

Table 1. Summary of planting dates, agronomic management and plot size for Exp. 1 through 6.

Exp. no.	Region	Year	Sowing date	Plot size	N rate	Mepiquat chloride squaring	Mepiquat chloride flowering	No. of irrigations	In-crop rainfall	No. of insect sprays
				m	kg ha^{-1}	mL ha^{-1}			mm	
1	Narrabri	2001	16 Nov.	15 by 12	100	nil	nil	6	256	7
2	Narrabri	2002	10 Oct.	15 by 12	120	nil	nil	6	173	1
3	Hillston	2002	5 Oct.	15 by 12	135	nil	nil	7	88	16
4	Breeza	2002	11 Oct.	15 by 8	110	nil	nil	1	249	0
5	Narrabri	2003	23 Oct.	15 by 12	120	600	600	5	433	6
6	Hillston	2003	6 Oct.	15 by 12	108	600	300	10	114	9

Two of the experiments included a comparison of the effect of the growth regulator mepiquat chloride (Pix, BASF, Ludwigshafen, Germany) on UNR and conventionally spaced rows. Mepiquat chloride has been considered necessary to control excessive growth in height in UNR crops resulting from increased plant competition (Wright et al., 2004) although this has not been explicitly investigated. Crop maturity, lint yield, yield components, fiber quality, final fruit distribution on the plant, and plant architecture characteristics were recorded and compared. Subsequent manuscripts will investigate in detail underlying differences in yield and maturity responses in UNR by comparing biomass accumulation and partitioning, dynamics of fruit development and retention, and investigating the relationship between crop growth and fruit production.

MATERIALS AND METHODS

Six field experiments were conducted over three growing seasons and at three locations in New South Wales, Australia with distinct climates and soil types typical of Australian production systems (Table 1).

Experiments 1, 2, and 5 were grown at the Australian Cotton Research Institute, near Narrabri, in a semiarid environment of northwest New South Wales, Australia. Mean annual rainfall is 650 mm with a mean maximum temperature of 26.5°C and mean minimum of 11.7°C. The soil was a uniform gray cracking clay (Typic Haplustert). These soils are alkaline and have a high clay fraction.

Experiment 4 was grown near Breeza, in a semiarid environment of northwest New South Wales, Australia. Annual rainfall is 520 mm with a mean maximum temperature of 25.2°C and mean minimum of 10.9°C. The soil was a uniform black earth (Typic Haplotorrert). These soils are alkaline and have a high clay fraction.

Experiments 3 and 6 were grown near Hillston, in an arid environment of southwest New South Wales, Australia. Annual rainfall is 360 mm with a mean maximum temperature of 24.2°C and mean minimum of 10.9°C. The soil was a red clay with a sodic subsoil (Chromic Haplustert). These soils are alkaline and have a high clay fraction. Both Breeza and Hillston are production areas that have shorter growing seasons for cotton in Australia.

For each experiment a randomized complete block design was used. Exp. 1, 2, 3, 5, and 6 had four replicates, while Exp. 2 and 4 had three. The UNR (25 cm) and conventional (1 m) row spacing treatments were included in all six experiments.

To eliminate differences in soil preparation, all treatments in all experiments were planted on 2 m wide beds with a furrow either side of the bed for irrigation. In the 25 cm UNR treatment, the row configuration was six rows spaced 25 cm apart on a 2 m bed sown with 36 plants m^{-2}. In the conventionally spaced treatment, the row configuration was two rows spaced 1 m apart on a 2 m bed sown with 12 plants m^{-2}.

All experiments used the cultivar Sicala V-3RRi (Reid, 2001). This cultivar is a medium season cultivar with compact growth habit recommended for UNR production systems in the areas in this study (CSD, 2000). It performs well in both conventionally spaced and UNR production systems. Sicala V-3RRi is a transgenic cultivar containing the gene to produce the *Bacillus thuringiensis* (*Bt*) Cry1Ac insecticidal protein (Ingard cotton, Monsanto, St. Louis, MO), which provides control of most Lepidopteran pests, and the Roundup Ready (Monsanto, St Louis, MO) gene which enables the plant to tolerate over-the-top sprays of glyphosate until the crop reaches four true leaves. This is important for weed control in UNR systems (Fowler et al., 1999).

In Exp. 5 and 6, an extra treatment was added to determine if there was an interaction between the application of the growth regulator (mepiquat chloride- Pix- BASF, Ludwigshafen, Germany–antigibberellin) and row spacing. In Exp. 5, Pix was applied at a rate of 600 mL ha^{-1} at first square and first flower on both row spacing treatments. In Exp. 6 two applications were originally planned similar to Exp. 5; however, 1 wk before the second application was due there was an accidental application of 300 mL Pix over the whole trial. No further application of Pix occurred and although the control had this one application of Pix it is referred to as the "No Pix" treatment. However, the differences in Pix treatments between Exp. 5 and 6 meant no comparisons between the two experiments could be made.

Management for all experiments followed current commercial practices with high input management and insect control as described by Hearn and Fitt (1992). Each experiment was managed according to the crops needs with management the same across all treatments in each experiment. Experiment 4 however, received no insect sprays and only one irrigation, as water was limited due to drought conditions. A summary of plot size, sowing date, irrigations, fertilizer, and pesticide applications is presented in Table 1.

Measurements

In each experiment, time to maturity (defined as days after sowing to 60% of bolls open), lint yield and fiber quality were determined. To measure yield and time to maturity, all open bolls in a 2 m^2 section in each plot were hand picked weekly. In both treatments all open bolls were taken from all rows across the 2 m bed (furrow to furrow) for 1 m in row length. This sampling began once three bolls m^{-2} had opened (open bolls defined as when two sutures on the boll dehisce), and continued until the last boll had opened. Maturity was determined by calculating the date at which 60% of the bolls had opened. The seed cotton samples were ginned in a 10-saw gin (Continental Eagle Corp, Prattville, AL). Lint yields (g m^{-2}) were calculated from ginned lint sample weights. Fiber quality of ginned lint samples was measured using a Spinlab High Volume Instrument (HVI) model 900 (Zellweger Uster, Knoxville, TN). The most common parameters for examining fiber quality, fiber upper half mean (UHM), length, micronaire (a measure of linear density and maturity), strength, uniformity percent (ratio between the mean length and UHM length) and short fiber index (proportion by weight of fiber shorter than 12.7 mm) are reported for these experiments.

Final fruit retention and plant architecture characteristics were determined through plant mapping. After all bolls were open and the crop had been defoliated, four plants were harvested from each plot. Final plant height and number of nodes were recorded for each plant. Each fruiting site was mapped and final boll position recorded to obtain number of fruiting branches, position of first fruiting branch, and total fruit retention. Fruit retention was calculated as the percentage of final open boll number to total fruiting site number.

Statistical analyses were conducted using Genstat software (VSN International, Rothamstead, UK). Unless stated otherwise significant differences were considered at 95% confidence intervals ($P < 0.05$). To test for differences between UNR and conventionally spaced systems a combined analysis across all experiments was undertaken using generalized linear modeling (GLM). In this analysis the main factors were row spacing, Pix treatment and experiment (Exp.* × row spacing treatment + Pix treatment), and the random factors replicate and experiment (Exp.* × rep). In Exp. 5 and 6 where row spacing and Pix treatments were compared a two-way ANOVA for a randomized block design was used. As there were no interactions between Pix treatments and row spacing, only the main effects for row spacing are presented.

RESULTS AND DISCUSSION

Ultra-Narrow Row Management Affected Lint Yield but Not Maturity

Maturity did not differ significantly between row spacings in the combined analysis across the six experiments (Tables 2 and 3). Other studies also report little difference in maturity between row spacings in cotton (Gerik et al., 1998; Hawkins and Peacock, 1973), while some report significantly earlier maturity (Cawley et al., 1998, 1999; Hearn and Hughes, 1975; Young et al., 1980), and others report inconsistent maturity differences between row spacings in different years of their studies (Constable, 1977b; Jost and Cothren, 2001). There was also no interaction of the application of mepiquat chloride and row spacing on maturity (Table 4), suggesting that the effect was consistent across spacing treatments.

For lint yield the combined analysis showed that the mean lint yield of the UNR treatments was significantly higher (on average by 14.4% or 32 g m^{-2}) than the conventionally spaced treatments (Tables 2 and 3). Again there was also no interaction of the application of mepiquat chloride and row spacing on yield (Table 4). Lint yield varied considerably among experiments with the highest average yield in Exp. 1 and relatively lowest in Exp. 4. Excluding Exp. 1 from the combined analysis, because it had substantial differences in means between treatments, did

Table 2. Summary of significant differences from combined analysis of experiments for lint yield, yield components, maturity, fiber quality, fruit retention, and plant architecture characteristics. Error df = 44, Pix treatment df = 1. LSDs are calculated at the *P* < 0.05 level.

Variable	Row spacing treatment	Experiment	Row spacing treatment × Experiment
	df = 5	df = 1	df = 5
Lint yield, g m^{-2}	18.0	32.3	
DAS† to maturity, 60% open bolls		4.7	
Gin out-turn, %		0.01	
Final boll number, bolls m^{-2}	11.0	19.5	
Mean boll size, g $boll^{-1}$	0.19	0.36	0.49
Fiber length, decimal inches		0.02	
Micronaire		0.34	
Fiber strength, g tex^{-1}	0.66	1.32	
Fiber uniformity, %		0.96	
Short fiber index, %		0.62	
Final height, cm	2.73	8.07	9.09
Final node number	0.46	1.35	1.53
Retention of mature bolls at maturity, %	0.03	0.06	

† DAS, days after sowing.

Table 3. Means for row spacing treatments in Exp. 1 through 6 for lint yield and days after sowing to maturity. The table includes experiment and row spacing treatment means from combined analyses. Treatment differences and LSDs are presented in Table 2.

Variable	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 6	Row spacing mean
Lint yield, g m^{-2}							
Conventional	245	270	237	123	244	214	222
25 cm UNR†	340	292	259	149	253	236	254
Exp. mean	292	281	248	136	248	225	
DAS to maturity, 60% open bolls							
Conventional	149	148	174	154	150	166	157
25 cm UNR	144	146	172	155	156	170	157
Exp. mean	146	147	173	154	153	168	

† UNR, ultra-narrow row; DAS, days after sowing.

Table 4. Means for lint yield and days after sowing to maturity for row spacing and mepiquat chloride (Pix) treatments in Exp. 5 and 6.

Variable	Exp. 5		Exp. 6	
	Conventional	25 cm UNR‡	Conventional	25 cm UNR
Lint yield, g m^{-2}				
Pix	249	253	220	230
No Pix	239	252	208	241
LSD Pix × row spacing				ns†
DAS to maturity 60% open bolls				
Pix	154	151	166	168
No Pix	150	156	166	171
LSD Pix × row spacing				ns

† ns, no significant difference.

‡ UNR, ultra-narrow row; DAS, days after sowing.

Table 5. Means for row spacing treatments in Exp. 1 through 6 for gin out-turn, final boll number, and boll size. The table includes experiment and row spacing treatment means from combined analyses. Treatment differences and LSDs are presented in Table 2.

Variable	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 6	Row spacing mean
Gin out-turn, %							
Conventional	42.5	43.0	40.3	40.3	41.0	39.7	41.1
25 cm UNR†	44.8	43.9	41.1	40.1	40.1	39.4	41.6
Exp. mean	43.6	43.5	40.7	40.2	40.8	39.3	
Final boll number, bolls m^{-2}							
Conventional	101	106	174	65	107	116	111
25 cm UNR	146	123	202	99	127	149	141
Exp. mean	123	190	187	122	119	129	
Mean boll size, g $boll^{-1}$							
Conventional	5.70	5.92	3.38	4.61	5.39	4.52	4.85
25 cm UNR	3.60	5.33	3.24	3.72	5.01	4.14	4.07
Exp. mean	4.68	5.11	3.34	4.20	5.15	4.38	

† UNR, ultra-narrow row.

not affect the outcome. The low yield in Exp. 4 was expected as it received only one irrigation due to drought conditions. Yield data are from handpicks, which tend to be approximately 10% greater than those obtained by machine picking in Australian irrigated cotton production (W.N. Stiller, personal communication, 2005). The yields from these experiments were similar to commercial yields in the regions (Dowling, 2009) where the experiments were conducted and were higher than 1800 kg lint ha^{-1}.

Table 6. Means for row spacing treatments in Exp. 1 through 6 for fiber quality parameters. The table includes experiment and row spacing treatment means from combined analyses. Treatment differences and LSDs are presented in Table 2.

Variable	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 6	Row spacing mean
Fiber length, decimal inches							
Conventional	1.14	1.13	1.16	1.04	1.16	1.14	1.13
25 cm UNR†	1.13	1.12	1.14	1.07	1.15	1.15	1.13
Exp. mean	1.14	1.13	1.15	1.06	1.15	1.15	
Micronaire							
Conventional	3.92	4.37	4.58	4.00	4.38	4.75	4.18
25 cm UNR	3.92	3.97	4.73	4.03	3.90	4.45	4.08
Exp. mean	3.81	4.03	4.53	3.88	3.94	4.56	
Strength, g tex^{-1}							
Conventional	28.9	31.0	31.6	30.6	31.8	32.1	31.1
25 cm UNR	28.6	30.6	31.1	30.5	30.7	31.6	30.6
Exp. mean	28.8	30.9	31.4	30.6	31.2	32.2	
Uniformity, %							
Conventional	83.9	84.4	85.1	82.3	84.4	85.1	84.2
25 cm UNR	84.5	84.6	84.6	82.8	84.4	84.8	84.3
Exp. mean	84.2	84.5	84.8	82.6	84.1	85.2	
Short fiber index, %							
Conventional	5.35	8.57	7.90	9.80	8.33	7.55	8.01
25 cm UNR	5.23	8.23	7.77	9.67	8.92	7.75	7.99
Exp. mean	5.36	8.47	7.91	9.81	8.69	7.73	

† UNR, ultra-narrow row.

In low input systems differences in yield between row spacings have been variable with no consistent yield benefit with the use of UNR spacings. Some studies have reported higher yields in UNR crops (Atwell, 1996; Bader and Culpepper, 2002; Gerik et al., 1999, 1998, 2000; Gwathmey, 1996, 1998; Gwathmey et al., 1999; Hawkins and Peacock, 1973; Heitholt et al., 1992; Koli and Morrill, 1976; Nichols et al., 2003, 2004; Steglich et al., 2000; Vories et al., 2001), others have reported that differences in yield when comparing UNR and conventionally spaced cotton are not consistent across years (Bader and Culpepper, 2002; Cawley et al., 1998, 1999; Constable, 1977a, 1977b; Jost and Cothren, 2001; Nichols et al., 2004; Vories et al., 2001). There are studies that report no yield benefit in UNR cotton (Baker, 1976; Bednarz et al., 1999; Clawson and Cothren, 2002; Marois et al., 2004; Nichols et al., 2004), or yield was lower (Boquet. 2005). Lint yields in this study were higher than the highest UNR yield reported by these authors which was <1500 kg lint ha^{-1}. Many of these studies have focused on the agronomy and management of UNR rather than detailed physiological studies that seek to explain any differences.

Ultra-Narrow Row Systems Generally Had More but Smaller Bolls

Interactions were identified between experiments and row spacing treatments for mean boll size (Tables 2 and 5). These interactions could be due to climatic or management differences between experiments. Experiment 3 had much lower mean boll size than the other experiments and the UNR treatment in this experiment was only slightly lower. Across experiments boll size was 16.1% smaller for UNR compared with conventional spacing. Smaller boll size is commonly reported in UNR studies (Baker, 1976; Bednarz et al., 1999; Boquet, 2005; Constable, 1977b; Witten and Cothren, 2000) although not always (Gerik et al., 1999; Hawkins and Peacock, 1973). Constable (1977a) found that the smaller boll size in the narrow row (18 cm row spacing) treatments in his experiments was due to fewer seeds per boll compared to conventionally spaced rows. This indicated that conditions at flower bud formation and ovule fertilization were important in the narrower row crops as these stages determine the number of seeds per boll (Constable, 1977b).

Smaller or fewer bolls in UNR cotton production would limit the potential yield of UNR cotton and may delay maturity. The combined analysis showed higher final boll number in the UNR treatments, which explains why yield across all the experiments was higher (Tables 2 and 5). The 27.0% increase in boll number more than compensated for the 16.1% decrease in boll size in the UNR treatments. In other studies yield increase in UNR cotton compared to conventionally spaced cotton has been associated with higher boll numbers per unit area (Bednarz et al., 1999; Gerik et al., 1999, 1998, 2000; Heitholt et al., 1992). The increase in yield in the UNR crop may be due to greater biomass production or increased partitioning to fruit (Charles-Edwards et al., 1986).

Ultra-Narrow Row Systems Did Not Differ in Fiber Quality

Smaller boll size in the UNR crops suggests that there may have been limited assimilates for boll development; this did not affect micronaire however, strength was slightly lower in the UNR treatment (Tables 2 and 6). Some researchers have reported lower micronaire in UNR production systems (Hearn and Hughes, 1975; Vories et al., 2001) and Jost (2000) reported that fiber length was shorter. Other authors have reported no effect on fiber quality (Boquet, 2005; Gerik et al., 1998, 2000; Gwathmey, 1996; Hawkins and Peacock, 1973; Heitholt et al., 1993; Jost and Cothren, 2001; Nichols et al., 2004).

Ultra-Narrow Row Systems Differed in Plant Architecture and Had Reduced Fruit Retention

Although interactions were found between experiment and row spacing treatments in the combined analysis (plant height in Exp. 5 and nodes in Exp.1), they were consistent with overall mean decreases in plant height and nodes in the UNR crop (Tables 2 and 7). The shorter and more compact UNR plants produced fewer fruiting sites and mature fruit per plant (Table 7). Similar responses to higher plant populations and narrow row spacings have been found in a number of studies (Bednarz et al., 2000; Constable, 1977b; Galanopoulou-Sendouka et al., 1980). Importantly, although the morphology of UNR plants found in this study fitted the concept of a smaller plant with fewer bolls, the theoretical earlier maturity did not eventuate in any of the experiments.

The combined analysis for overall fruit retention per plant showed that in the UNR crops averaged 6% less than for plants in the conventionally spaced crops. If more fruit were shed on the UNR plants they may compensate by producing fruit later, perhaps leading to delayed maturity. Lower retention in the UNR plants may indicate reduced assimilate supply to support boll retention. Lower retention has been found in other studies on UNR cotton (Baker, 1976; Constable, 1975, 1977a, 1977b; Galanopoulou-Sendouka et al., 1980; Kerby et al., 1990) but its effect on maturity of UNR has not been studied explicitly.

CONCLUSIONS

The conceptual notion that a UNR system could produce a similar yield to a conventional system with earlier maturity was not supported by this study. Higher yields could be achieved using UNR in high input systems, but results were variable in magnitude (3.7–38.8%) for each experiment. However, earlier maturity was not achieved with UNR. Higher yields were associated with a greater number of bolls per unit area and may be due to greater biomass production per unit area or increased partitioning to fruit. More bolls per unit area in UNR more than compensated for the associated smaller boll size. Plants grown under the UNR system were smaller and produced fewer and smaller bolls, however, this did not lead to earlier crop maturity than the larger plants grown in the conventional spaced system. Lower retention was measured in the UNR crops and may be a key reason for delayed maturity. Further research is being undertaken to determine causes of these effects on yield and maturity observed in high-yielding, high-input UNR production systems. The use of mepiquat chloride on UNR crops also did not improve the yield or maturity outcomes of this study.

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Table 7. Means for row spacing treatments in Exp. 1 through 6 for plant mapping characteristics. The table includes experiment and row spacing treatment means from combined analyses. Treatment differences and LSDs are presented in Table 2.

Variable	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 6	Row spacing mean
Final height, cm							
Conventional	88.0	85.0	70.8	60.3	96.6	64.5	78.2
25 cm UNR†	60.5	56.1	53.1	41.7	85.9	49.6	58.3
Exp. mean	68.9	65.1	56.8	45.1	83.4	54.4	
Final node number							
Conventional	18.7	21.8	21.3	19.4	20.8	19.0	20.2
25 cm UNR	14.8	18.4	18.1	17.8	18.3	17.9	17.5
Exp. mean	16.6	19.8	19.5	18.3	19.0	18.7	
Retention of mature bolls, %							
Conventional	25.4	49.2	45.7	37.5	48.7	67.5	46.3
25 cm UNR	24.7	31.3	47.7	29.4	40.5	65.0	40.9
Exp. mean	24.3	38.1	44.7	31.7	45.4	61.3	

† UNR, ultra-narrow row.

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Determining physiological cutout in ultra-narrow row cotton

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Abstract

Cotton is a perennial plant that is grown as an annual crop. Production of new fruiting sites continues until the demand on the resource supply by developing fruit leaves no surplus for the initiation of new leaves and fruiting sites. This stage is termed physiological cutout. The timing of physiological cutout is strongly correlated to the timing of crop maturity. Determining cutout is important for managing the crop to ensure that there has been sufficient time to produce yield and that unfavourable conditions at harvest are avoided. For conventionally spaced crops (1 m row spacing), previous studies have related timing of physiological cutout to the time at which the number of nodes above the highest white flower (NAWF) declines to four. Data were collated from six field experiments conducted over four seasons to investigate whether ultra-narrow row cotton (UNR, rows < 40 cm apart) production systems affect (1) the response of NAWF vs. days after sowing, and (2) the relationship between physiological cutout and physiological maturity. Across the experiments the UNR crops reached NAWF = 4 significantly earlier than conventionally spaced crops. However, the timing of cutout was not a good indicator of crop maturity in UNR crops as there were no differences between row spacings in time to 60% mature bolls. Further investigations are needed to determine whether using a different number of NAWF can be linked to crop maturity or whether other tools will need to be developed to assist with late season crop management decision (e.g. determining the timing of last irrigation) for UNR crops.

Key Words

cotton, row spacing, nodes above white flower, maturity, cutout

Introduction

Cotton is an indeterminate species. The timing of crop maturity is determined by when the plant stops producing new fruit (‘cutout’) due to the demand on the assimilate supply by growing fruit leaving none for the initiation of new fruiting sites (Hearn 1994). Cotton growers need to manage the timing of cutout for their particular region and season as it has important implications for maintaining both cotton yield and fibre quality. An early cutout and thus early maturity may reduce yield (Bange and Milroy 2004), while a late cutout can lower fibre quality as harvest preparation (chemical defoliation) and the harvest operation may cause increased trash and more immature fibre as a result of cold and wet conditions (Bange *et al.* 2010). Monitoring the timing of cutout also has important implications for application of growth regulants and late season pest and irrigation management.

To optimize yield and quality, the timing of cutout should allow for all the fruit on the plant to mature and open. This time can be estimated by

predicting the date when the last effective flower is produced. A technique that has been employed by growers in conventionally spaced (1m rows) crops to monitor when and how quickly they are approaching cutout is to track the number of nodes above the last white flower present on the plant (NAWF). Previous research has shown that when the last effective flower is produced (the time of physiological cutout) it coincides with when NAWF equals 4 (Bourland *et al.* 2001; Bourland *et al.* 1992). Other studies have shown that at this time the crop has attained 98% of it harvestable yield (Hake *et al.* 1996a).

Few studies have investigated the use of NAWF for determining cutout in ultra-narrow spaced cotton systems (UNR - rows < 40 cm apart). UNR cotton plants tend to be smaller with fewer fruiting branches resulting in less fruit per plant (Brodrick *et al.* 2010) compared to conventionally spaced cotton. These differences may change the time course of NAWF as well as the relationship of physiological cutout to NAWF=4. These relationships need to be assessed to ensure they provide appropriate tools for managing UNR crops. To assess the utility of the NAWF approach to assist in late season management of UNR cotton, growth and NAWF data from conventionally and UNR spaced crops grown in Australia were collated and compared.

Methods

The development of NAWF and the relationship of NAWF=4 to physiological cutout between UNR and conventionally spaced systems were compared by collating data from six experiments grown across four years near Narrabri, Australia (Table 1). All crops were provided with appropriate nutrition and used commercial insect control. All crops were fully irrigated with the exception of Exp. 2 that had a treatment with the second last irrigation skipped. Management was similar across all experiments and treatments.

Table 1. Sowing date, treatments and varieties in Exps. 1 to 6.

Exp	Sowing Date	Treatments	Variety
1	10 Oct 2001	Variety Conventionally Spaced	Eight varieties differing in morphology, background and maturity, listed in Bange and Milroy (2004)
2	13 Nov 2002	Variety Conventionally Spaced Late stress (skipped second last irrigation)	As above
3	16 Nov 2001	UNR Conventionally Spaced	Sicala V-3RRi
4	10 Oct 2002	UNR Conventionally Spaced	Sicala V-3RRi
5	23 Oct 2003	UNR Conventionally Spaced	Sicala V-3RRi

6	17 Oct 2006	UNR Conventionally Spaced	Sicot 71BR

UNR and conventionally spaced production systems were compared in four experiments (Table 1). UNR plots consisted of six rows spaced 0.25 m apart on a 2 m bed sown with 36 plants/m^2 and conventionally spaced plots of two rows spaced 1 m apart on a 2 m bed sown with 12 plants/m^2.

In all experiments starting just before first square, 1 m^2 plant samples were harvested approximately every 10 days and leaf area, dry weight of fruit, leaf and stem determined. Crop growth rate and fruit growth rate were derived from the differential of the logistic function of average total dry matter and fruit dry matter versus days after sowing (DAS). Physiological cutout (carbon balance equals zero) was calculated as the days after sowing where fruit growth rate equalled crop growth rate (Bange and Milroy 2004). Mean values of NAWF for each row spacing were determined from regressions of the NAWF against DAS. NAWF was measured weekly from first flower on 10 plants in each plot (Hake *et al.* 1996b). To determine maturity (60% bolls open), four to five successive counts and harvests of open bolls in 2 m^2 of each plot were taken in all experiments.

Results

In experiments 3 to 6 the UNR crops reached NAWF = 4 significantly earlier (8 d) than the conventionally spaced crops (Figure 1). Across all experiments there was a significant linear relationship between physiological cutout and the DAS when NAWF = 4 (Figure 2). Stepwise linear regression analysis showed that for this relationship, UNR and conventionally spaced treatments did not differ significantly. However, in experiments 3 to 6 DAS to 60% open bolls (crop maturity) did not differ significantly between row spacing treatments (Table 2).

Table 2. Days after sowing to crop maturity in UNR and conventionally spaced treatments in Exps. 3 to 6. (n.s = no significant difference).

Experiment	UNR	Conventionally Spaced	LSD
3	144.3	148.8	n.s.
4	146.0	148.3	n.s.
5	156.1	150.0	n.s.
6	174.0	177.7	n.s.

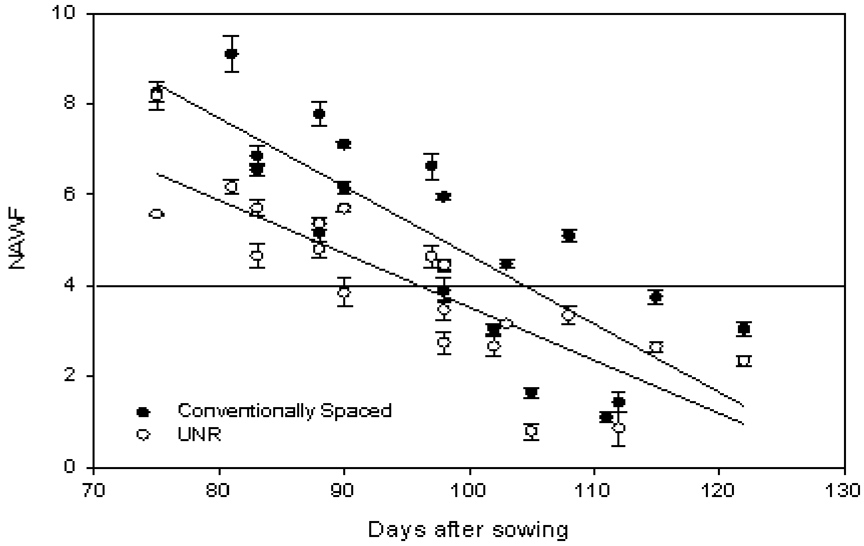

Figure 1. Average nodes above white flower versus days after sowing for conventionally spaced and UNR treatments in Exps. 3 to 6. Error bars are two standard errors of the mean.

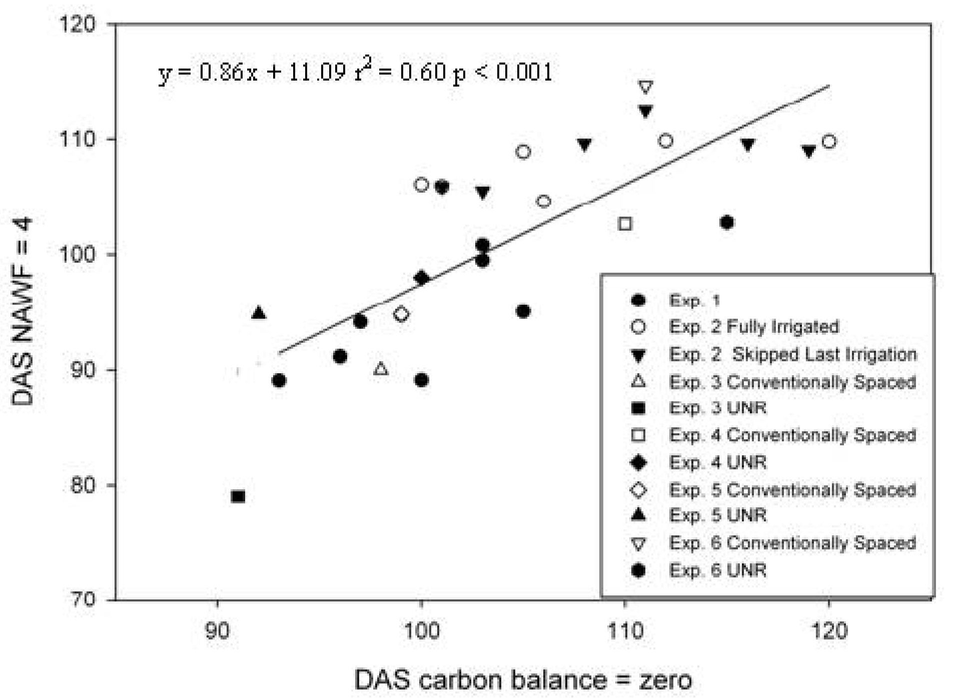

Figure 2. Relationship between physiological cutout (carbon balance equals zero) and DAS to NAWF equal 4 for Exps. 1 to 6.

Discussion

The aim of this study was to determine whether using NAWF=4 could be used as a tool to estimate cutout and assist in making late season management decisions in UNR spaced crops grown in Australia. We showed that the relationship between physiological cutout (carbon balance equals zero) and NAWF=4 was not affected by row spacing. Using a relationship of physiological cutout to NAWF=4 using a carbon balance approach for whole crop growth (CGR=FGR) was the first attempt of this kind for both

conventional and UNR crops. Across four seasons and six experiments carbon balance = zero showed a significant linear relationship to NAWF =4. Bourland et al. (1992) used a carbon balance approach that employed leaf photosynthesis and boll growth and were able to demonstrate that cutout and the last effective flower occurred at NAWF=5 for a conventionally spaced crop in Arkansas. Others have used last effective flower and % of final yield as an indicator of cutout and compared these to the number of NAWF to further assess this relationship and found that effective flowering contributing to yield can range from NAWF 3 to 6 across a range of environments (Bednarz and Nichols 2005; Viator *et al.* 2008).

Physiological cutout has been linked to crop maturity in conventionally spaced cotton (McConnell *et al.* 1995). However, for UNR spaced crops in this study, although they reached NAWF=4, and hence cutout much earlier than the conventionally spaced crops, this did not translate into differences in crop maturity. Gwathmey et al. (1999) in Tennessee U.S.A. also found that NAWF was earlier for UNR compared with conventionally spaced cotton and that using the same NAWF to estimate cutout in conventionally spaced cotton crops did not represent last effective flower contributing to the timing of maturity in UNR. Their study also showed that as much as 98% of yield of the crop had not yet been set by cutout in UNR compared with the conventionally spaced systems. Viator et al. (2008) assessed NAWF between conventionally spaced and 19-25 cm UNR spaced rows across a wide range of environments in the U.S.A concluded that last effective boll in UNR crops occurred NAWF 2 and at NAWF 3 for conventionally spaced crops.

Further investigations into the relationship between physiological cutout, NAWF and crop maturity are needed to determine the utility of NAWF approach for UNR crops in Australia. Last effective flower and maturity may be predicted by a different number of NAWF than currently used in conventionally spaced crops or possibly other monitoring techniques could be needed to be developed to assist with late season crop management decisions (e.g. timing of late pest control; last irrigation) in UNR crops.

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Overview of recent research into ultra-narrow row cotton in Australia

CSIRO Plant Industry

Rose Brodrick and Michael Bange

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Cover photos

Main: Planting with UNR planter at Narrabri. Photo: CSIRO

Small, left to right: UNR Responsive Management Experiment 2007-08, Merrowie, Hillston. Photos: Malcolm Pritchard

Introduction

Typically cotton in Australia is planted in rows spaced one metre apart. Historically this spacing was the narrowest spacing that would facilitate the use of draft animals. When tractors started to mechanise production, rows were kept at one metre for hand picking, then when harvesting was mechanised, rows needed to be at least 91cm apart to accommodate equipment.

Ultra-narrow row (UNR) systems (rows spaced <40 cm apart) were first developed in the United States in the 1950's and 1960's, for cotton production in areas with limited growth and low yield potential (short growing seasons, dryland situations, poor soils, etc). Since then advances in technologies such as growth regulators (e.g. Pix), transgenic varieties for improved insecticide and weed management, precision planters, narrow row spindle harvesters, and positive commercial experience generated renewed interest in narrow row production.

In theory UNR cotton (with more plants/m^2) should lead to earlier maturity without sacrificing yield. This would come about from having fewer early bolls on maturing plants and the higher plant population would compensate for less bolls per plant.

Other perceived advantages included earlier and more efficient light interception (as canopy closure would occur sooner) and that the smaller plants in UNR are less vegetative and will allocate a greater proportion of resources to bolls. In practice, this earliness has been difficult to achieve consistently in UNR trials both in Australia and the US.

Research was required to understand the complexity of UNR especially given the higher yield potential in Australia. Research led by Dr. Rose Brodrick studied UNR systems in detail over seven years (2001-2008) to determine how it differed in its growth and development to conventional 1 m spaced systems. The aim was to provide growers with guidelines for determining the appropriate plant population (row and plant spacing), and agronomic practices (e.g. water, N and Pix) to optimise yield and quality. All experiments used transgenic Bollgard II, Roundup Ready varieties.

> Ready for harvest: 1 m rows in foreground, UNR in background at Narrabri, NSW. Photo: CSIRO

What did we learn?

Compared to conventional 1 m spacings, UNR did not mature earlier in Australian systems, because fruiting site development was slowed in response to early plant competition impeding the opportunity for early fruit maturity. This response occurred much earlier and much more often than was previously thought. Yield however, was marginally higher in UNR (although highly variable) and this was achieved by having more bolls per area from the increased population. Bolls were smaller but the greater number of bolls in UNR compensated this. The use of Pix and changes in early season crop management for water and nutrition did not improve UNR yields. Primary fibre quality properties were unaffected in UNR systems, although grades can be reduced with stripper harvesters.

> Rose Brodrick checking plant establishment in row spacing experiments in Narrabri. Photo: CSIRO

UNR Comparisons with 1 m Spacings

Numerous field experiments were conducted to compare 1 m row spacing with 38 cm and 25 cm spacings over four regions and seven seasons to assess growth, maturity, yield and quality of cotton. Apart from one experiment these were all planted on 2 m beds. In addition, some experiments had extra treatments added to investigate management effects on UNR, such as variety (early maturing, Bollgard II, cluster type), the use of Pix, and the use of additional nitrogen and water. Management effects are discussed in the section on agronomy of UNR.

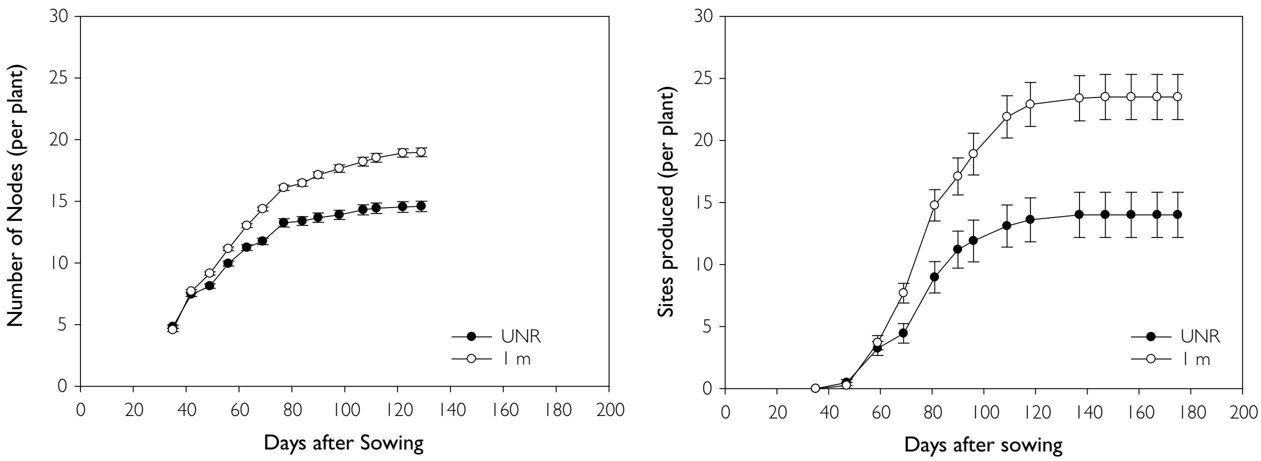
> Table: Summary table of yield and maturity differences from comparisons of UNR and 1m row spacings in four regions over seven years. X is no difference; up arrow means that treatment named had better yield or was earlier.

Year	Location	Row Configuration	Additional Management Treatment	Yield	Maturity
01/02	Narrabri	25cm, 1 m	Early Maturity/Normal Variety	×	×
02/03	Narrabri	25cm, 1 m	Cluster/Normal Plant Type	×	×
02/03	Breeza	25cm, 38 cm, 1 m	Twin row	×	×
02/03	Hillston	25cm, 38cm, 1 m		×	×
03/04	Narrabri	25cm, 38cm, 1m	No Pix vs. Pix Bollgard II vs.Non Bollgard II	×	×
03/04	Hillston	25cm, 1m	No Pix vs. Pix	×	×
04/05	Narrabri	25cm, 38cm, 1m	Bollgard II vs.Non Bollgard II	×	×
05/06	Narrabri	25cm, 38cm, 1m	Responsive Management	×	×
05/06	Hillston	38cm, 1m	Responsive Management	×	×
05/06	Hay	38cm, 1m	Responsive Management	↑ UNR	×
06/07	Narrabri	25cm, 38cm, 1m	Extra Early Irrigation Extra N Applied Extra N and Early Irrigation	×	×
07/08	Narrabri	25cm, 38cm, 1m		↑ Conv.	↑ UNR
07/08	Hillston	38cm, 1m		↑ UNR	×

UNR Growth and Development

A key finding of this research is that competition for resources between plants occurs very early (before flowering) and is much higher than expected in UNR plantings. This stress results in slower node development resulting in fewer fruiting sites (see Figure). For UNR plants to mature earlier, early node production and fruiting site production rates need to be similar to conventionally 1 m spaced crops.

The increased competition between plants in UNR also leads to smaller boll size (average of 9% in 25 cm and 4% in 38 cm) and lower final fruit retention on individual plants. Yield was not impacted as the smaller boll size was more than compensated by the increased plant population raising final boll numbers in UNR spacings (average of 21% in 25 cm and 7% in 38 cm).



> Node and fruiting site development per plant of 25 cm UNR and 1 m spaced cotton. Note that both node and fruiting site development slowed much earlier in the UNR plants compared with the 1 m space cotton.

Crop Maturity, Yield and Quality

Maturity

There was little evidence that narrow row spacings affected maturity (days after sowing to 60% open bolls). When data from all experiments was analysed together neither 25 cm or 38 cm spaced rows had earlier crop maturity compared to the 1m spaced rows. Only on one occasion in the 2007/08 season in Narrabri was crop maturity earlier. The 25 cm or 38 cm spacings were significantly earlier by 3 and 3.8 days respectively.

Yield

When UNR was compared with 1 m spacing for yield it was statistically higher on only two occasions. However when data from all experiments was combined and analysed the 25 cm row spacing was the only row spacing that differed from 1 m spacing (7% on average higher in UNR). This was due to increased boll numbers in the 25 cm UNR spaced crops. There was no improvement in yield of 38 cm spacing compared to the 1 m spacing.

Fibre Quality

Across all experiments there were no differences between the row spacings in terms of fibre quality.

> Ready for harvest UNR (38cm) responsive management experiment 2007-08, Merrowie, Hillston. Photo: Malcolm Pritchard

Agronomy of UNR

Plant populations

Two experiments were also undertaken to determine if arranging plants to give a more equidistant arrangement gave a yield or maturity advantage. 1m spaced rows were compared with 38 cm and 25 cm spaced rows which were sown to establish populations equivalent to 12, 24, 36 (only in 25 cm rows) plant m^{-2}. Overall the stability of cotton's yield and maturity response was maintained, with no consistent difference across inter- or intra-row spacings. Again, no differences in fibre quality were measured.

The only exception was higher lint yield in the 12 plants m^{-2} plant population in the 38 cm row spacing in the first experiment suggesting that there may be a yield advantage with more equidistant arrangement of plants; however, this relationship was not confirmed in the second experiment or in any of the other treatments.

Importantly, these experiments found that there were no consistent relationships between increased plant densities with 38 cm and 25 cm row spacings. Not having to use higher plant densities significantly reduces the costs of UNR cotton production. Seed costs using current recommended densities of 12 plants m-^{2} is only 3.82 % (\$88.80 ha^{-1}) of the total variable cost of cotton production compared with 7.43 % (\$177.6 ha^{-1}) and 10.75 % (\$266.4 ha^{-1}) for 24 plants m^{-2} and 36 plants m^{-2} respectively.

However, like other recent plant population research in 1 m spaced rows has reinforced the importance of getting even plant establishment. Therefore in areas where establishment can be difficult, lowering the sowing rate could result in patchy establishment and lower yields.

> UNR crop at Narrabri ready for harvest. Photo: CSIRO

Pix

The use of Pix in UNR did not improve yield. While maturity was earlier in UNR with Pix it had a similar effect on the 1 m spacing treatments.

Nutrition and Irrigation

These studies found that early plant competition in narrow systems limited yield potential and negated early maturity benefits. In an attempt to overcome this plant stress early, a large scale experiment in Narrabri with 38 cm and 1 m row spacing was undertaken to determine whether specific management practices could be developed to raise yields and provide earlier crop maturity. Treatments included applying prior to first square, an extra 60 kg/ha N, an extra irrigation, and an additional treatment with both extra N and water to both 38 cm and 1 m rows. The results of this experiment showed both extra early irrigation and nitrogen did not benefit the 38 cm crop. The only effect measured was an increase in yield in the 1 m crop from an extra irrigation. Importantly these results indicate that increasing early inputs did not alleviate the competition stress between plants which is most likely a result of more complex physiological processes (e.g. competition for space and light).

Varieties

There were no differences in the response of Bollgard II varieties to UNR measured in these experiments. Other experiments compared Bollgard II to conventional varieties, cluster type varieties and extremely early varieties to normal varieties, and none performed better or differently in the UNR spaced crops compared to the 1 m spaced crops.

Responsive Management Comparisons

Four 'responsive management' experiments were developed in consultation with growers and extension officers to assess impact of commercial on-farm management at a larger scale on UNR. Experiments were conducted at Hillston (repeated in two seasons), Hay and in Narrabri. These experiments were designed to allow 38 cm and 1 m crops to be managed as required. This allowed for Pix or additional nutrients to be applied (monitored by vegetative growth rates, and plant nutritional status). In addition these treatments were also compared to a "normal" management regime that was applied similarly across both row spacings.

Across all four experiments the narrow row spacing did not require different nutrient or growth regulator management. Differences between the row spacing only occurred in Hay for yield, however there were concerns that the 1 m spacing treatment had been unfairly biased as an inter-row cultivation may have caused damaged to plant roots.

Overview of Seven Years of Research

- Narrow row systems (25 cm and 38 cm) did not consistently improve yield, quality, or cause earlier maturity.
- Plant population differences from both changes in inter- and intra row spacing had little or no consistent response on yield, quality or maturity.
- The addition of earlier and higher inputs of water and nitrogen did not overcome plant competition effects that delay maturity in narrow row spacings.
- Different Pix management was not required between conventional and narrow row systems. Pix did not help raise yields of narrow row systems.
- No differences were identified in the response of non-Bollgard II and Bollgard II varieties to changes in plant population (including row spacing).
- UNR systems did not respond to varieties with different plant types (e.g. cluster fruiting), maturity or fruit retention when compared to 1 m spaced systems.
- Uniform plant population is vital for achieving optimum yield.

Other issues to consider

- A quality precision planter is needed.
- Good bed formation is important.
- Poor subbing at the centre of beds can occur despite irrigation allowed to run.
- There are limited numbers of contractors with narrow row pickers. Picking can therefore be delayed.
- Picking efficiency was less in high yielding crops.
- Picking was delayed for longer after rain as there is less air flow through the crop. Cutting after harvest can also be more difficult as plants are not dry.
- Shorter picking days can result as cotton needs to be about 9% moisture for effective picking in narrow rows compared with 12% for 1 m spacing.
- Narrow row systems can involve higher initial seed costs.
- Inter-row cultivation is limited to furrows under UNR systems. Chippers can also find it difficult to remove weeds effectively.
- Need to disc soil post harvest as root cutting is not possible after UNR.

Management Recommendations

- Management considerations for narrow row are not different to 1 m row spacing.
- Intangible issues need considering.
- No change in management for high fruit retention Bollgard II crops.
- Choose a variety that is regionally adapted.
- Uniform plant establishment is critical to maximise yield.

Conclusion

From such detailed research it can be concluded that although the 1 m spacing systems may have evolved to meet practical and mechanical requirements, cotton's growth habit allows it to be grown across a range of row and plant spacings. For growers considering narrower row spacings, this research has provided management suggestions. A key message is that uniform plant establishment is vital, whichever row configuration/plant population is adopted.

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Do sowing rules change for Bollgard II cotton?

By Michael Bange[1] and Rose Brodrick[2]

Bollgard II cotton reduces the need to use chemical pesticides to control *Helicoverpa spp.*, which feed preferentially on young growing tips or reproductive structures of cotton plants. As a consequence of the improved insect control and the reduced use of chemical pesticides conserving beneficial insect activity, the retention of squares (flower buds) and young bolls (fruit) is improved, resulting in earlier and overall higher fruit retention of Bollgard II varieties.

As cotton is an indeterminate species, the timing of crop maturity is largely determined by the capacity of the plant to continue the production of new fruiting sites.

A crop reaches 'cutout' when the demand on crop resources increases to a point when none remains for the initiation and support of new fruiting sites.

A limitation may occur with high fruit retention crops if the demands of high early fruit load (due to the high retention) reduce resources available for continued growth and fruit initiation – leading to smaller plants, earlier cutout and lower yield. To overcome this potential problem, two approaches have been suggested.

First, sowing of Bollgard II varieties maybe delayed by up to a month. The warmer conditions associated with this would increase canopy size, which would help meet the greater demand from the higher earlier fruit load.

Second, plant population could be increased beyond the recommended number of eight to 12 plants per square metre. The higher plant population would compensate for the smaller plants that may result from higher fruit retention of Bollgard II.

AT A GLANCE...

- We examined whether Bollgard II had different responses to sowing date and plant population compared to non-Bollgard II varieties.
- Sowing date comparisons were made across three seasons in Narrabri, while plant population comparisons were made in two seasons in Narrabri, and in a single season each in Moree and Hillston.
- These experiments found that Bollgard II had a wider sowing date window but there was no evidence that plant population affected yield or quality when compared to non-Bollgard II varieties.
- The agronomic principles for plant population are essentially the same for Bollgard II varieties.

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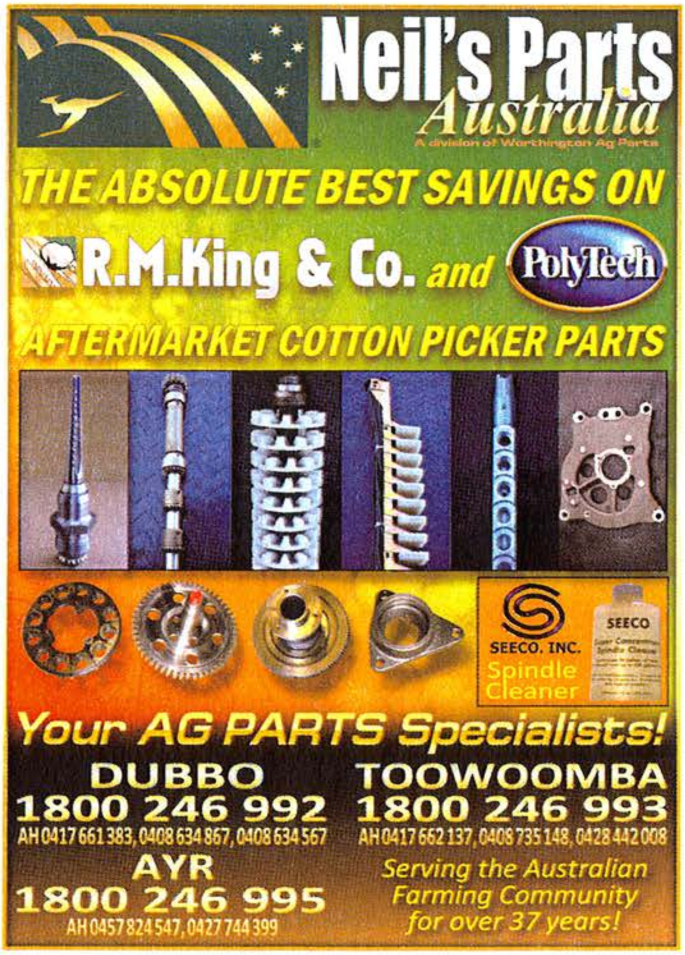


Seven field (three sowing date, four plant population) experiments compared the yield and fibre quality performance of Bollgard II with non-Bollgard equivalent varieties.

METHODS

Cultural details

All sowing time field experiments were conducted at the Australian Cotton Research Institute (ACRI) Narrabri from 2002 to 2005, while two plant population experiments were sown in 2005 and 2006 (Table 1). A further two population experiments were conducted at Moree (Glen Prairie) and Hillston (Merrowie). Sowing time experiments (three replications per treatment) consisted of three sowing dates ranging from September 24 to November 28 using Sicot 189 for the non-Bollgard II variety and Sicot 289B for the Bollgard II variety. Plant population experiments (four replications per treatment) consisted of target plant populations of 4, 8, 12, 16 plants per metre of row with one metre row spacing.

Varieties used in Narrabri and Hillston experiments were Sicot 71BR for the Bollgard II variety and Sicot 71RR for the non-Bollgard II variety. The Moree experiment used Sicot 71 and Sicot 71B.

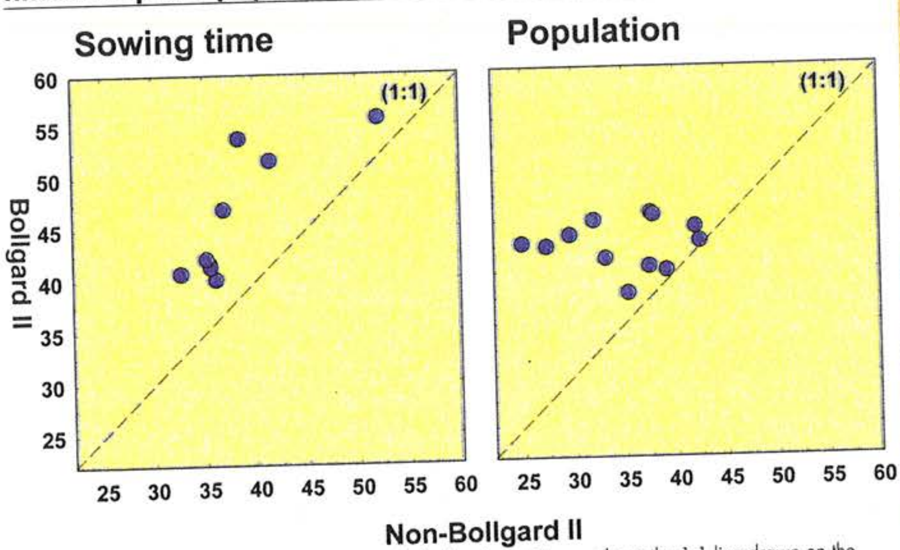
Due to the limited amount of available Bollgard II seed for the sowing time experiments, plots were small and handpicked to attain lint yield and quality. Plots were larger in the population experiments and were machine picked. Final total fruit retention was measured on one square metre in each plot when 100 per cent of bolls were open. Fruit retention is expressed as the percentage of open bolls relative to the number of total fruiting sites present. Fibre quality was measured using HVI.

RESULTS

Fruit retention

Across all sowing time and population experiments, total fruit retention was generally greater for the Bollgard II variety (Figure 1). In the sowing time experiments there was no significant interaction for fruit retention with sowing date and variety, but there was one experiment (sowing 2003) where the level of retention declined significantly with later sowing. There was no significant interaction of variety and plant population on fruit retention. Total fruit retention was only affected by plant population.

FIGURE 1: A plot of total fruit retention of the Bollgard II varieties versus the non-Bollgard II varieties for the sowing time and plant population studies



Also shown is the 1:1 line. In this comparison the further the points are above the 1:1 line drawn on the graph the greater the retention of Bollgard II compared to the corresponding non-Bollgard II treatment.

TABLE 1: Summary of experiment details of sowing date and plant population experiments

Experiment	Sowing date	Established plant population (plant/m²)
Sowing date Exp. Narrabri – 2002	24 Sep., 15 Oct., 11 Nov.	12.0
Sowing date Exp. Narrabri – 2003	13 Oct., 5 Nov., 28 Nov.	11.0
Sowing date Exp. Narrabri – 2004	6 Oct., 22 Oct., 4 Nov.	13.5
Plant Population Exp. Narrabri – 2005	25 Oct.	4.4, 8.3, 10.5, 14.1
Plant Population Exp. Moree – 2005	6 Oct.	4.7, 7.2, 11.4, 15.2
Plant Population Exp. Hillston – 2005	1 Oct.	2.8, 7.1, 10.5, 11.2
Plant Population Exp. Narrabri – 2006	18 Oct.	5.2, 8.1, 12.2, 16.4

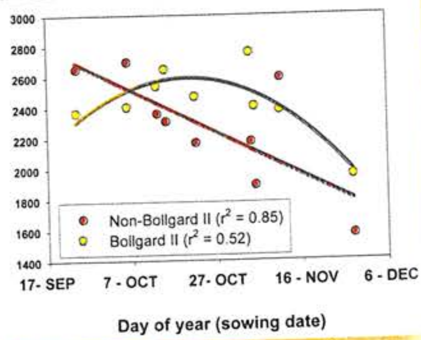
YIELD

Yields were consistently lower for the non-Bollgard II variety with later sowing dates in all experiments, while yield only substantially declined for the Bollgard II with the much later sowing in 2004. Pooling data across all experiments showed that the relationship between yield and sowing date differed significantly between the Bollgard II and non-Bollgard II varieties (Figure 2).

Yield of the non-Bollgard II variety declined linearly with sowing date while Bollgard II yields were less affected until the very late sowing on November 28.

When the lint yields for different plant populations were compared within an experiment, there was no significant interaction of variety and plant population on lint yield (Figure 3). This implied that there was no change in the response of Bollgard II to plant population compared with the non-Bollgard II varieties. Plant population only

FIGURE 2: The effect of sowing date in Narrabri on yield (handpicked) of Bollgard II and non-Bollgard II varieties



affected yield in the Hillston experiment where the lowest population of 2.8 plants per square metre yielded significantly less. Establishment was patchy in this treatment due to cool conditions after sowing. Significant variety differences in lint yield were measured in the Narrabri and Moree experiments sown in 2005.

In Narrabri, Bollgard II yielded more than the non-Bollgard variety (Sicot 71BR = 2909 and Sicot 71RR = 2659 kg/ha) and was associated with higher boll numbers. While in the Moree experiment, the non-Bollgard II variety had a significantly higher yield than the Bollgard II variety (Sicot 71 = 2658 and Sicot 71B = 2484 kg/ha) and was associated with a larger boll size and higher gin turnout in the non-Bollgard II variety.

When data was pooled across all experiments there were no significant relationships developed between relative yield (average population treatment yield divided by the maximum yield measured in that experiment) and plant population (Figure 5) between Bollgard and non-Bollgard II varieties.

FIBRE QUALITY

Fibre length and micronaire was affected by time of sowing for both non-Bollgard and Bollgard II varieties (Figure 4). Micronaire decreased while fibre length increased for both varieties as sowing date was delayed. Fibre strength was unaffected by variety or sowing date in all experiments in this study.

Individually within experiments, there was no significant interaction of variety and plant population on fibre quality parameters. This again implied that there was no change in the response of Bollgard II to plant population compared with the non-Bollgard II varieties. The response to plant population was similar for fibre quality as the response to yield. When data across all experiments was pooled there were no significant relationships between relative yield and plant population between Bollgard and non-Bollgard II varieties (Figure 5).

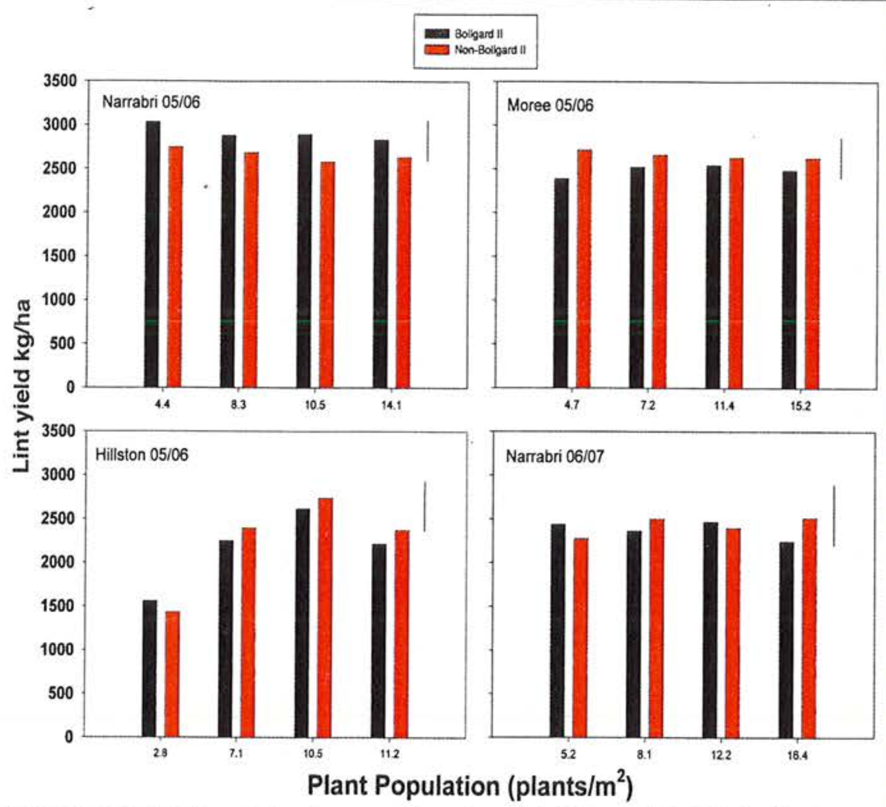
DISCUSSION

These studies highlighted the opportunity to delay sowing of Bollgard II and not affect yield but improve quality. The yield of the non-Bollgard II variety declined linearly with sowing dates later than mid-late October which is consistent with previous reports of responses to sowing time in non-Bollgard varieties in studies by Greg Constable in the 1970s. In contrast, the Bollgard II variety maintained high yields until December before declining. This is most likely due to the higher season long fruit retention of Bollgard II across all sowings, leading to a shorter fruiting cycle (first flower to maturity).

This means that the reduced time between flowering and the end of the potential growing season that resulted from later sowing would have had less impact on the capacity of the crop to complete its fruiting cycle and mature the same number of bolls as at normal sowing dates. The non-Bollgard II variety, with lower season long fruit retention across all sowings, required more time to set and mature its fruit load.

There was also no evidence in these studies that Bollgard II varieties at any population limited yield compared with its non-Bollgard II equivalent. With the exception of the low plant population at Hillston

FIGURE 3: Lint yield for each plant population experiment comparing Bollgard II and non-Bollgard II varieties



Differences greater than the error bar shown on each graph mean that there are statistically significant interactions between variety and plant population.

Large scale population trial conducted at Glen Prairie Moree in 2005–06 comparing Bollgard II to non-Bollgard II varieties.

FIGURE 4: The effect of sowing date in Narrabri on fibre length and micronaire of Bollgard II and non-Bollgard II varieties

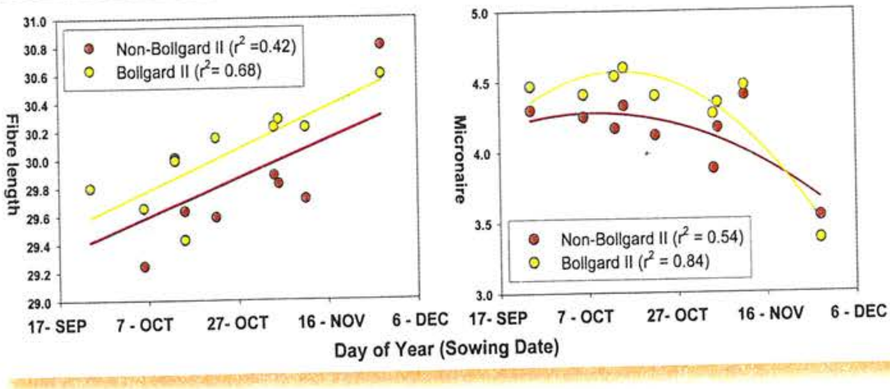
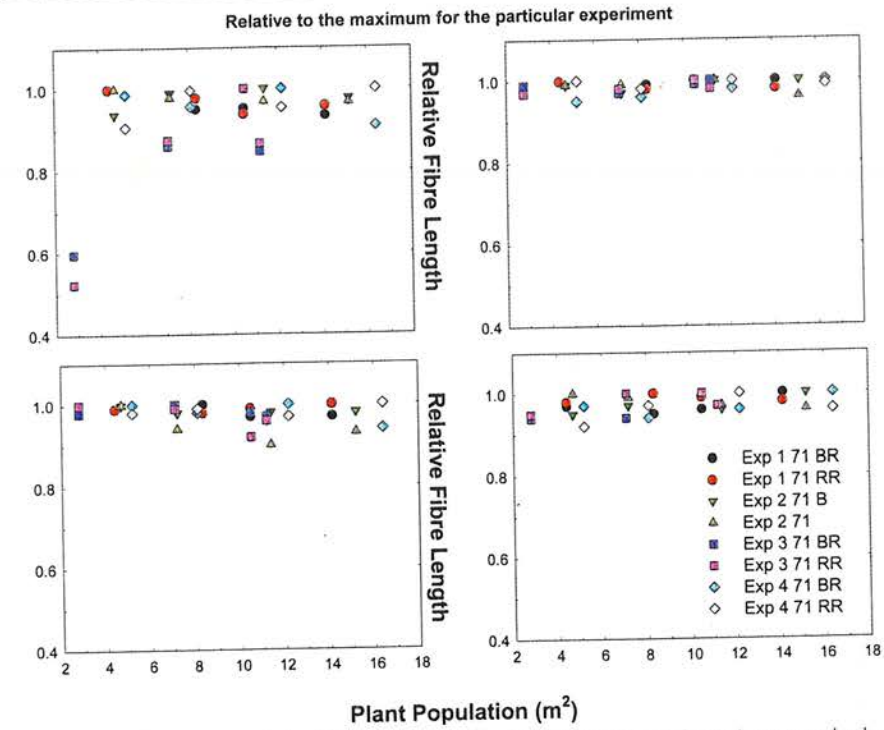


FIGURE 5: Relative yield and fibre quality traits for the four field experiments that investigated the impact of plant population between Bollgard II and non-Bollgard II varieties



Relative yield or quality is calculated for each treatment by dividing the average for each treatment by the maximum average treatment measured in the same experiment.

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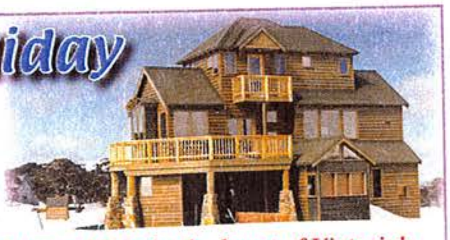

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of 2.8 plants per square metre, yield and quality did not change (range four to 17 plants per square metre). At Hillston, the cooler temperatures at the beginning of the growing season led to poorer plant establishment.

CONCLUSION

The improved fruit retention of Bollgard II offers opportunities to consider later than normal sowing dates in longer season locations such as Narrabri without impacting on yield and quality. Given this opportunity, research is also investigating the opportunity to improve resource use efficiencies (such as water and nitrogen). This was not an option with non-Bollgard II varieties as yield was reduced as crops were sown later.

Previous research into the plant population of non-Bollgard varieties has found in Australia the optimum population for one metre row spacing was around eight to 12 plants per square metre. These studies showed no reason to revise recommended plant populations for Bollgard II varieties in Australia and re-emphasised the importance of establishing a uniform crop stand to optimise yield and quality.

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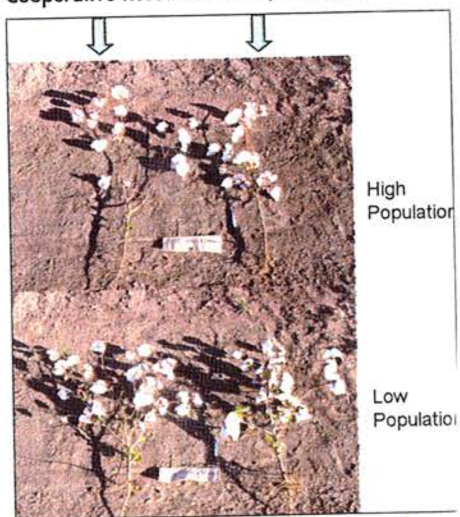
[2]Cotton Catchment Communities Cooperative Research Centre, Narrabri.



Despite changes in plant structure and fruit distribution across plant populations at Glen Prairie in 2005–06, there were no changes in yield or quality response to plant population between Bollgard II and non Bollgard II varieties.