Rural R&D for Profit Programme

Irrigation Agronomy for Tailored and Responsive Management with Limited Water
Final Report

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Dr Hizbullah Jamali and Dr Michael Bange

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Department of Agriculture and Water Resources
Postal address GPO Box 858 Canberra ACT 2601
Telephone 1800 900 090
Web agriculture.gov.au

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Plain English summary

Cotton production in Australia is limited by the lack of water availability in most years. This project aimed to enable growers to adapt and tailor their irrigations to an uncertain future climate and water availability situations based on definitive data to manage risk. Earlier research supported by the CRDC enabled developing an irrigation scheduling method for furrow irrigated cotton based on canopy temperature monitoring. Through being strongly related to soil water availability, canopy temperature measurements enable continuous monitoring of a crop's requirement for irrigation using a plant-based method that is practical to use on commercial farms. Through this project the canopy temperature method was further refined for fully irrigated systems and its use tested in partially irrigation situations. The three key areas of research for this project were:

1. **Integrated Irrigation Agronomy for High Yielding Systems**:

To achieve the highest yields the irrigation management of the crop needs optimizing through the entire crop development period. We conducted detailed research trials at the Australian Cotton Research Institute (ACRI) near Wee Waa (NSW) to optimize irrigation strategies at planting and during early, mid and late season which are explained below:

We conducted a comparative investigation of **pre-watering** and **watering up** at the ACRI to determine the best irrigation strategies for crop establishment. Watering up one day after planting resulted in slower germination and 25% less plants established compared with the crop pre-irrigated a week before planting. Soil temperature in the watered up treatment was up to 2.4 °C cooler than in pre-watered soil which most likely affected germination and establishment. These results are important in that there was only one cold shock (i.e. minimum air temperature <12 °C) during this trial in 2015-16 season compared with 20 and 10 cold shocks in the following two years, respectively, yet plant establishment was affected. It is important to consider these effects of watering up in cotton and, where watering up is unavoidable because of other farm factors, planting time may be adjusted to avoid cooler soil temperatures.

The **timing of first in-season irrigation** (excluding at planting) drives the establishment of a plant with sufficient vegetative growth to support high yields. Bollgard® varieties with high fruit retention may benefit from vigorous plant growth translating into high yields. A trial conducted at ACRI during 2015-16 to optimize the timing of first irrigation did not generate the expected treatment differences in plant development and yield because of wet weather conditions. It was identified that thermal cameras can be an effective tool for monitoring plant water stress during early season when canopy temperature infrared sensors cannot be used because of smaller canopy.

Timely application of **mid-season irrigations** is most important in terms of its effect on yield. In practical situations most cotton farmers may have to make an irrigation decision few days in advance. We investigated integrating canopy temperature and short-term weather forecast to make an irrigation decision five days in advance. Irrigations were planned in advance by either using an average daily stress time value based on historic data (treatment 1), or applied earlier or later than the predicted date based on short term weather forecast using dynamic deficit approach (treatment 2). Both the treatments underestimated the canopy temperature stress time compared with the measured observations. It was concluded that an irrigation decision

made in advance should be based on canopy temperature that is predicted from short term weather forecast rather than historical climate data.

Detailed trials were conducted at the ACRI to optimize the **timing of last irrigation** using canopy temperature sensors in a fully irrigated cotton system. The results showed canopy temperature sensors can be used for scheduling last irrigation with a need for further testing in different weather conditions to build confidence in the results.

2. Irrigation scheduling with limited water

We conducted detailed trials to develop irrigation decision frameworks in limited water situations to limit the risk and seasonal variability. The utility of canopy temperature sensors was investigated in partially irrigated systems with three different row configurations commonly used in cotton industry. There were strong relationships between yield and canopy temperature (and its derivatives) in all row configurations. As canopy temperature is affected by a plant's access to (or lack of) soil water, regardless of location of water within soil profile, this method may help improve irrigation scheduling in partially irrigated systems where different row configurations are used. We tested applying a single irrigation during flowering at canopy temperature stress thresholds higher than that used in fully irrigated systems. In the years we conducted these studies we could extend/delay our irrigations with little impact on yield and yield gains in one instance. Further research will be needed to understand how we can best utilize our ability to better quantify stress (using canopy temperature sensors) in years that are dissimilar to those experienced in this study to manage risk in limited water situations.

3. Research Support for high impact delivery and adoption

Research support was provided in collaboration with the Cottoninfo team through on-farm trials and field days. On-farm trials were conducted in different cotton growing valleys in New South Wales (Wee Waa, Rowena, Walgett) and Queensland (Emerald, St. George), where farmers integrated the canopy temperature approach in their irrigation decision making. The overarching philosophy of these trials was to provide farmers the opportunity to integrate different tools for making an irrigation decision. Trials in Emerald and St. George resulted in saving at least one irrigation on both farms using canopy temperature sensors without impacting yield. This research enabled farmers to use an irrigation scheduling tool that is based on real-time monitoring of a crop's need for water. A commercial partner has been identified to extend canopy temperature approach of irrigation scheduling to the Australian cotton industry.

Some important **future research** areas are: 1) Utility of plant-based method of irrigating such as canopy temperature for optimizing crop water use efficiency from the perspective of less water use; 2) capturing spatial variability on large farms with canopy temperature sensors, and/or how many canopy sensors per farm are required to make the best irrigation decisions? 3) Continuing research on utility of canopy temperature sensors in partially irrigated systems, and 4) Utility of thermal images in assessing crop stress during early cotton season.

This project was funded by the Department of Agriculture and Water Resources, and the Cotton Research and Development Corporation through Rural R & D for Profit program.

Abbreviations and glossary

Abbreviation	**Explanation**
ACRI	Australian Cotton Research Institute
BIOTIC	Biologically Identified Optimum Temperature Interactive Console
CRD	Completely Randomized Design
CSD	Cotton Seed Distributors
DAS	Days after sowing
DD	Degree days
DH	Deficit hours
FF	First flower
GPWUI	Gross Production Water Use Index
IWUI	Irrigation Water Use Index
RCBD	Randomized Complete Block Design
SH	Stress hours
ST	Stress time

1 Project rationale and objectives

Irrigation management relies on growers taking many things into account to make an irrigation decision. Irrigation timing is critical to minimise negative effects on cotton yield and fibre quality. Successful managers do this well, but often need to rely on experience rather than definitive data to make decisions. Across the industry, there remains a significant gap between the yield and water use efficiency of the highest achievers and the industry average.

Improved irrigation agronomy and ongoing industry leadership in irrigation research to support growers in all regions is critical to close this gap. When faced with changing conditions (e.g. water availability, hot/cool conditions, new fields, new varieties) all managers need strategies to assist them to confidently decide the best time to irrigate. Differences in soil type, regional climate, water availability, system capacity, attitude to risk and the amount of data collected means that irrigation management has to be tailored and responsive.

Variable climates, new varieties and limited water availability has highlighted a need for developing new integrating strategies for difficult irrigation decisions at different stages of crop development in a fully irrigated system. In addition there is a need for ongoing research into limited water scheduling to understand the physiological response to water stress in partially irrigated conditions grown in different row configurations. Using canopy temperature stress triggers offers significant opportunities for scheduling in limited water situations. There is a need to characterise risk in these systems to enable the development of decision making frameworks that limit risk and seasonal variability.

The overall aim of this project was to develop new irrigation strategies to take the guesswork out of irrigation decisions, enabling growers to adapt and tailor their irrigation to an uncertain future climate and water availability situations.

Three key areas of research are proposed to optimise yield, quality, efficiency and profit through:

1. Integrated Irrigation Agronomy for High Yielding Systems: developing novel integrating strategies for difficult irrigation decisions through the entire irrigation period. Undertaking research specifically aiming to: determine the best irrigation strategies for crop establishment (pre-irrigating vs. watering up); determine and assess tools to assist in determining when to apply the first irrigation to establish a plant with sufficient vegetative growth to support high yields ; mid-season irrigation decision making to ensure timeliness of irrigating during this critical period (e.g. integrating canopy temperature and dynamic deficit approaches with the short-term forecasts); and developing strategies and tools for determining the optimum timing of the last two irrigations.

2. Limited Water Scheduling: research aiming to develop partially irrigated decision making frameworks limiting risk and seasonal variability.

3. Research Support for high impact Delivery and Adoption: in collaboration with the Cottoninfo team, partnering with grower groups to develop scientific protocols for

experiments that aim to test the latest knowledge and tools to address grower led regionally specific irrigation agronomy research questions.

2 Method and project locations

Overview of trials

A series of trials were conducted at the Australian Cotton Research Institute (ACRI) and at commercial farms at different locations in New South Wales and Queensland (Table 1, Fig. 1) during the three cotton seasons (2015-2018). Weather has been highly variable duirng the three cotton season in most valleys where research was conducted. A summary of weather conditions at the ACRI where most of detailed trials were conducted is given in table 2 below. Weather conditions were most optimum for cotton growth during the 2015-16 season which received highest in-season rainfall (352 mm) and least number of cold shocks (1) and heatwaves (2). The 2016-17 season was the worst for cotton growth with the highest number of cold shocks (18) as well heat waves (20). The 2017-18 season received 12 heatwaves and 10 cold shocks with least amount of rain (205mm) among three seasons (Table 2); however, delaying planting to late October and early November resulted in the best crop establishment during 2017-18 as weather had warmed up by then with negligible cold shocks then on. Evaporative demand was also highly variable and decreased in the order 2016-17 > 2017-18 > 2015-16 (Table 2).

Table 1: A summary of trials conducted at different locations during the course of project spanning over three cotton seasons

Season	**Location**	**Trial name**
2015-16	ACRI	Irrigation at planting
	ACRI	Early season irrigation
	ACRI	Mid-season irrigation
	ACRI	Late season irrigation
	ACRI	Limited water
	Emerald	Grower trial
2016-17	ACRI	Late season irrigation
	ACRI	Early season stress
	ACRI	Limited water
	ACRI	Dial in a yield
	St. George	Grower trial

	Emerald	Grower trial
	Wee Waa	Grower trial
2017-18	ACRI	Last Irrigation
	ACRI	Limited water
	St. George	Grower trial
	Wee Waa	Grower trial
	Walgett	Grower trial
	Rowena	Grower trial

Ten (10) trials were conducted at the ACRI with detailed agronomic measurements and eight (8) trials conducted at commercial farms mostly in collaboration with the CottonInfo extension team. These trials investigated the irrigation strategies to optimize yield in fully and partially irrigated cotton systems. A major focus of these trials has been utilizing canopy temperature infrared sensor technology which is a direct measure of response to plant's access (or lack thereof) to soil water. At ACRI, the trials during 2015-16 season used Bollgard II (Sicot 74BRF) seed variety. In subsequent two seasons Bollgard® III (Sicot 746B3F) seed variety was used. Trials on commercial farms also used Bollgard® II during 2015-16 and Bollgard III seed varieties during 2016-17 and 2017-18 seasons. The three seasons were highly variable in terms of climate (Table 2). Genstat statistical package (VSN International, UK) and R (RStudio Inc, Boston, MA, USA) were used for all statistical analyses in this report.

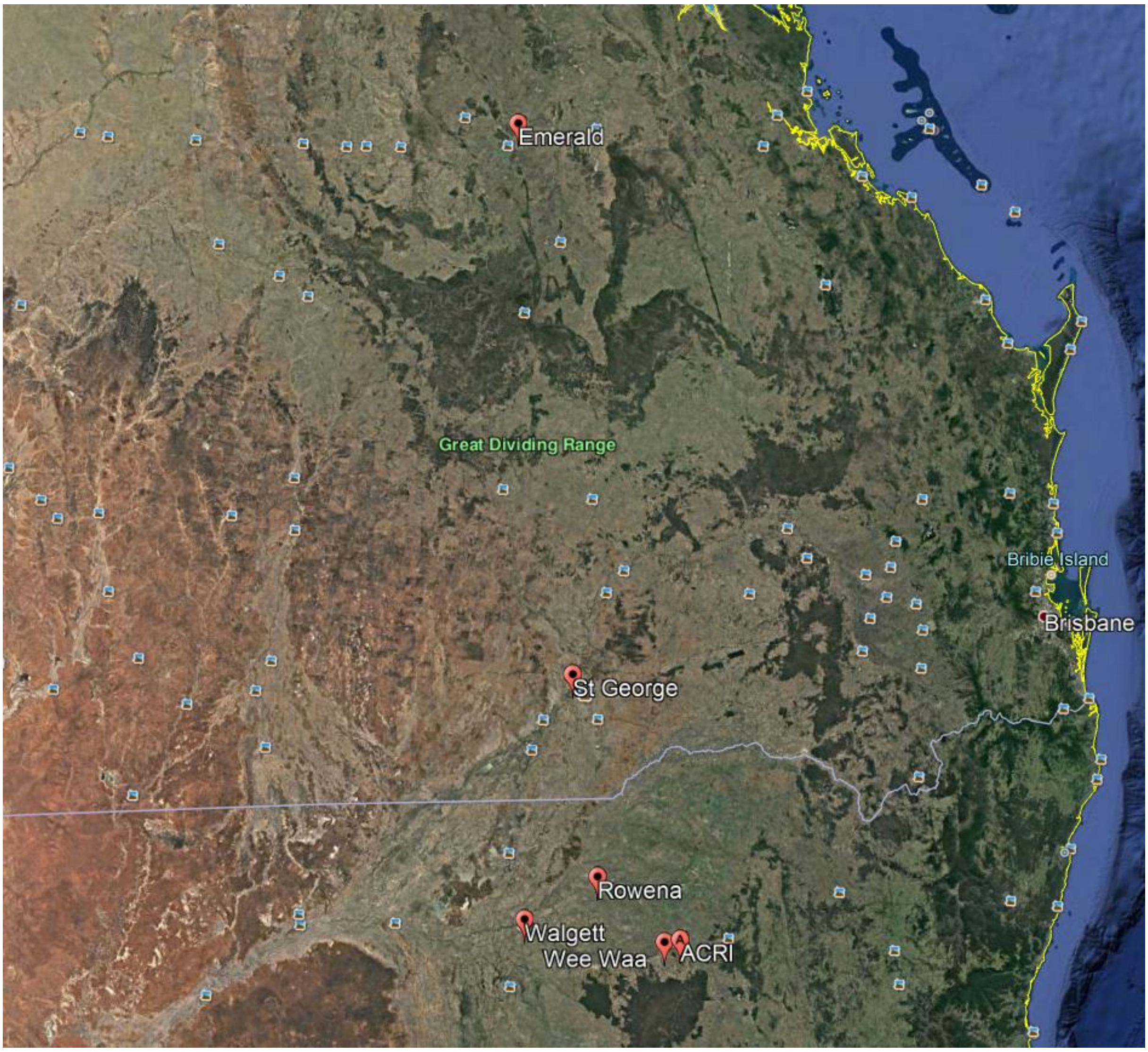

Figure 1: Location of trials shown in red markers conducted in different cotton growing regions in New South Wales and Queensland

Table 2: Summary of weather conditions at the Australian Cotton Research Institute (ACRI) during three cotton seasons (15 October – 15 March)

Season	**Avg. Max. T**	**Avg. Min. T**	**>40 °C**	**<11 °C**	**Rainfall**
	°C	**°C**	**Days**	**Days**	**mm**
2015-16	34	18	2	1	352
2016-17	34	18	18	20	225
2017-18	33	18	12	10	205

Objective 1: Integrated Irrigation Agronomy for High Yielding Systems

Managing a cotton crop for high yield and fibre quality requires optimizing irrigation strategies from planting to throughout crop development. Poor crop establishment or water stress or over watering at any stages of crop development may result in yield penalties. Detailed research trials were conducted at the Australian Cotton Research Institute (ACRI) as well as on farms to optimize irrigation strategies for different crop development stages as below:

1. Germination and crop establishment
2. Early season irrigation
3. Mid-season irrigation scheduling
4. Late-season irrigations

Irrigation strategies for germination and crop establishment

A research trial was conducted in field A2 at the ACRI during 2015-16 cotton season to investigate the effect of irrigation management strategies at planting on crop establishment, early growth and yield. This trial included two treatments:

1) Pre-watering
2) Watering up

Each treatment consisted of a single large plot of 16 rows with 60 m row lengths. Field was planted with Sicot 74BRF seeds at 3.5 cm depth on 15th October 2015. Solid row configuration was used with 1 m (~40 inch) spacing between rows. Pre-irrigation treatment was irrigated on 7th October (i.e. a week before planting) while watered up treatment received an irrigation one on 16th October (i.e. one day after planting). Soil temperature was monitored every 30 minutes using tiny tag sensors placed at 5 cm depth. Plant emergence was measured by counting the number of new plants emerged every two to three days in four subplots of 5m in measurement row of each plot. Crop establishment was measured at squaring in the same plots used for emergence counts. Ten plants were marked in each plot and number of nodes and plant height measured weekly. Plant biomass was measured weekly between one-true leaf stage to when nodes above white flower (NAWF) were <4 by harvesting plants in 1 m^2 plots. A subsample of four plants was used to monitor plant height, leaf area, number of nodes, squares and bolls, and dry mass of leaves, stems, squares and bolls separately. Soil water content was monitored by taking neutron probe measurements every 10 days, and before and after irrigation applications (data not presented). Irrigations in the mid- and late-season were applied following standard farmer practice. Cotton was harvested using a single row picker from the middle row which was designated as measurement row at the start of season and received minimum human traffic during in-season crop measurements. Harvested samples were ginned at the ACRI to separate lint from seed. Fibre quality was also measured at the CSIRO HVI facility based at the ACRI. A student's t-test was used to analyse the differences in yield and fibre quality.

Timing of early season irrigations

One detailed experiment was conducted at the ACRI during 2015-16 cotton season to determine the implications of stress prior to squaring on vegetative growth and ultimately yield. Two treatments included:

1. Control (grower practice)
2. Early first irrigation

A Completely Randomized Design (CRD) with two treatments and three replicates was used. Each plot consisted of 16 rows each with 60 m row lengths. Field was planted with Sicot 74BRF seeds at 3.5 cm depth on 15th October 2015 in solid row configuration with 1 m spacing between rows. Plant development measurements were made as described for the previous experiment. Soil moisture in the surface (0-10 cm) layer was monitored between sowing and first irrigation weekly by using theta probes and gravimetrically. During the mid- and late-season, soil water content was monitored by taking neutron probe measurements every 10 days, and before and after irrigation applications. Irrigations in the mid- and late-season were applied following standard farmer practice. Cotton was harvested using a single row picker from the middle row which was designated as measurement row at the start of season and received minimum disturbance during in-season crop measurements. Harvested samples were ginned at the ACRI to separate lint from seed. Fibre quality was also measured at the CSIRO HVI facility at the ACRI. A student's t-test was used to analyse the differences in yield and fibre quality between the treatments.

Estimating crop stress with thermal images

A major focus of this project has been to build on previous research for developing irrigation strategies using canopy temperature – a plant-based measurement. However, canopy temperature sensors cannot be used to schedule irrigations earlier in the season when canopy is smaller because of soil in the background which is generally warmer than the plant canopy. Canopy closure generally occurs between squaring to first flowering. A preliminary trial was conducted at the ACRI to investigate the utility of thermal imaging to measure canopy temperature during the early season to the accuracy required for calculating plant water stress. A FLIR camera was used to take thermal images at 15 minute frequency (Fig. 2). Images were downloaded manually every day. In the first instance the aim was to determine if differences in stress of young plants could be detected using thermal images. Ultimately the aim of future research would be to develop algorithms that separate the cotton canopy from soil background and use the temperature of separated canopy leaves to calculate crop stress.

Figure 2: Thermal camera on a tower taking images to monitor crop stress during early cotton season at ACRI.

Mid-season irrigation scheduling

Plants have optimum temperatures for different physiological functions and beyond these optimal, growth is impaired and yield limited. For cotton the canopy temperature for optimum physiological functioning (e.g. photosynthesis and stomatal conductance) is 28 °C (Conaty et al. 2011). But some plants, including cotton, can maintain certain physiological functions even after their optimum temperature is breached for a short period. The time a crop's canopy temperature stays above optimum temperature is referred to as stress time, stress hours or deficit hours – these terms are used interchangeably in this report. It is critical to determine the cumulative stress time threshold – i.e. the cumulative stress hours for a crop before its starts to lose yield. Recent research has adapted the BIOTIC (Biologically Identified Optimum Temperature Interactive Console) stress time threshold that can be used in Australian furrow irrigated systems (Coast et al. unpublished).

The underlining principle behind a stress time threshold using canopy temperature is that by using plant-based measurement such as canopy temperature, in conjunction with measurements of atmospheric conditions that impose water stress on a plant can be determined and the information used to signal the initiation of irrigation. This is so because, when demand for and loss of water exceeds supply, plants close their stomata which with time results in increased plant internal and canopy temperature. Irrigation is triggered when the cumulative canopy temperature stress exceeds the set optimum threshold.

Scheduling irrigations in advance

We use wireless infrared thermometers (IRTs) to continuously measures and logs plant canopy temperature (Fig. 3). Currently, we are able to successfully schedule irrigations one or two days in advance using canopy temperature sensors, however this is only practical in an experimental setting and there is a need to develop predictive capacity to enable growers to schedule irrigation a number of days in advance. Farm size and layout and its distance from the source of irrigation water (e.g. storage dam) are some of the key factors that determine the number of days a farmer has to make a decision in advance. By integrating research that uses the short term forecast to predict crop water use (dynamic deficits) and canopy temperature we may be able to refine irrigation scheduling to be more closely linked with the current and future predictions of crop stress, and optimise irrigation water use.

A replicated trial was conducted at the ACRI during 2015-16 cotton season to evaluate the integration of different "refined scheduling" techniques to investigate the impacts of these techniques to predict future crop stress/water use and understand how this impacts on crop stress, growth, yield and water use. A Completely Randomized Design was used with three replicates and two treatments. All plots were pre-watered and planted with Sicot 74BRF at seed depth of 3.5 cm on 15th October 2015 in solid row configuration and 1 m spacing between rows. Treatments included:

1) Tc Average:
2) Tc Forecast:

For the Tc Average treatment, irrigation date was determined five days in advance using a daily average stress hours of 6.39 stress hours based on energy balance analyses of historic climate and canopy temperature data of last ~5 years that calculated the number of stress hours a fully irrigated crop would experience under average weather conditions. For the Tc Forecast treatment, daily stress hour of 6.39 was used when forecasted evapotranspiration (ETo) rates were between 5 mm day^{-1} and 7 mm day^{-1}; however, daily stress hours were adjusted to 4.5 or 8 hours when forecasted ETo was less than 5 mm day^{-1} or greater than 7mm day^{-1}, respectively.

The field was planted with Sicot 74BRF seeds at 3.5 cm depth on 15th October 2015 in solid row configuration with 1 m spacing between rows. Plant development measurements were made as described for the previous experiment. In the middle row of each plot two infrared sensors (ArduCrop, CSIRO, Canberra) were installed to monitor canopy temperature at five minute intervals. These canopy sensors are wireless and transmit data to a central database (SensorDB, CSIRO, Canberra) using 3G network. Canopy temperature data was converted to stress time using the BIOTIC algorithms.

Figure 3: Canopy temperature sensors installed in a cotton field at ACRI

Late-season irrigations

Two field experiments were conducted at ACRI in 2016-17 and 2017-18 seasons to assess the utility of canopy temperature sensors for deciding the timing of last irrigation in a fully irrigated cotton crop. Experimental design included a Randomized Complete Block Design (RCBD) with three treatments and three blocks. Treatments included:

1) Control
2) Medium Stress
3) High Stress

Each plot consisted of 16 rows planted in solid row configuration with 1m row spacing. In 2016-17 season the plot length was 60 m with two canopy sensors installed per plot. In 2017-18, plot length was 30 m with one sensor installed per plot. A buffer of 10 m and 60 m planted in solid row configuration was left at head ditch and tail drain, respectively. All plots were irrigated on the same day using the pre-determined deficit hour threshold (Coast et al.) between squaring to the irrigation just before 20% open bolls. Last irrigation was triggered when 20% bolls were open. Total number of bolls was counted in a 1m subplot in each plot at cut-out. Open bolls were hand picking at least once a week in the 1m subplots to determine percent open bolls.

Other in season and yield measurements were completed using the protocol described for other trials above.

Objective 2: Limited Water Scheduling

2015-16 Limited Water Trial at ACRI

The aims of this trial were to identify the crop stress triggers using canopy temperature in partially irrigated cotton grown under different row configurations, and assess opportunities to characterise risk of impacts on yield of irrigating or not at the time of the irrigation decision.

The objectives of this trial were to:

- Optimize the irrigation strategies when water availability in post-flowering period is limited to a single irrigation.

- Establish the relationships between crop stress and yield under different irrigation management scenarios and different row configurations, and
- Compare the yield potential of different combinations of skip row configurations and irrigation treatments.

A Randomized Complete Block Design was used with two blocks, six irrigation treatments and three row configuration treatments. This experiment enabled testing different combinations of row configurations and irrigation management. Row configurations included solid, single skip and 1in1out (2m) as shown in Fig. 4.

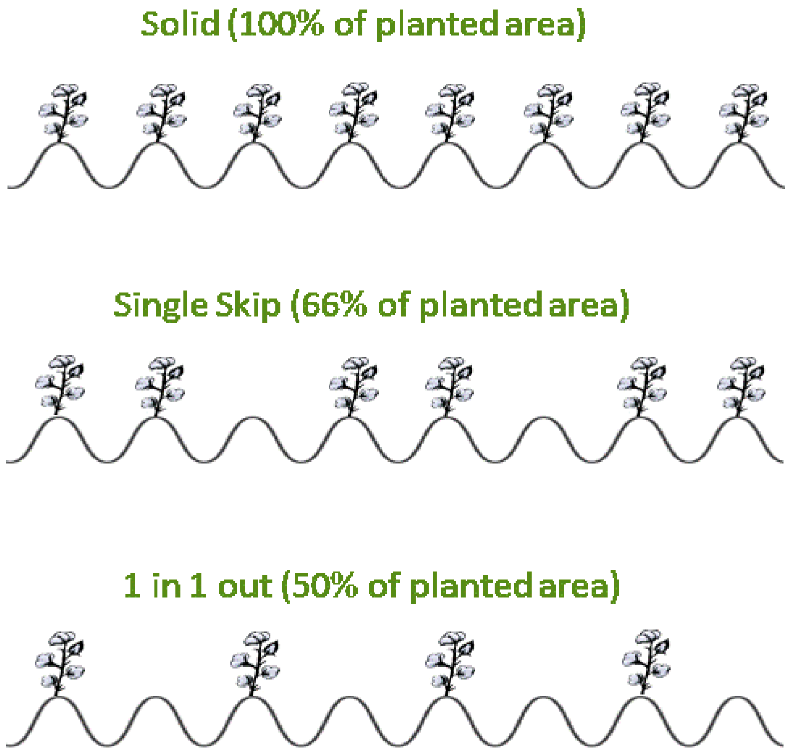

Figure 4: Row configurations used in the limited water experiments

The irrigation treatments included:

1. Full irrigation (irrigated every 7-10 days)
2. Skip every second irrigation from treatment 1
3. First irrigation + 10 days after first flower
4. Single irrigation at first flower
5. Single irrigation 10 days after first flower
6. Single irrigation 20 days after first flower

Each plot consisted of 8 rows of 14m each with a buffer of fours between treatments. Field was planted with Sicot 74BRF (Bollgard® II) variety. Standard on-farm sowing and crop management practices were followed. Irrigations were only applied in the middle 5 furrows to avoid lateral movement of water to adjacent plots (Fig. 5).

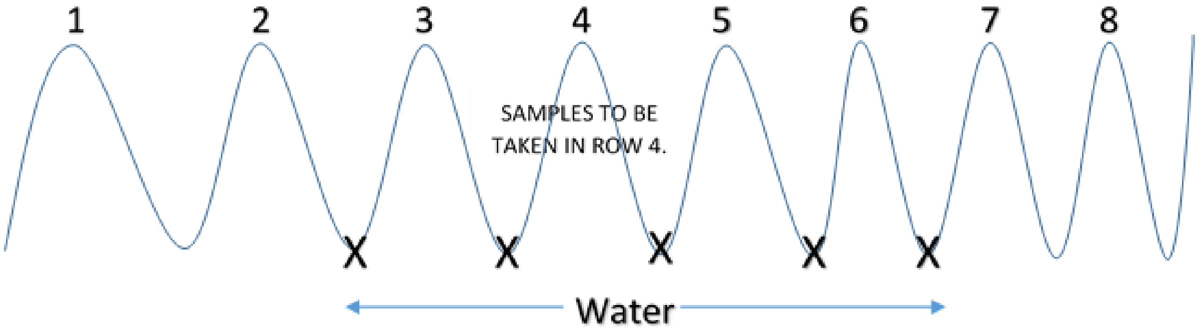

Figure 5: Method of irrigation application to limit lateral movement of water to adjacent plots.

Canopy temperature was monitored in row 4 of plots. Soil moisture was monitored every 10 days and before and after and irrigation event using an EM38. Twenty (20) plants were tagged in select plots from each treatment and squares counted until 50% of the plants have reached first square. At squaring number of plants was counted in 5m subplots plots to determine plant establishment. Biomass harvests were conducted fortnightly to study the effect of treatments on plant development. Other plant development measurements were completed as described in previous sections.

2016-17 and 2017-18 limited water trials

Two trials were conducted at ACRI during 2016-17 and 2017-18 to test the hypotheses that canopy temperature stress threshold developed for fully irrigated cotton may also be used to irrigate a crop with access to limited water. This hypothesis was based on the findings from limited water trial conducted in 2015-16 (above). Specifically, these trials were conducted to optimize the timing of a single irrigation after first flower. Although data was collected from three different row configurations during this trial, the irrigation treatments were only tested on plots planted in single skip row configuration.

In 2016-17 season, treatments included:
1) Early, 2) Control, and 3) Medium Stress.

In 2017-18 season, building on previous year's trial, treatments were modified to:
1) Control, 2) Medium Stress and 3) High Stress.

Trial was conducted in a RCBD with three treatments, two blocks and two subplots. In both years an irrigation was applied to all plots when first flower was established (i.e. 50% plots had a flower) which reset the canopy temperature deficit hours and triggered treatments. After this period each treatment received a single irrigation only but at different stress levels based on real-time canopy temperature measurements. Canopy temperature and weather data was processed using BIOTIC protocol to calculate stress time. The control treatment received an irrigation when canopy temperature deficit hours reached that recommended for a fully irrigated cotton crop. The Early and Medium stress treatment were irrigated at 50% less or 50% more canopy temperature stress time, respectively, than control treatment. The High stress treatment was irrigated at canopy temperature stress time twice that of control treatment. Soil moisture was monitored every ten days and before and after irrigations using an EM38.

Analyses of variance (ANOVA) was used to test the significance of difference in yield between treatments.

Figure 6: Limited water trial in field B2 at ACRI showing plastic sheets used to exclude rain from measurement rows of the trial

2016-17 Dial in a yield trial

The results from the limited water experiments conducted in last season showed a strong linear relationship between canopy temperature stress time and yield with row configuration affecting yield potential. In theory if a crop is irrigated using a specific stress time between irrigations, it may achieve the corresponding yield against that stress time. This management paradigm may enable growers to set a target yield at the start of season based on water availability and manage (dial) irrigations to achieve the target yield. The objective of this trial was to test dialling a yield of 8 bales ha^{-1} in solid and single row configurations. Against the same target yield, the row configurations received irrigations at different durations because of differences in slope and intercept of the relationship between stress time and yield.

Objective 3: Research Support for high impact delivery and adoption

A total of eight trials were conducted on commercial farms to engage with growers to investigate optimizing the irrigation scheduling in fully and partially irrigated systems. Most of these trials were conducted in collaboration with the CottonInfo extension team. The overarching philosophy of these trials was to evaluate practicality and usefulness of various scheduling techniques and their combined usage from a grower's perspective as opposed to the rigorous application of treatments based on hard and fast numbers. Canopy temperature sensors were installed on all farms. In most cases the canopy temperature data was processed in real time using BIOTIC algorithms and growers provided with information to use in irrigation scheduling decision making during the cotton season. In some instances, growers were provided with advice post season to assess the timeliness of their irrigations compared with the canopy temperature approach.

Emerald, Queensland (Fully Irrigated)

In Emerald trials were conducted in 2015-16 and 2016-17 seasons to optimize irrigation scheduling of fully irrigated crops. The trial during 2015-16 was continuation of similar trials conducted in seasons 2013-14 and 2014-15 under other CRDC funded projects (DAQ1404, CSP1305) to compare various scheduling techniques. This trial was conducted in collaboration with Dr Lance Pendergast of Queensland Department of Agriculture and Food. This trial had four treatments:

1) **Control** which was irrigated when soil water deficit reached 60 mm;

2) **BIOTIC** which was irrigated using canopy temperature stress threshold;

3) **Dynamic** deficit approach using forecast ETo data.

In the dynamic deficit approach an irrigation was brought forward by up to 40% if the 5 day forecast was for conditions with ETo higher than 7 mm/day (Brodrick et al.). An irrigation was delayed by up to 40% when the ETo forecast was lower than 5 mm/day. These were developed from the previous project's data that look at the relationship between plant stress (using leaf water potential) and soil water and climatic variables.

During 2016-17 cotton season there were no treatments. Instead, the grower was provided with processed canopy temperature data with a recommendation for irrigation date to incorporate in his irrigation decision making.

St. George, Queensland (Fully Irrigated)

At St. George canopy temperature was used for three cotton seasons on the same farm (Fig. 7). In the 2014-15 season grower used only soil moisture probe to schedule irrigations while canopy temperature data was collected for post-season comparison. In the following two seasons, grower was provided feedback on their canopy temperature data once or twice a week to help optimize their irrigation decision making. In 2016-17 and 2017-18 the grower made the irrigation decisions by integrating the information from soil moisture probes and canopy temperature sensors.

Figure 7: Canopy temperature sensor installed at a cotton farm in St. George, Queensland

Waverly (Wee Waa), NSW (Fully and partially irrigated)

At Waverly, canopy temperature was monitored during 2016-17 and 2017-18 seasons. In 2016-17 crop was planted in solid row configuration and was fully irrigated. In 2017-18 season, because of limited water availability cotton was planted in single skip row configuration and was partially irrigated. The grower was provided the feedback in real time on crop water stress levels based on canopy temperature sensor data during 2016-17 season only.

Rowena, NSW (Limited Water)

The trial at Rowena was conducted to understand the irrigation strategy of growers with limited water in Rowena region. Grower had applied four in-season irrigations. Canopy temperature was monitored in two fields with field "East" receiving an irrigation roughly 24 hours earlier than field "West". Soil moisture was monitored to 1m depth throughout season using a capacitance probe in field "East" only.

Walgett, NSW (Limited Water)

The objective of this trial was to optimize the irrigation strategy in limited water situations for the generally hot and dry conditions of Walgett. Crop was sown late (December) as a strategy to reduce season length and therefore less exposure to potential water stress. Recent research has shown that, when water is limited for a single irrigation, it might be beneficial to apply the irrigation earlier in the season but after flowering. This farm had water available for four to five irrigations. By applying irrigations earlier, crop is being set for a higher yield and therefore may benefit from possible rain better than a crop that has been partially stressed by stretching irrigations to distribute stress evenly over greater part of season. The latter would set the crop for a lower yield potential.

This trial had three stress treatments:

1) Control: In this treatment crop was treated as fully irrigated until all irrigation water was used. Irrigations were scheduled using canopy temperature sensors.
2) Stretch: In this treatment irrigations were applied at few days longer interval than control treatment.
3) Super Stretch: In this treatment the interval between irrigations was further stretched

Treatments were not implemented in the strictest sense because of limited water and irrigation system capacity of the farm. Nonetheless, this experiment might provide valuable information on strategies to optimize irrigation scheduling in limited water situations.

4. Project achievements

Objective 1: Integrated Irrigation Agronomy for High Yielding Systems

Irrigation strategies for germination and crop establishment

Plant emergence was faster in pre-watering treatment compared with the watered up treatment. Although the difference in emergence between the two treatments progressively reduced, pre-watering treatment still had the larger number of plants emerged (11.7± 0.3 plants m^{-2}) compared with that in watered up treatment (10.3 ± 0.9 plants m^{-2}) at the last count on 30th October 2015 (Fig. 8).

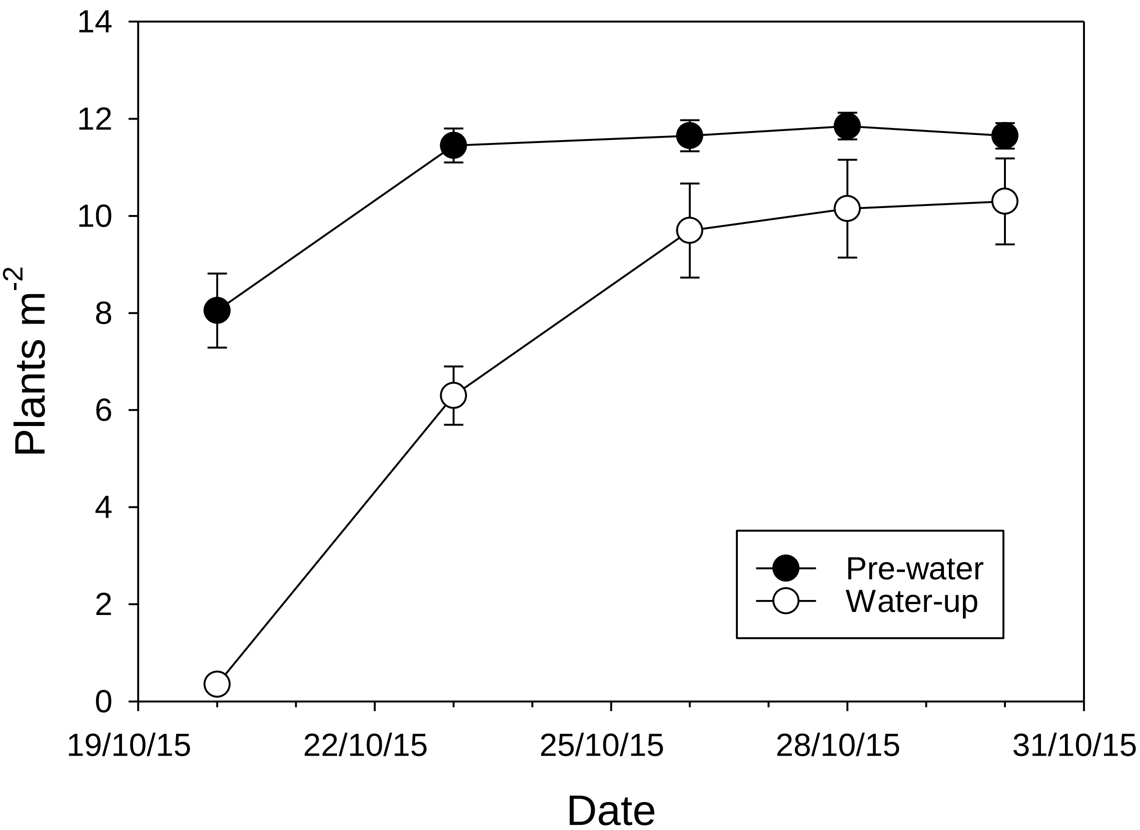

Figure 8: The difference in plant emergence between two treatments for a cotton crop planted on 15th October 2015 at ACRI, Myall Vale; error bars are standard errors of the mean

The number of established plants was higher in the pre-watering treatment (11.3 plants m^{-2}) compared with that in watered up treatment (9 plants m^{-2}) on 3rd December, 2015; however, the difference was not significant (Fig. 3). The recommended number of established plants for optimum plant development and yield is 10 to 12 plants m^{-2}, which was achieved in the pre-watering treatment with watered up field falling short. There was lag in plant development with plants in pre-watering treatment reaching first square (30th November 2015) few days earlier than in watered up treatment (3rd December 2015). This lag in development was also apparent in the differences in plant height (Fig. 9).

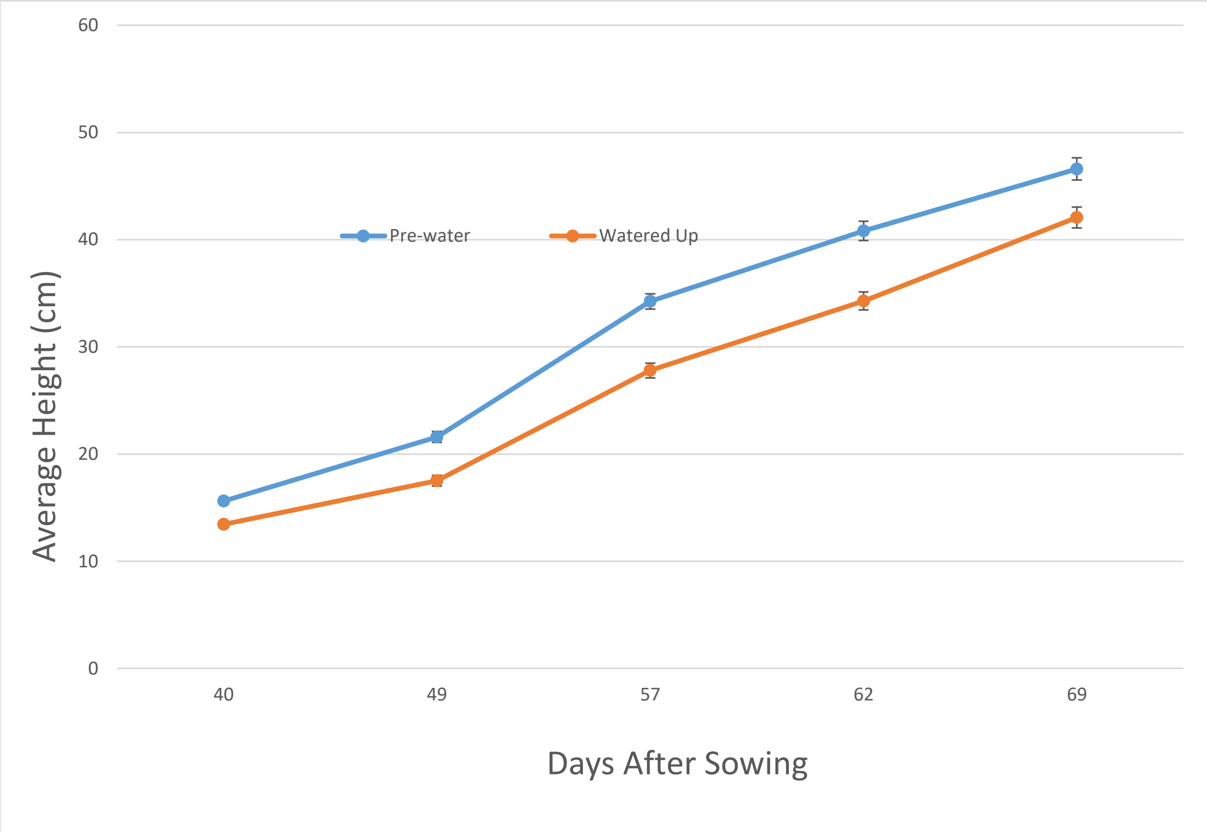

Figure 9: Average height of plants in pre-watered and watered up plots in a trial during 2015-16 season at the ACRI

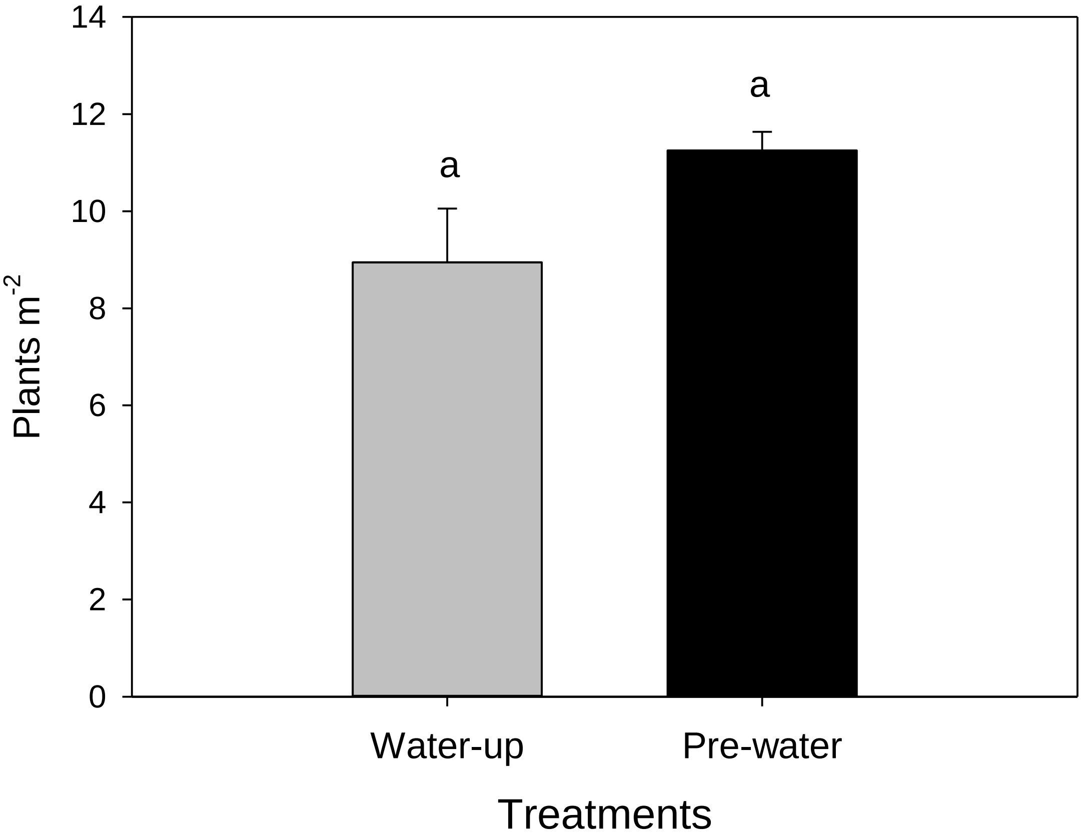

Figure 10: The number of plants established on 03/12/2015 in the pre-watering and watered up treatments for an experiment conducted at ACRI, Myall Vale during 2015-16 cotton season; error bars are standard errors of the mean

Results show that watering up one day after planting (16 October 2015) resulted in significantly ($P < 0.05$) lower soil temperatures (Fig. 11) possibly because of colder water temperature. Soil temperature in pre-watering treatment was up to 2.4 °C warmer than watered up soil (Fig. 11b). The difference in soil temperatures of the two treatments was negligible after two weeks of watering up date (Fig. 11b). It appears lower soil temperatures might have been the major reason for slower germination and smaller plant establishment in the watered up treatment. Lower soil temperatures were considered the major cause of poor germination and establishment in some cotton growing regions in the 2016-17 season which received 20 cold shocks compared with 1 and 10 cold shocks in the preceding and following years, respectively (Table 2).

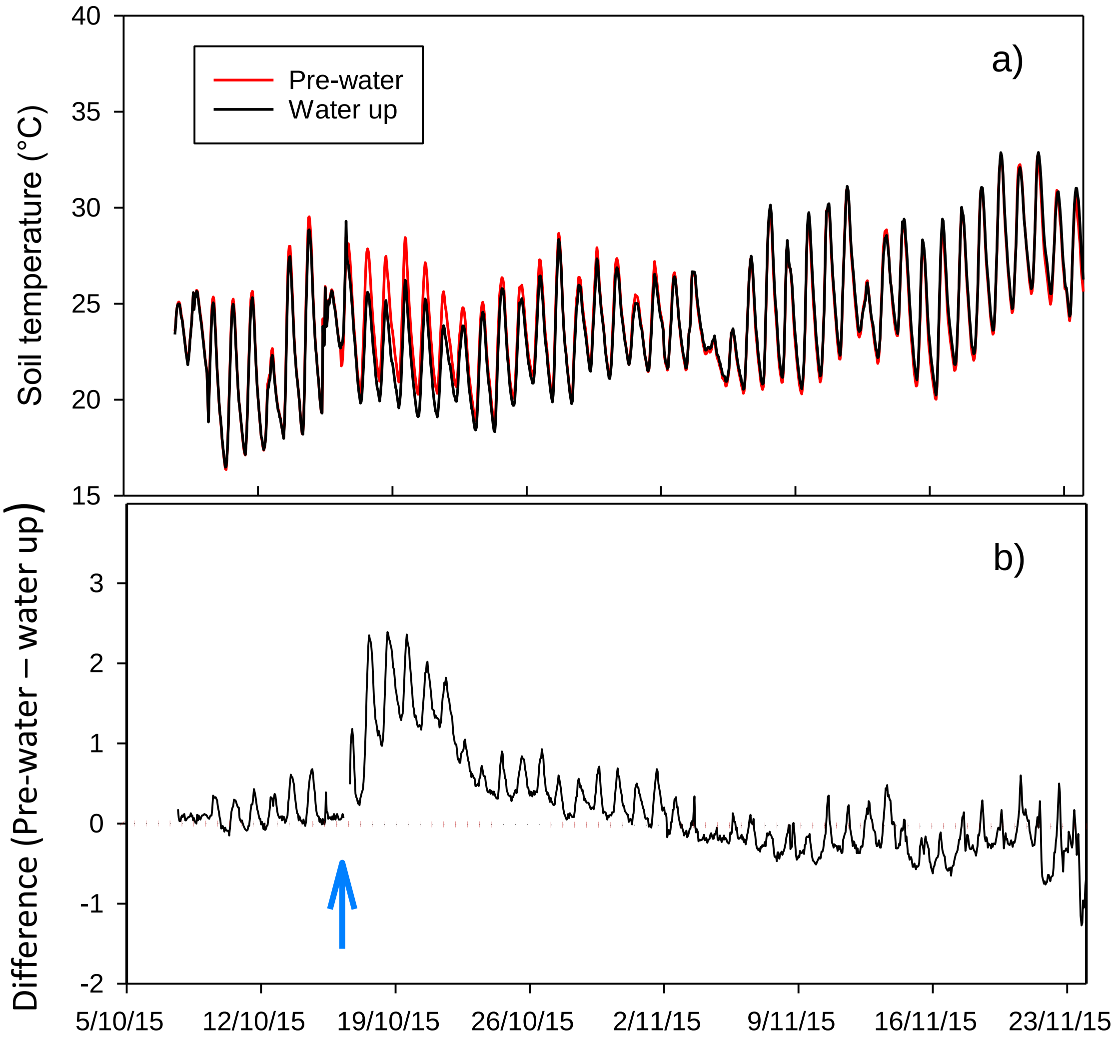

Figure 11: Average soil temperature (a) of treatments either pre-watered or watered up, and the difference in temperature of two treatments (b). Blue arrow shows the timing of watering up after planting

These results emphasize the need to consider soil temperature as an important factor when making an irrigation decision at planting. There are several other factors that need to be considered when choosing between pre-watering and watering up which are discussed in detail in WaterPAK (http://www.cottoninfo.com.au/publications/waterpak). For example, unlike heavy clay soil used in this trial, soils that dry too quickly may need watering up. In uneven fields, watering up might be necessary to avoid non-uniform germination. However, where watering up is unavoidable, efforts should be made to plant when soil temperatures are optimum.

The lint yield in pre-watering treatment (14.9 bales ha^{-1}) was slightly higher than that of Watered Up treatment (13.6 bales ha^{-1}) although these differences in yield were statistically not significant (Fig. 12).

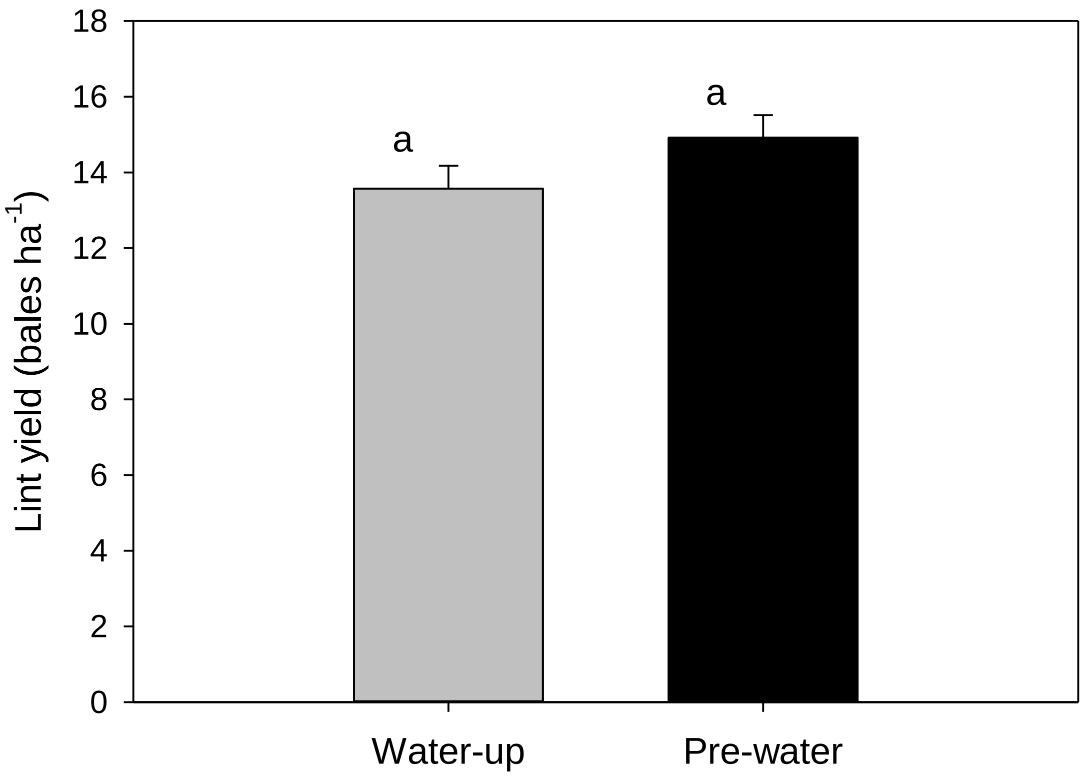

Figure 12: The difference in lint yield between two treatments for an experiment conducted at ACRI, Myall Vale during 2015-16 cotton season; error bars are standard errors of the mean

Timing of early season irrigations

The early irrigation treatment received first irrigation after sowing on 25th November, 2015, i.e. six days earlier than the control (farmer practice) treatment which received the first irrigation on 1st December, 2015. Early application of first irrigation resulted in an immediate increase in biomass, height and the number of nodes; however, these differences became negligible as the season progressed (Fig. 13). Lint yield was also similar in the two treatments i.e. ~12 bales ha^{-1} (Fig. 14). The increase in vegetative growth did not increase yield because it most likely exceeded the needs of the reproductive demand. Similar results are often associated with rank growth of cotton crops.

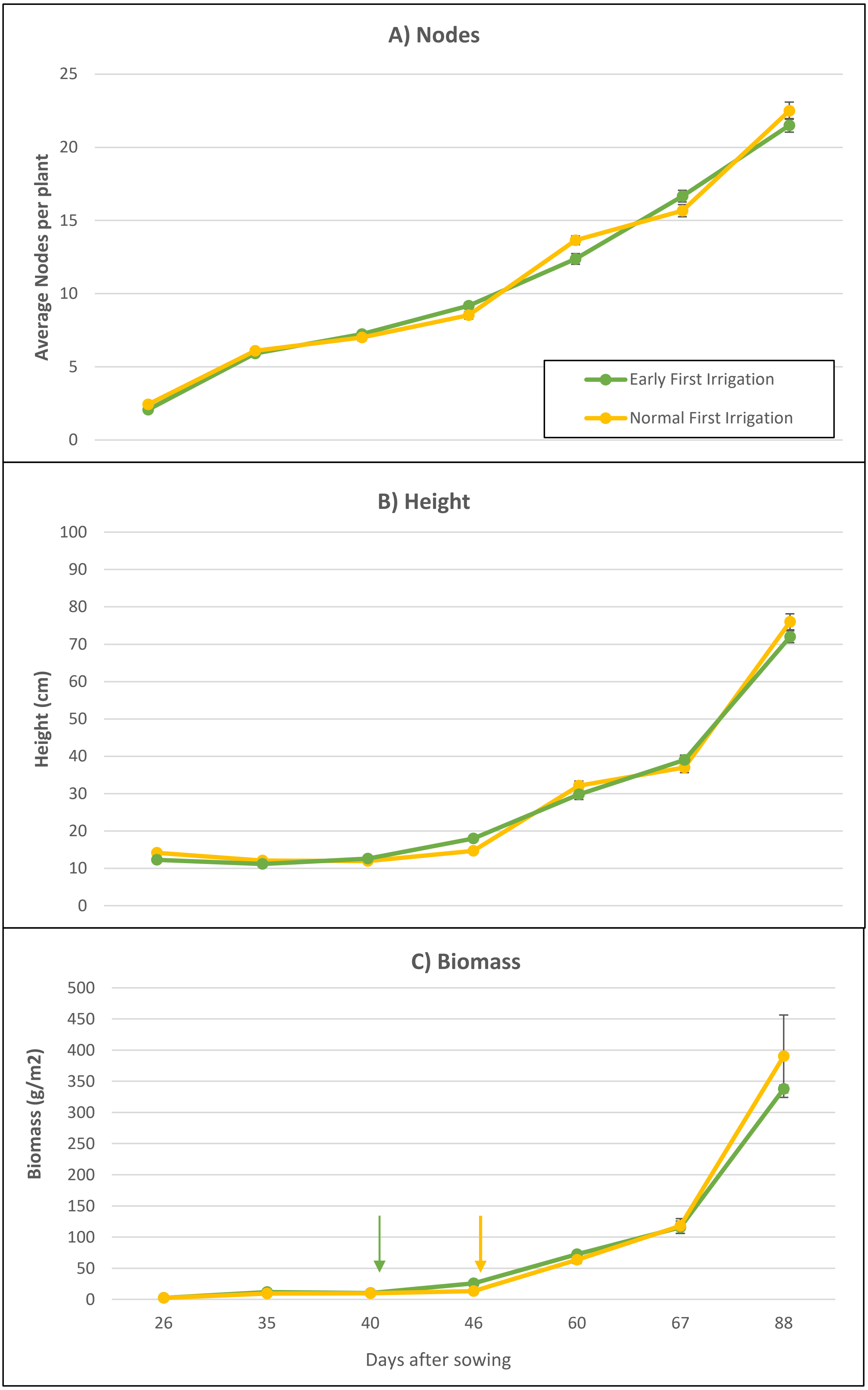
A) Nodes
Average Nodes per plant
25
20
15
10
5
0
Early First Irrigation
Normal First Irrigation
B) Height
Height (cm)
100
90
80
70
60
50
40
30
20
10
0
C) Biomass
Biomass (g/m2)
500
450
400
350
300
250
200
150
100
50
0
26
35
40
46
60
67
88
Days after sowing

Figure 13: The development of nodes (A), height (B) and total dry biomass (C) in early irrigation and control treatments during 2015-16 season at ACRI, Myall Vale; arrows on graph (C) show the timing of first irrigation in respective colours in two treatments

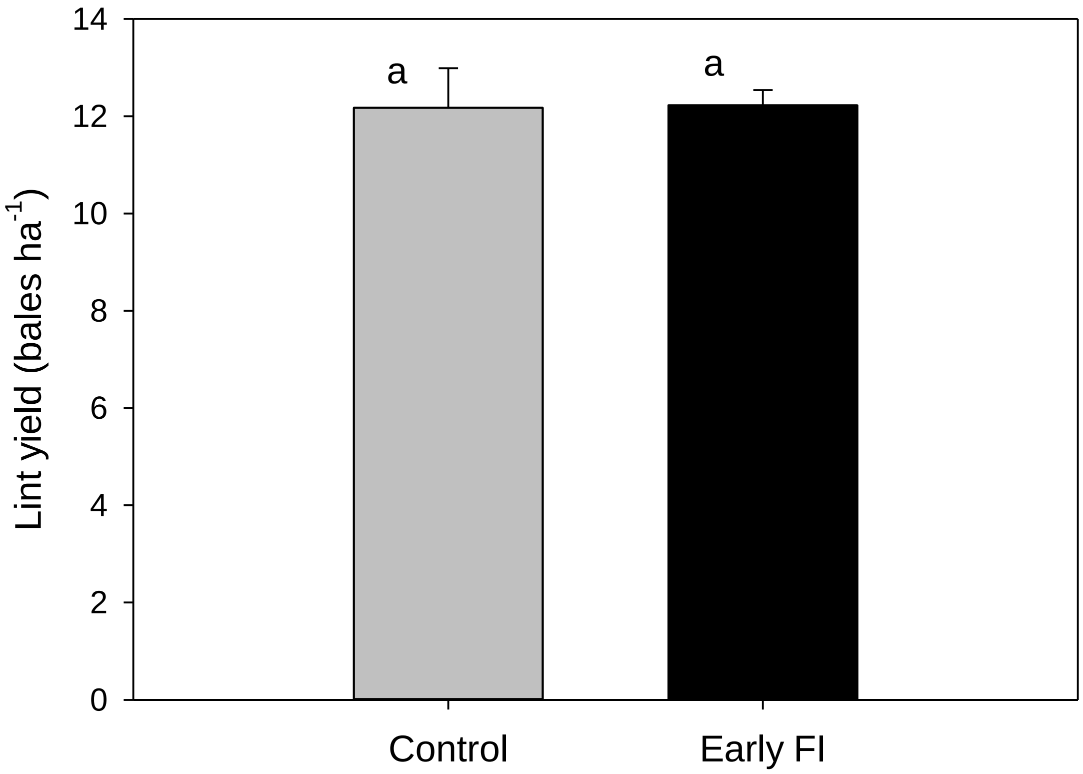

Figure 14: The difference in lint yield between two treatments for an experiment conducted at ACRI, Myall Vale during 2015-16 cotton season; letters on top of bars show the statistical difference in yield of the two treatments; error bars are standard errors of the mean

Above results are more a reflection of seasonal conditions in 2015-16 rather than lack of treatment effect. For example, crop received ~140mm rainfall between planting and end of November which resulted in non-stressed conditions for both the treatments with only a small difference in soil water content of the two treatments when the first irrigation was applied (Fig. 15). The results would likely have been different in a drier year.

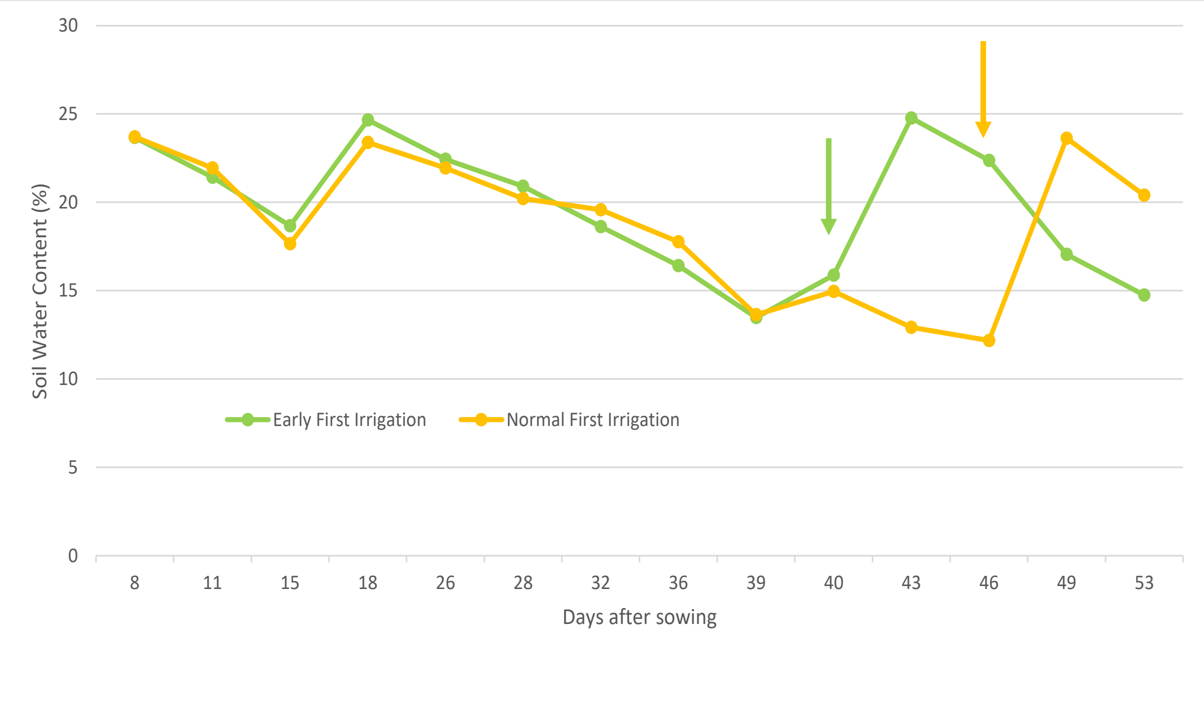

Figure 15: Volumetric soil water content in early season irrigation trial in field A2 at ACRI during cotton season 2015-6; arrows show timing of first irrigation in respective colours

Above results highlight the importance of measuring crop's demand for water directly from the plant itself. For example, irrigation management based on a fixed water deficit or crop development stage (e.g. number of nodes) my need adjusting based on weather conditions. Warmer weather conditions may require an irrigation application earlier than suggested by soil water deficit and vice versa.

From the preliminary measurements it appears thermal imaging (Fig. 16) can be a promising tool for measuring crop water stress at any crop development stage including earlier in the season when canopy is not fully closed. A thermal image in addition to measuring object temperature similar to an infrared canopy temperature sensor also allows separating two objects, e.g. the canopy from the background soil. This will then enable using the temperature of the desired object only, i.e. cotton canopy. However, manually separating plants from soil in each image is not practical for the application of this technology in commercial situations as images need to be taken frequently. For example, feeding thermal image data into BIOTIC algorithms would require images taken at 15 minute frequency. Utility of thermal imaging is a future area of research with potential for its application to other crops. Reducing the requirement of frequent images though difficult may increase the adoption of technology with the possibility of using drones. The relatively high cost of thermal cameras compared with canopy temperature sensors is one of the biggest hurdles in development of this technology for application at commercial scale. Better internet connectivity may also be required to use this technology in remote locations in real time. Nevertheless, it is important to progress this research as both cost and connectivity is fast improving across the world including in remote locations of Australia.

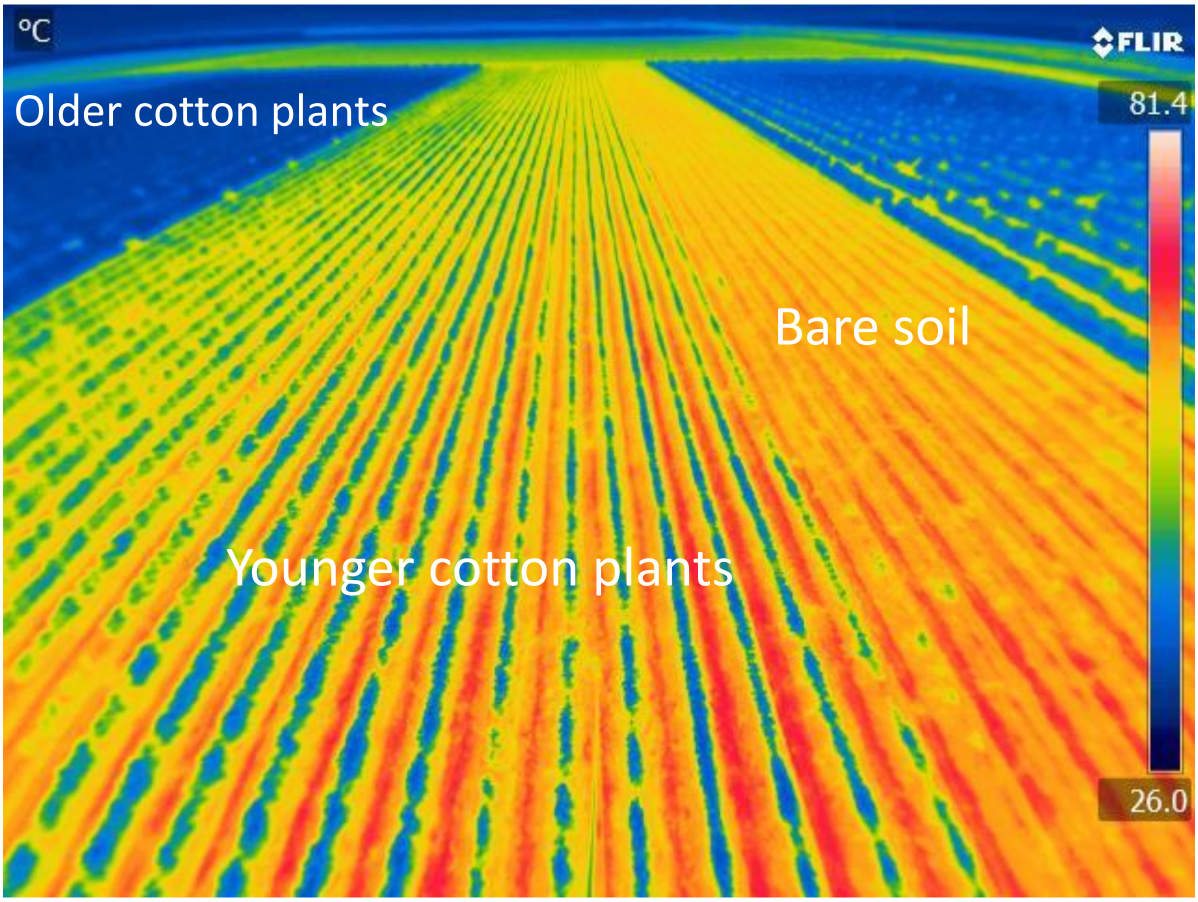

Figure 16: Thermal image taken from late sown trial at ACRI for developing a method for early season irrigation decision making

Mid-season irrigation scheduling: Scheduling irrigations in advance

A replicated trial was conducted at the ACRI during 2015-16 cotton season to evaluate the integration of different "refined scheduling" techniques to investigate the impacts of these techniques to predict future crop stress. In this trial irrigations were scheduled five days in advance based on either using a pre-determined average daily stress hours of 6.39 (Average Tc) or adjusting the daily stress hours based on forecasted ETo using the dynamic deficit approach (Tc Forecast).

As weather conditions were fairly average during 2015-16 season, the changes to irrigation schedule based on dynamic deficit (Tc Forecast) was made on one occasion only when an irrigation was applied to Tc Forecast treatment three days earlier (26 February) than Tc Average (29 February). Remaining irrigations were applied on the same day to both treatments. Both the methods significantly underestimated the future water stress as the accumulated stress hours between irrigations exceeded the established threshold on most occasions (Fig. 17). These results are not unexpected. Daily stress hours are calculated from canopy temperature which in a fully irrigated crop (e.g. this experiment) is strongly related to weather variables such as air temperature, solar radiation and relative humidity. These weather variables change over the course of season. As such using an average stress time value based on historic data will only provide an accurate estimate of future stress if future weather conditions match the historic average weather conditions which will likely be a rare occurrence.

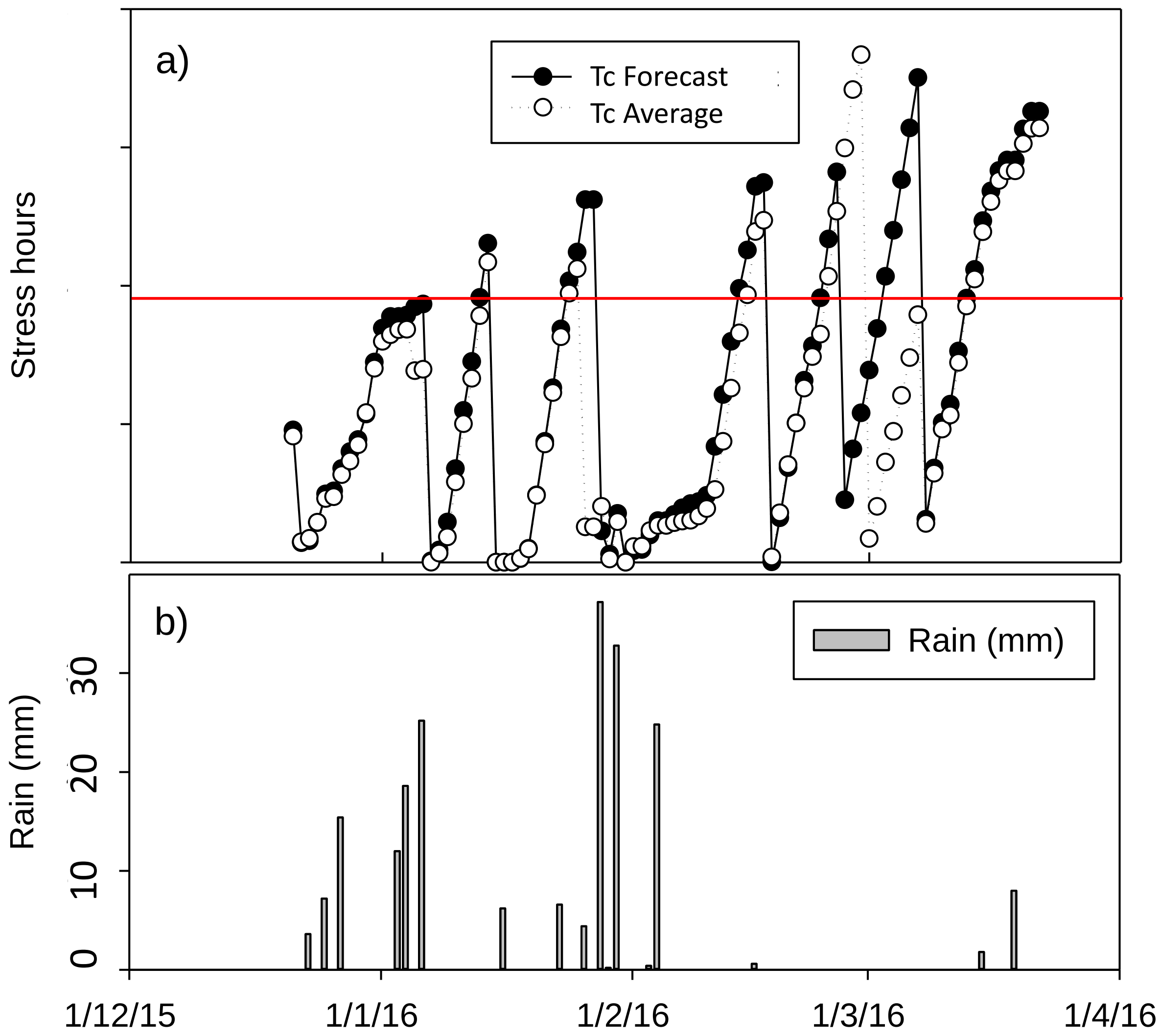

Figure 17: a) Cumulative stress hours between irrigations in two treatments; redline shows the target threshold; b) rainfall received at ACRI site

Table 3: Yield and fibre quality of the trial for predicting irrigations in advance conducted at ACRI during 2015-16 cotton season; similar letters show differences were not significant

Treatment	Yield (bales ha^{-1})	Fibre length (mm)	Micronaire	Strength (g tex^{-1})
Tc Average	12.3 (0.28)a	29.4a	4.7a	28.1a

Tc Forecast	13.1 (0.25)a	29.5a	4.9a	28.2a

Yield and fibre quality were similar between the two treatments (Table 3) which was expected as they received most irrigations on same days. Above results show that it is important to develop algorithms for predicting canopy temperature based on forecasted weather data rather than using historic data to predict future water stress as was trialled in this study. This is more achievable in a fully irrigated crop where effect of soil water availability on canopy temperature is minimum, and canopy temperature is mainly a function of aerial environment. The principle of dynamic deficit should still be considered when reliable canopy temperature forecast is available for scheduling irrigations, for example, by delaying an irrigation beyond the recommended threshold when forecasted weather conditions are cooler when there is a rain forecast. Integrating dynamic deficit approach will especially be useful in low rainfall and water limited years.

Late season irrigation scheduling

Two replicated trials were conducted one each during 2016-17 and 2017-18 seasons at the ACRI. The research station (ACRI) received a rainfall of ~100mm in the second week of March which meant the crop did not need the last irrigation. Therefore, the originally planned treatments for last irrigation could not be executed. As last attempt, three of the nine plots were applied an extra irrigation on 28th March to investigate if such late irrigation might help increase yield, however this extra irrigation did not result in yield differences (Table 4).

The last irrigation trial was repeated during 2017-18 season with successful application of treatments. Last irrigation was applied on 20th March (Control), 23rd March (Medium Stress) and 28th March (High Stress) in different treatments.

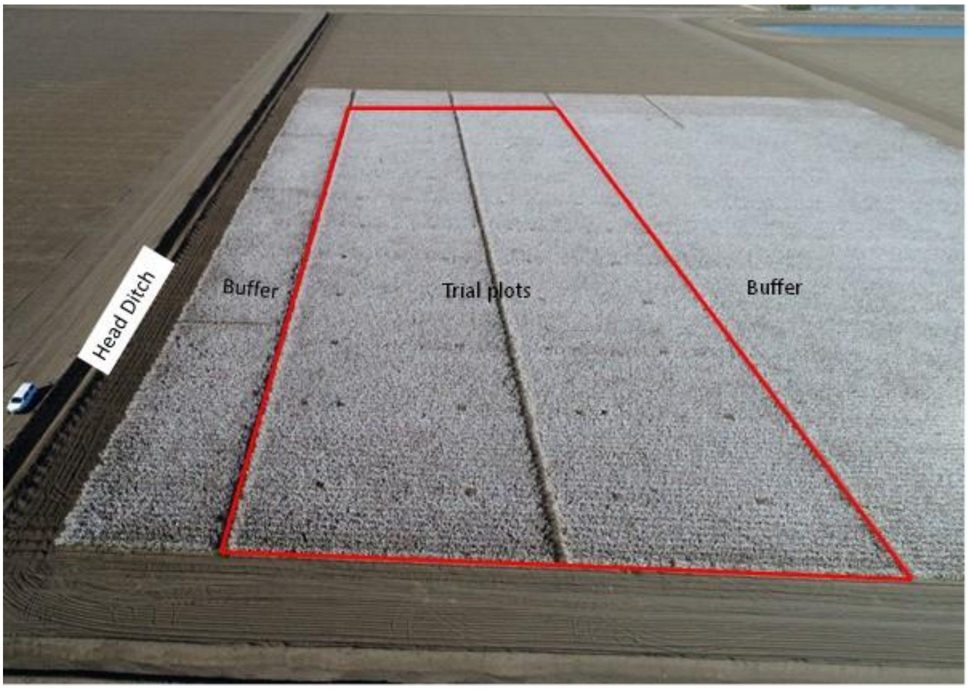

Figure 18: Field trial at field A2 at ACRI during season 2017-18 for optimizing last irrigation decision making

Table 4: Yield and fibre quality results from the late season irrigation trial conducted in Field A2 at ACRI during cotton seasons 2016-17 and 2017-18

Season	Treatment	Yield (ba ha^{-1})	Length (mm)	Mic	Strength (g tex^{-1})
2016-17	Normal irrigations	11.3 (0.4)a	31.2 (0.25)a	4.84 (0.03)a	32.9 (0.26)a
	Extra last irrigation	11.1 (0.2)a	31.0 (0.25)a	4.83 (0.03)a	32.67 (0.31)a
2017-18	Control	12.9 (0.27)a	⋆	⋆	⋆
	Medium Stress	13.3 (0.10)a	⋆	⋆	⋆
	High Stress	12.5 (0.23)a	⋆	⋆	⋆

⋆ samples under process

During 2017-18 trial, on average the control and medium stress treatments yielded 0.8 and 0.4 bales ha^{-1} higher than the high stress treatment, respectively (Table 4), although differences were not significant but only marginally ($p=0.054$). The crop in control treatment matured (i.e. 60% bolls open) one day earlier than the remaining two treatments which matured on the same day. Delaying the last irrigation by 50% more stress than control slightly increased yield but further increasing stress showed a decline in yield. Although the differences in yield are not significant, these results identified a pattern in the relationship between yield and stress that needs further testing in variable weather conditions to optimize late season irrigations.

Objective 2: Irrigation scheduling in Limited Water situation

Three replicated trials were conducted at ACRI during the three cotton season from 2015 to 2018. The results from these trials are described below:

2015-16 Limited water trial at ACRI

The actual irrigation applications in some treatments were different from the original plan stated in methods above because of rain events. The treatments generated the intended range of stress hours regardless of changes. Table 5 below shows the changes to the original irrigation plan:

Table 5: Original treatment plan and actual irrigations applied in field

Treatment	Original irrigation plan	Actual irrigation applications
1	Full irrigation	Full irrigation
2	Skip every second irrigation	Skip every second irrigation
3	First irrigation + 10 days after first flower	Single irrigation 28 days after FF
4	Single irrigation at first flower	Irrigated 8 days prior to FF and 28 days after FF
5	Single irrigation 10 days after first flower	Single irrigation 48 days after FF
6	Single irrigation 20 days after first flower	Single irrigation 62 days after FF

Lint yield ranged from 4.4 to 14.8 bales per hectare with significant effect of irrigation treatments and row configuration on yield (Fig. 19). Within an irrigation treatment yield (per unit area) decreased in the order solid > single skip > 1in1out which was a function of plant density. As expected treatment 1 and 2 yielded highest as these treatments received more irrigations than other treatments. An extra irrigation in treatment 4 (applied few days before first flower) did not generate yield benefits compared with treatments 3 and 5. This is because of rain events few days before and after first flower that neutralized the effect of any irrigations applied in this period. Treatment 5 which received only a single irrigation 48 days after first flower resulted in better yields compared with treatments 3 and 6 which also received a single irrigation 28 and 62 days after first flower, respectively (Fig. 20). Timing of irrigation application in terms of its distance from a major rain event was the main driver of these results. For example, treatment 5 received all rainfall till first week of February effectively and then received an irrigation when it started to accumulate stress. Treatment 6 also received all rainfall till first week of February effectively but received the irrigation 14 days later than treatment 5 exposing to water stress and therefore yield penalty (Fig. 20).

Figure 19: Limited water trial during 2017-18 at ACRI with three different row configurations - after defoliation and before cotton picking.

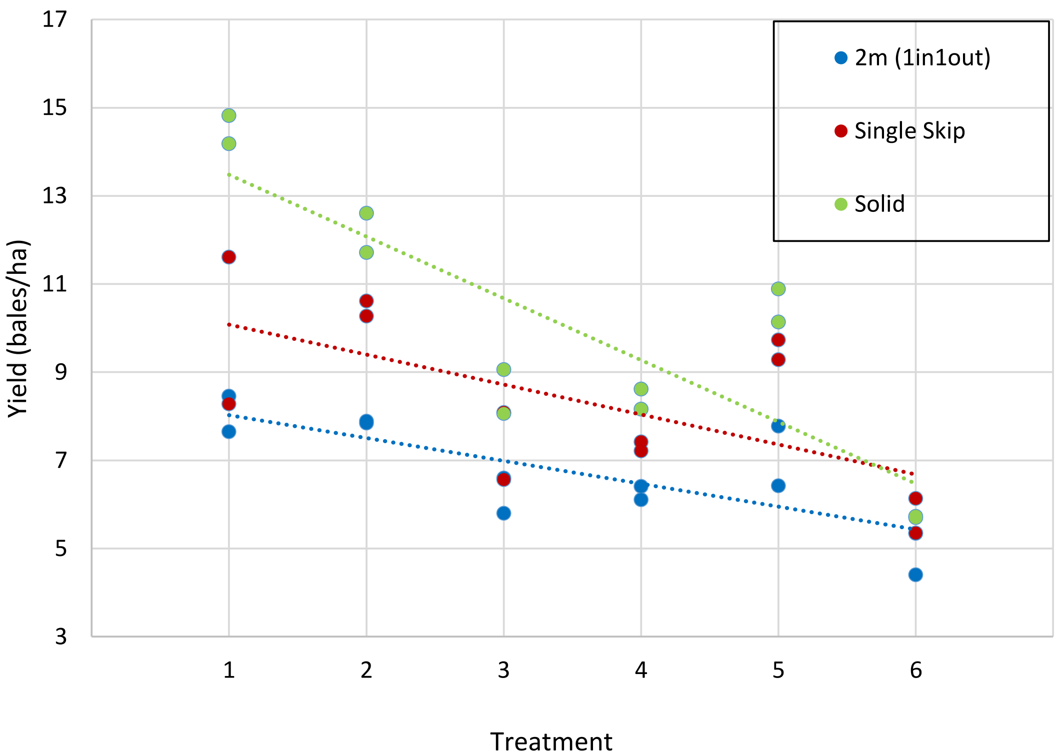

Figure 20: Lint yield in different irrigation treatments and row configurations; each point represents a plot

Micronaire in all treatments and row configurations ranged from 3.8 to 5.3 (data not shown) which is mostly within the range (3.5 – 5.0) accepted without penalty in Australia (Bange et al. 2009). Fibre length ranged from 27.51 mm to 30.33 mm which is below the premium grade (>31.75mm), however, 75% of plots had a fibre length >28.58 mm which is the threshold to avoid penalty in Australian markets (Bange et al. 2009). Fibre strength in all plots was ≥27.00 g tex-1 which is sufficient to avoid penalty in Australian market (Bange et al. 2009). Micronaire was negatively correlated with canopy temperature (data not shown) with weaker relationships in skip row configurations as observed for yield well. The relationship of fibre length and fibre strength with canopy temperature was relatively weaker (data not shown).

Treatments receiving more irrigations generally resulted in lower canopy temperature in daylight hours (Fig. 21) caused by increased evaporative cooling in well-watered treatments. Yield was significantly negatively related to average canopy temperature (Fig. 22), average daily stress hours (Fig. 23) and cumulative stress hours for whole season (Fig. 24). Row configuration affected the strength of these relationships which consistently decreased in the order solid > single skip > 1in1out. Weaker relationship in skip row configurations was a result of lower yield potential and therefore smaller variation in yield among different irrigation treatments. That is, at lower water stress levels (e.g. treatment 1) the row configurations with higher plant density (solid) benefited most from the water availability resulting in higher yields. In contrast, the skip row configurations could not benefit from the extra water available because of lower plant density resulting in lower yield potential. This is more obvious when comparing treatment 1 and 2. For example, yield significantly decreased from treatment 1 to treatment 2 in solid row configuration; however, in single skip and 1in1out row configurations treatments 1 and 2 resulted in similar yields on average (Fig. 20).

Significant relationships between yield and canopy temperature (and its derivatives) across different row configurations show the potential of canopy temperature approach in scheduling irrigations in limited water systems where skip row configurations are commonly used. It is a challenge to schedule irrigations in skip row configurations as soil moisture measurements cannot adequately inform plant's access to water when roots may or may not access water from unplanted/skip rows. Canopy temperature measurements are an important indicator of plant's access to (or lack thereof) soil water but independent of the volume and location of water in the soil profile. As canopy temperature of a plant integrates the effect of plant's soil and aerial environment, it can be used in all soil types and weather conditions for cotton irrigation scheduling without requiring any calibrations.

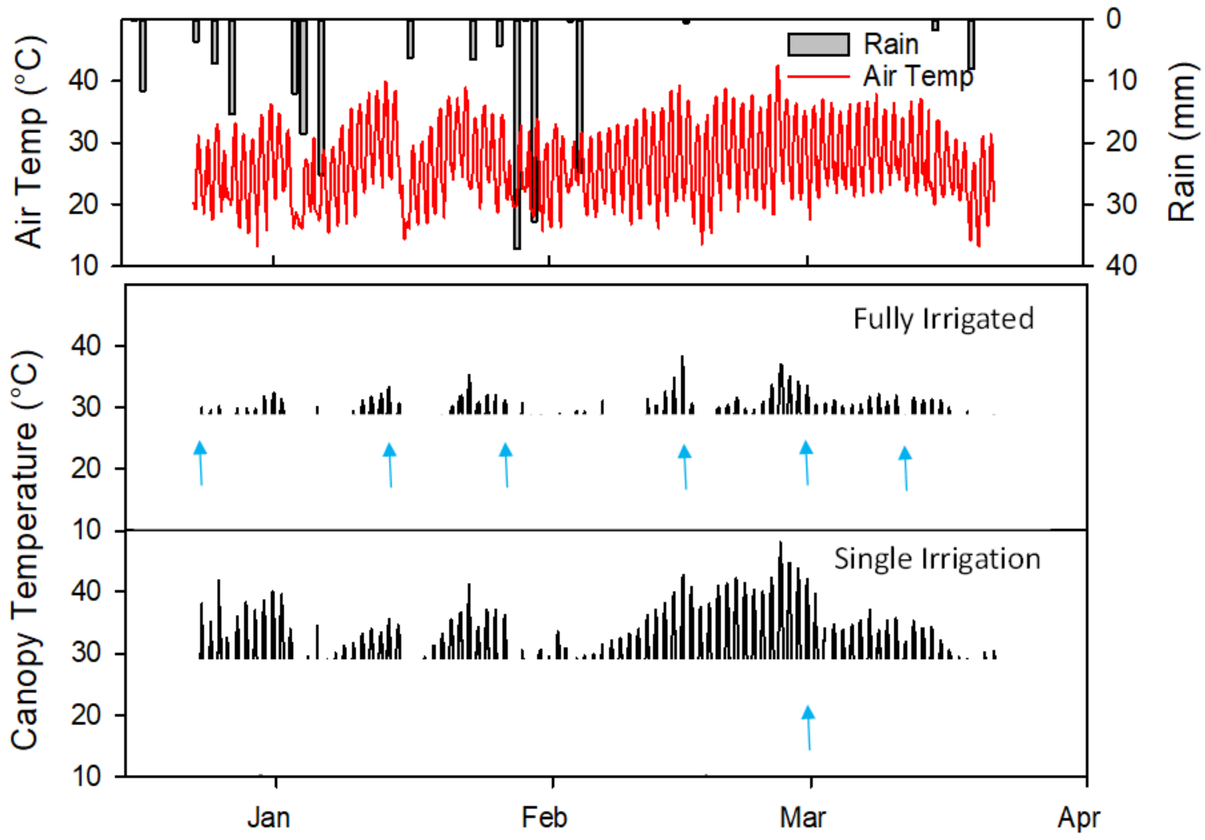

Figure 21: Weather (a) and canopy temperature of treatment 1 which was fully irrigated (b) and treatment 6 which received only one irrigation later in the season (c); arrows show the timing of irrigation

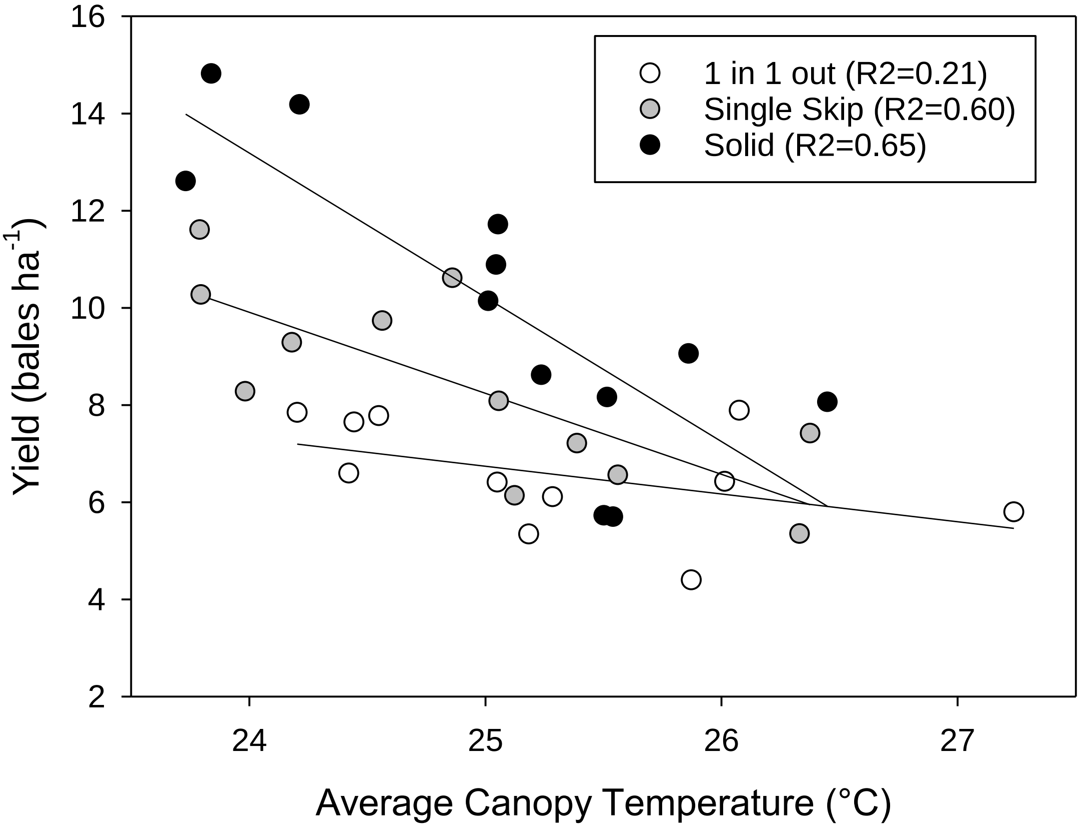
1 in 1 out (R2=0.21)
Single Skip (R2=0.60)
Solid (R2=0.65)
Yield (bales ha-1)
Average Canopy Temperature (°C)
16
14
12
10
8
6
4
2
24
25
26
27

Figure 22: Relationship between lint yield and average daily canopy temperature for the limited water trial conducted in filed A3 at ACRI during cotton season 2015-16

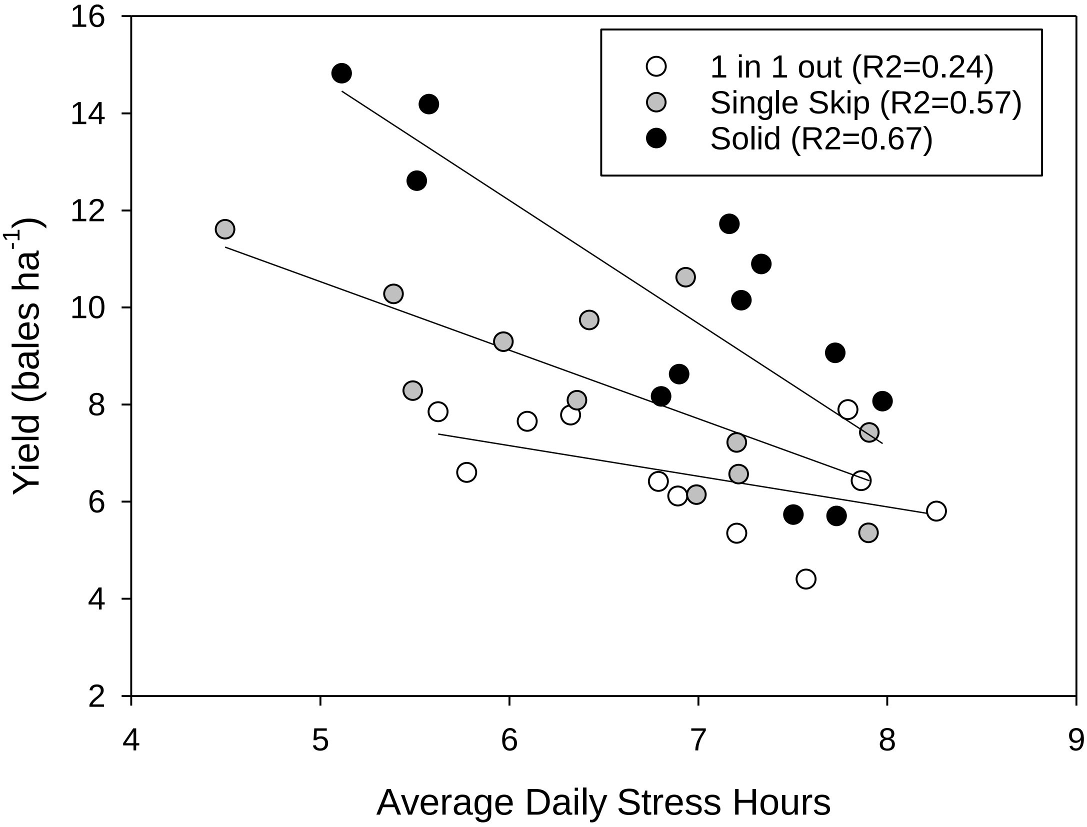

Figure 23: Relationship between lint yield and average daily stress hours for the limited water trial conducted in filed A3 at ACRI during cotton season 2015-16

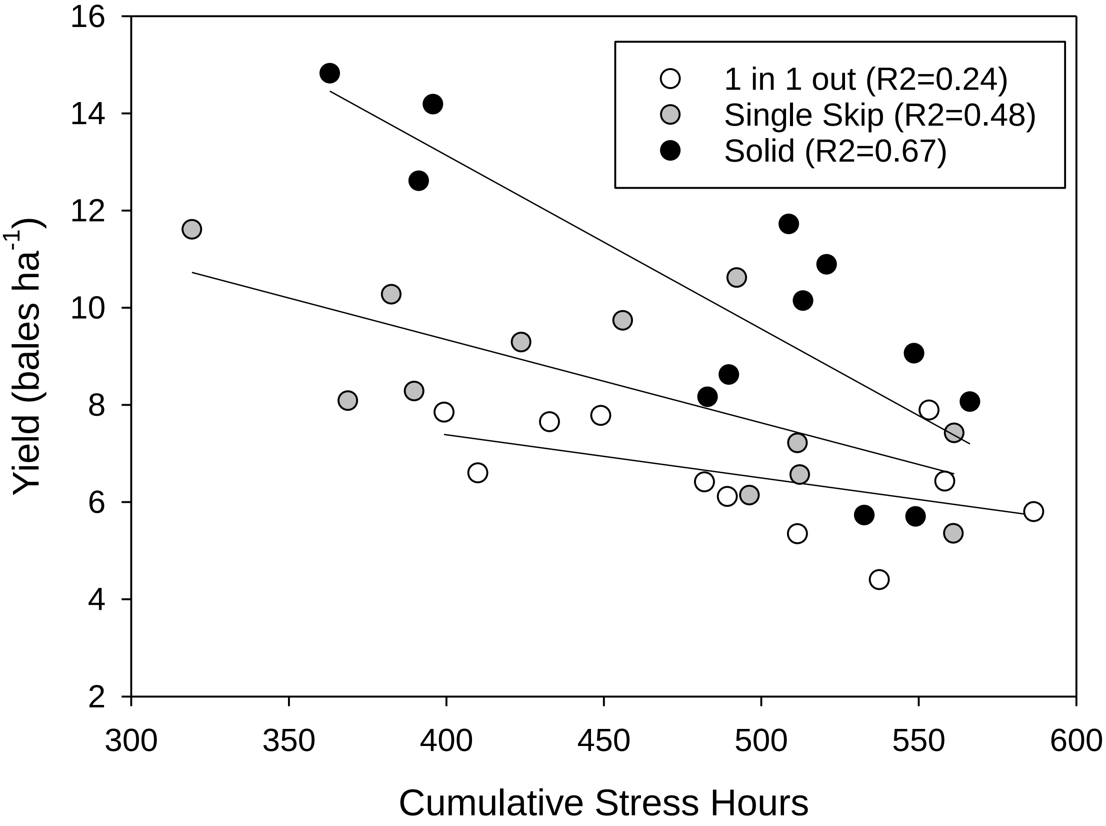

Figure 24: Relationship between lint yield and cumulative stress hours for the limited water trial conducted in filed A3 at ACRI during cotton season 2015-16

2016-17 Limited Water Trial at ACRI

A detailed field trial was conducted at ACRI during 2016-17 cotton season to optimize the timing of a single irrigation after first flower based on canopy temperature approach using single skip row configuration. This trial had three irrigation treatments: 1) Early 2) Control, and 3) Medium Stress. In control treatment the single irrigation was applied using the same canopy temperature stress time threshold that has been developed for fully irrigated furrow system. The other two treatments received the single irrigation at approximately 50% less or 50% more stress time than control. A rainfall event of 17.8 mm two days after the irrigation at first flower resulted in irrigations at slightly lower canopy temperature stress levels than originally planned but overall the trial was successful.

Table 6: Yield from the limited experiment conducted at ACRI during 2016-17 and 2017-18 seasons using single skip row configuration; standard errors are shown in parenthesis. Cumulative stress

hours are not absolute as there were gaps in data which were excluded in a manner that did affect treatment effect

Season	Treatment	Row Config.	Yield (bales ha^{-1})	Maturity (DAS)	Cumulative Stress Hours
2016-17	Early	Single Skip	6.5 (0.5)a	-	-
	Control	Single Skip	6.6 (0.2)a	-	-
	Medium Stress	Single Skip	7.1 (0.2)a	-	-
2017-18	Control	Single Skip	5.6 (0.03)a	136	374 (2)
	Medium Stress	Single Skip	6.1 (0.24)b	139	357 (8)
	High Stress	Single Skip	6.1 (0.14)b	139	333 (3)

The difference in yield among treatments was statistically not significant (Table 4); however, there was a trend in yield increasing from Early to Medium stress treatments (Fig. 28). Medium stress treatment resulted in highest yield of 7.1 ± 0.2 bales per hectare which was on average 0.6 and 0.5 bales per hectare higher than Early and Control treatments, respectively (Table 4).

2017-18 Limited Water Trial at ACRI

The trial in 2017-18 had three treatments: 1) Control, 2) Medium Stress, and 3) High Stress.

This trial was similar to the 2016-17 limited water trial except that “Early” treatment was replaced by “High Stress” treatment. All treatments received only a single irrigation after first flower. The Control and Medium treatments were similar to the 2016-17 trial described above in terms of canopy temperature stress hours. The High stress treatment received approximately twice the stress than that in Control treatment at the time of first irrigation based on canopy temperature approach. Yield was significantly ($p=0.028$) higher in Medium and High stress treatments compared with control, but similar between Medium and High treatments (Table 6).

The cumulative stress over the whole season decreased in the order Control > Medium stress > High Stress (Table 6), which is the complete opposite of the trend in stress used to apply the irrigation after first flower. Simply put stressing the crop earlier by delaying an irrigation resulted in decreased stress later in the season. It is possible that higher soil water deficit and larger soil cracks at the time of irrigation in Medium and High stress treatments might have resulted in a larger volume of water applied. This extra water availability might have compensated for the stress received before the irrigation application by reducing the stress later in the season. The soil water data collected using EM38 is being processed which may provide further insights into these results.

Delaying the irrigation from Medium to High Stress although decreased the cumulative stress, did not translate into yield benefit suggesting that stress should be monitored carefully where an irrigation is stretched. No difference in yield between Medium and High Stress treatments may be related to season length as Medium and High stress treatments reached maturity (60% open bolls) on the same day but three days later than the Control treatment (Table 6). Thus although High stress treatment received less cumulative stress, it did not have the season length to take advantage of extra resources.

Weather conditions during 2016-17 and 2017-18 cotton seasons were generally hotter and drier than average. Delaying an irrigation beyond the recommended threshold (control) potentially decreases yield potential, which in a wetter year may be a disadvantage. As such long term weather forecast may be taken into account to take full advantage of the season. These results show the optimum canopy temperature stress threshold for a limited water crop may be between Control and 50% above Control depending on weather conditions in a season. More trials are needed to understand yield response to these thresholds in different weather conditions.

Dial in a yield

Target yield of ≥8 bales per hectare was achieved successfully in single skip row configuration but fell short in solid row configuration (Table 2). Although yield is closer to the original target yield of 8 bales per hectare, it appears both treatments were dialled for higher yield than originally planned for but fell short of the target because of generally low yield potential during 2016-17 season driven by heat and disease. Thus, year effect needs to be taken into account when using the relationship between canopy temperature stress time and yield.

Table 7: Yield and fibre quality from Dial in a Yield trial conducted at Narrabri during 2016-17 season

Treatment	Planned target yield	Actual yield	Fibre length	Micronaire	Strength
	bales ha^{-1}	bales ha^{-1}	mm		g/tex
Solid	≥8	6.8 (0.13)	30.2 (0.25)	4.93 (0.04)	35.35 (0.48)
Single Skip	≥8	8.2 (0.2)	30.7 (0.25)	5.05 (0.04)	34.44 (0.36)

Objective 3: Research Support for high impact delivery and adoption

Engagement with growers has been pivotal in delivering the outcomes of this project which also helped understand the potential adoption barriers of new technologies such as canopy temperature sensors. Under a previous CRDC project, canopy temperature data had been collected from different farms during 2014-15 season where farmers applied irrigations using their experience and/or other tools excluding canopy temperature sensors. This data was analysed using the BIOTC protocol to compare the grower method irrigation scheduling with the canopy temperature approach. The results highlighted a significant opportunity to improve the timing of irrigations as irrigations on most occasions were applied earlier or later than suggested by canopy temperature data (e.g. Fig. 25 and Fig. 26).

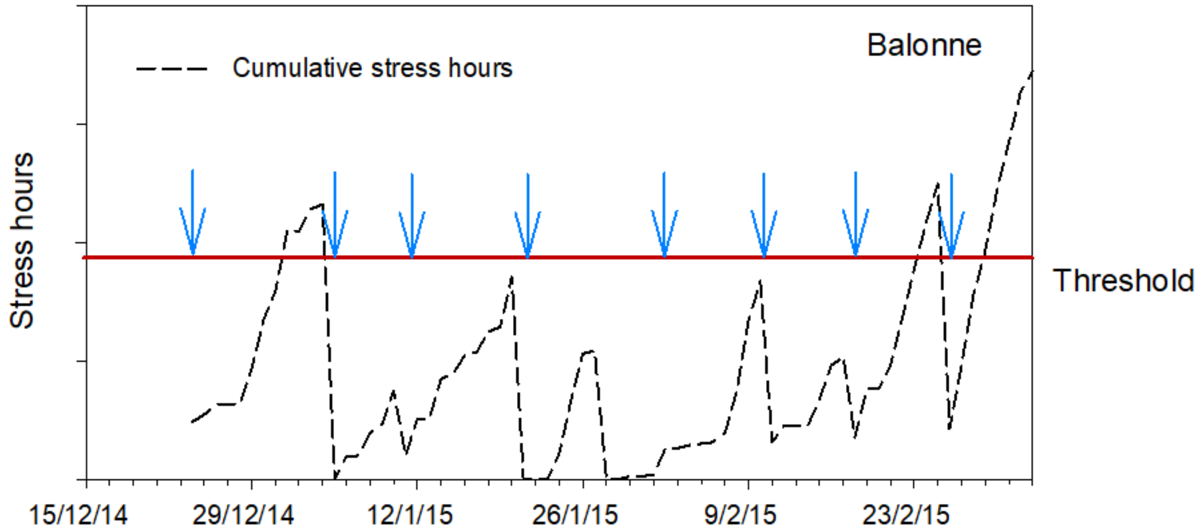

Figure 25: Canopy temperature data of a farm in Balonne valley that was irrigated using farmer practice

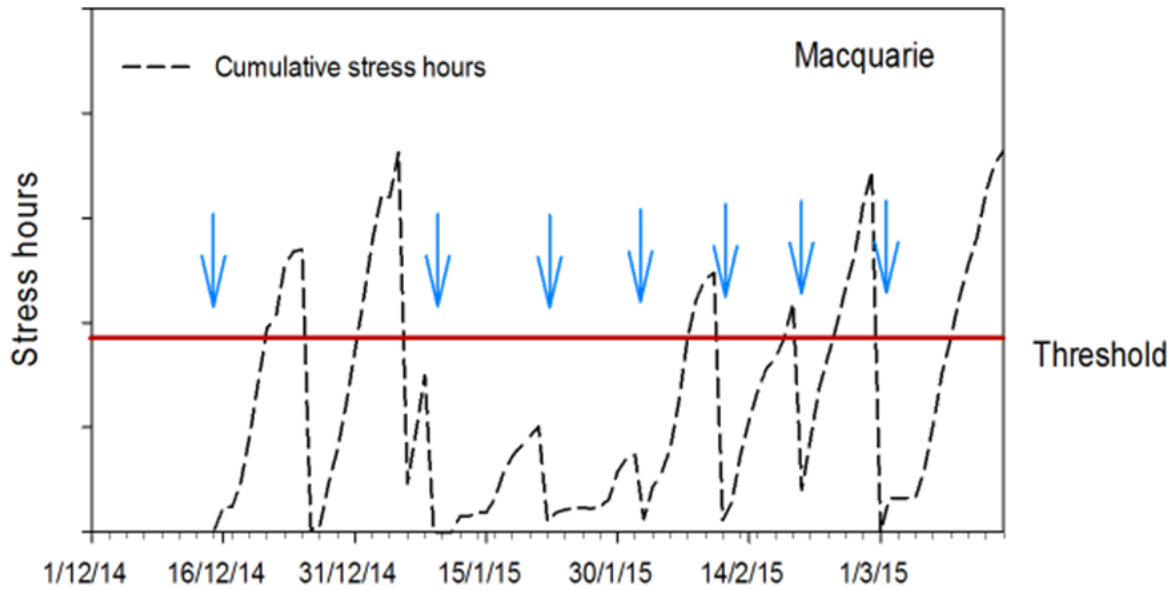

Figure 26: Canopy temperature data of a farm in Macquarie valley that was irrigated using farmer practice; red line shows the recommended stress threshold based on canopy temperature sensors

A series of new growers trials were also conducted under this project in different cotton growing valleys during three cotton seasons from 2015 to 2018. The overarching philosophy of these trials was to expose growers to plant-based sensing for managing their irrigations. We also used these trials as an opportunity to understand any adoption barriers for incorporating canopy temperature sensors into the toolbox that growers use for irrigation scheduling. In most cases growers also used a soil moisture probe for irrigation scheduling which enabled growers and research team to understand how different tools can complement each other to improve irrigation scheduling.

Table 8: Lint yield from grower trials in different valleys

Site	Season	Variety	Yield (ba ha^{-1})
Emerald	2015-16	Sicot754 B3F	10.9 - 11.2
Emerald	2016-17	Sicot754 B3F	10.7
St. George	2016-17	Sicot746B3F	11.5
St. George	2017-18	Sicot746B3F	11.5 - 12
Waverly	2016-17	Sicot714 BRF	*
Waverly	2017-18	*	*
Walgett	2017-18	Sicot746B3F	6.5 - 7
Rowena	2017-18	*	8.0 – 8.1

*data not available yet

2015-16 and 2016-17 trials at Emerald

One trial was conducted each in 2015-16 and 2016-17 seasons at a farm in Emerald. The Emerald trial during 2015-16 was continuation of similar trials conducted in seasons 2013-14 and 2014-15 under other CRDC funded projects (DAQ1404, CSP1305) to compare various irrigation scheduling techniques and explore integration options. The purpose of this trial was to evaluate practicality and usefulness of various scheduling techniques and their combined usage from a grower's perspective as opposed to the rigorous application of hard and fast numbers as evaluated in previous CRDC funded projects. The grower at Emerald has been utilizing canopy temperature sensors for last four seasons along with soil capacitance probes and is considered an experienced grower with a track record of achieving high yields for this region that matched those achieved using canopy temperature method of irrigating in trials conducted at his farm during 2013-14 and 2014-15 seasons.

During 2015-16 trial, the BIOTIC treatment received one less irrigation than the control (Table 9). The Dynamic Deficit was not triggered in this trial (2015-16) because of optimal weather conditions during the season. When the Control received its fourth irrigation the BIOTIC protocol indicated that this treatment's irrigation should be scheduled five days later. In the intervening period rainfall received negated the need to irrigate. This interception of effective rainfall translated to the BIOTIC treatment's marginally improved Irrigation Water Use Index (IWUI) and Gross Production Water Use Index (GPWUI) in comparison to the Control; however this difference was not statistically significant (Table 9).

In the irrigation trial at Emerald, the yield in different treatments did not differ significantly (Table 9).

Table 9: Performance of irrigation scheduling strategies during 2015-16 cotton season at Emerald

2015/16	Number of irrigations	Irrigation (ML/ha)	Minus tailwater (@ 7%)	Effective rainfall (ML/ha)	Irrigation & effective rainfall (ML/ha)	Yield (b/ha)	GPWUI (b/ML)	IWUI (b/ML)
Control	8	6.87	6.76	0.53	7.29	11.23a	1.54a	1.54a
Dynamic	8	6.77	6.39	0.53	6.92	10.89a	1.57a	1.70a
BIOTIC	7	5.78	5.89	0.7	6.59	11.06a	1.68a	1.88a
					SED (df = 3)	n.s	n.s	n.s

Means followed by the same letter within treatments and in the same column are not significantly different at 0.05 probability

These results show that while experienced irrigators are achieving high yields using the traditional methods, the canopy temperature method might help improve the water productivity. The grower identified that further refining the criteria for resetting stress hours following a rain event might increase the water use efficiency using BIOTIC method. Currently 25 mm rainfall is considered an irrigation equivalent to reset stress hours. The subsequent trial 2016-17 therefore reset stress hours only when a rainfall event filled the soil profile as monitored by soil moisture probe.

During 2016-17 season there were no treatments. Instead the grower integrated the canopy temperature and soil moisture data for his irrigation decision making. During 2016-17 season, the grower seemed to have irrigated well on most occasions. He stretched at least three irrigations beyond the recommended canopy temperature threshold in an attempt to catch forecasted rain but unfortunately on most occasions it rained shortly after he applied the irrigations (Fig. 27). Grower was happy that he was able to delay the irrigations to the extent he did fully aware his crop stress levels in definitive terms. Yield was 10.7 bales ha^{-1} during this season (Table 8).

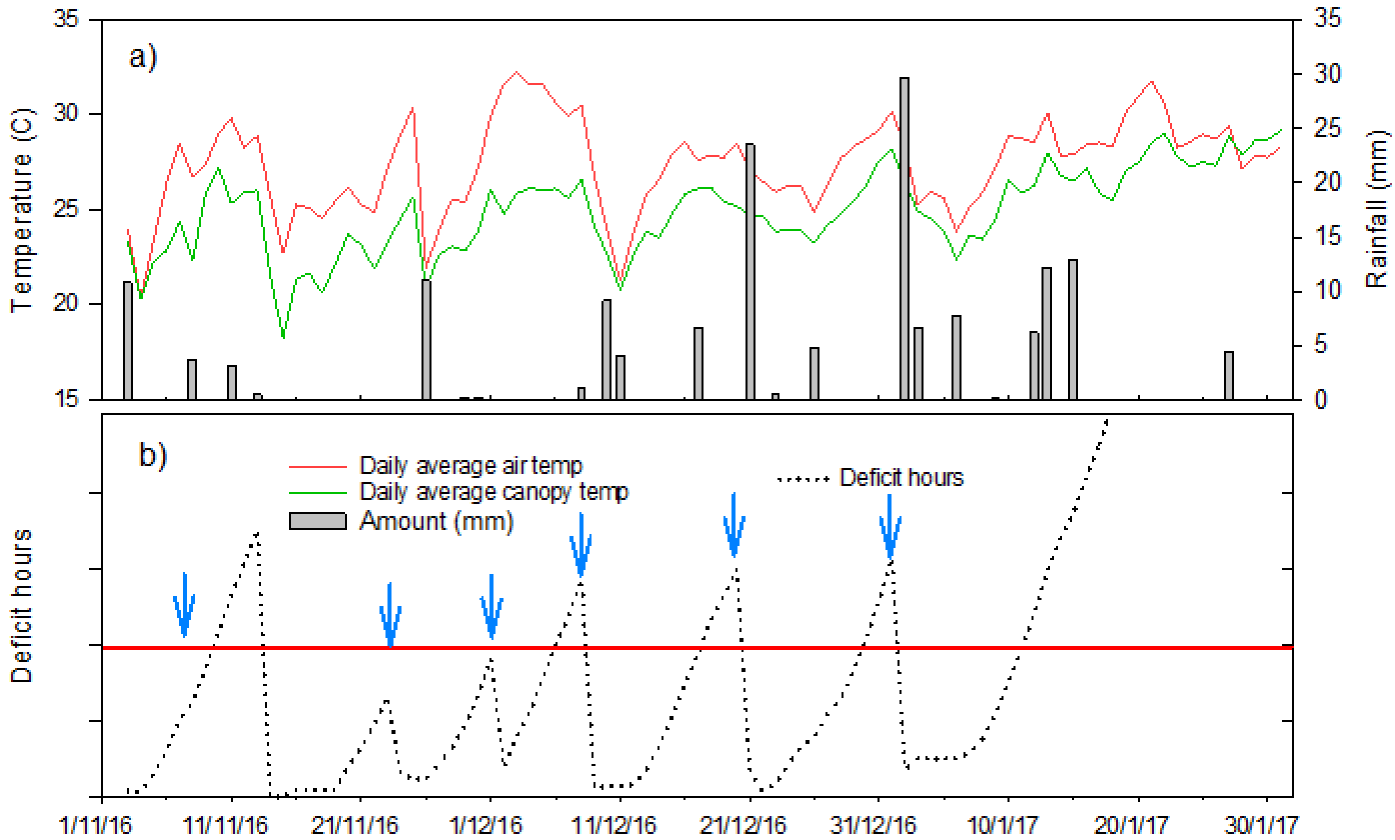

Figure 27: Canopy temperature and weather data collected at Cam Geddes Farm in Emerald during 2016-17 season; blue arrows show the timing of irrigation and red line is the recommended threshold based on canopy temperature method

2016-17 and 2017-18 trial at St. George

The grower was provided processed canopy temperature data once-twice a week or as requested by the grower. A canopy temperature sensor was installed next to a soil moisture capacitance probe. The grower actively engaged in understanding and integrating the canopy temperature method into his irrigation scheduling decision making. Irrigation dates generally closely matched with that recommended by canopy temperature method on most occasions (Fig. 32 and 33). Yield ranged from 11.5 to 12 bales ha^{-1} during the trial years (Table 8). This grower seemed to utilize canopy temperature more actively when there was a rain forecast. For example, he saved an irrigation in the first week of February 2018 by delaying an irrigation to capture rainfall. Although soil moisture probe reached the water deficit that generally triggered an irrigation (Fig. 29a), he delayed the irrigation based on canopy temperature data which did not show any plant stress (Fig. 29b). Lack of flexibility in farm irrigation system is a major reason where growers have limited control on the timing of an irrigation application. For example, the irrigation in the second week of February 2018 was applied earlier than recommended which allowed irrigating the last field on farm in time (Fig. 29). That is grower preferred over watering a field in order to avoid water stress in other fields which was a fair call from grower's point of view to maximize yield. Automation can increase the flexibility in irrigation systems.

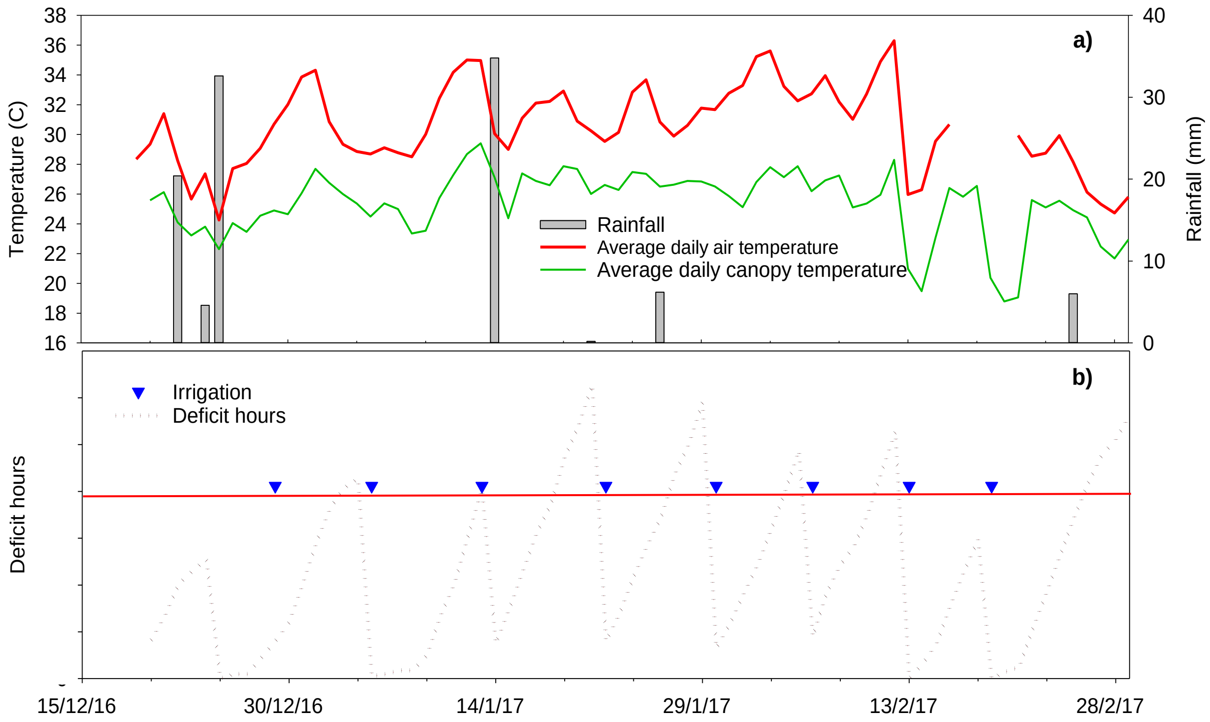

Figure 28: Canopy temperature and weather data collected near St. George during 2016-17 season; blue triangles show the timing of irrigations and red line is the recommended threshold based on canopy temperature method

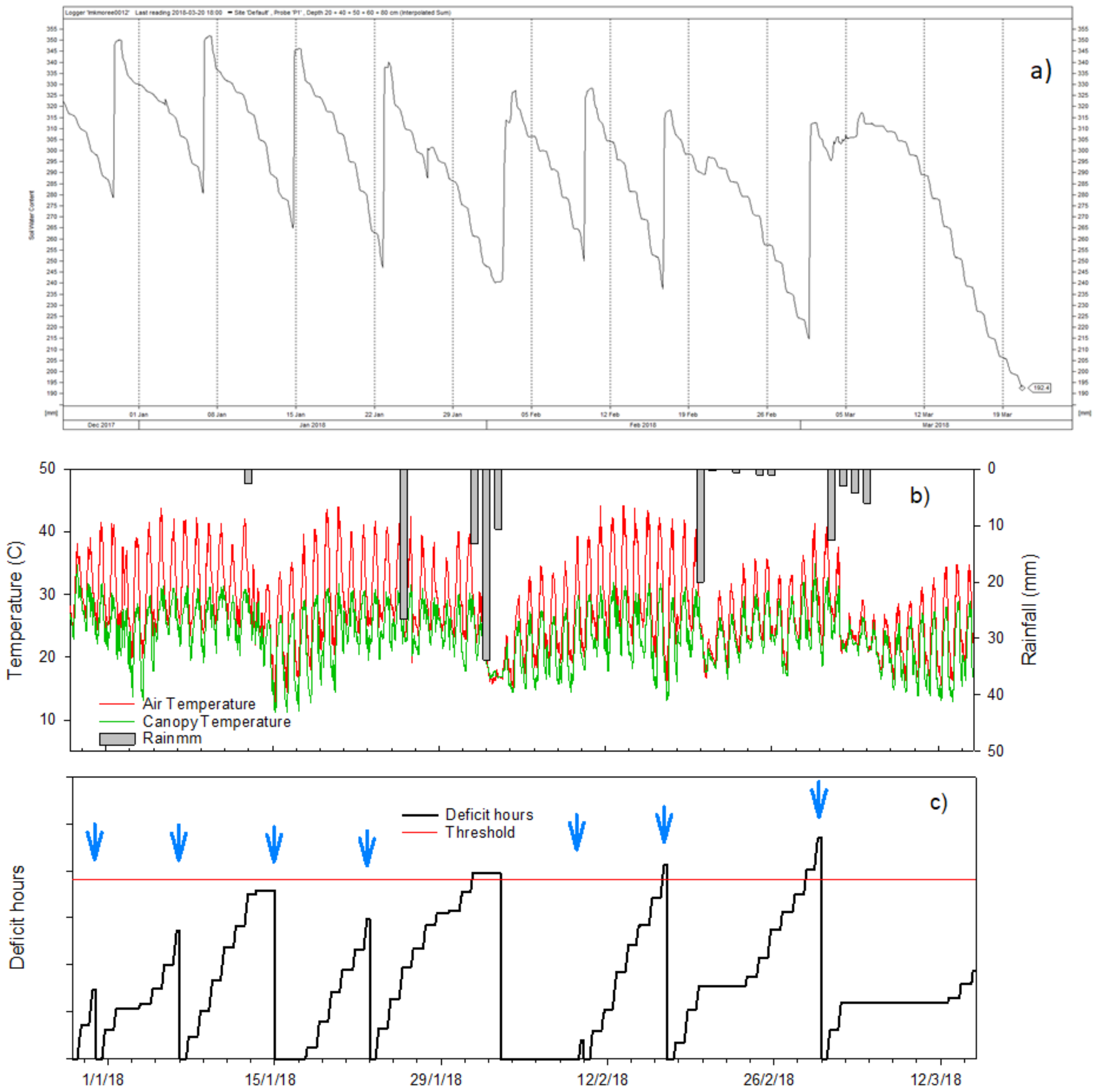

Figure 29: Farmer trial at St. George during 2017-18 cotton season showing a) Screenshot of soil water content (mm) from 0-80 cm, b) canopy temperature, air temperature and rainfall; and c) deficit hours calculated from the canopy temperature measured in the same field as soil moisture probe; blue arrows show the timing of irrigations.

2016-17 and 2017-18 trials at Waverly (Wee Waa)

During 2016-17 trial at Waverly, crop was exposed to water stress during early flowering (Fig. 30). This was part of grower's strategy to save water for mid-season when fruit load is higher and important to avoid fruit shedding because of water stress. During the mid-season crop was either irrigated earlier or delayed beyond the stress threshold based on canopy temperature data. We think such irrigation scheduling might have affected yield because of waterlogging or water stress, however, there is no definitive data to prove this. Data from 2017-18 trial was being processed at the time of filing this report.

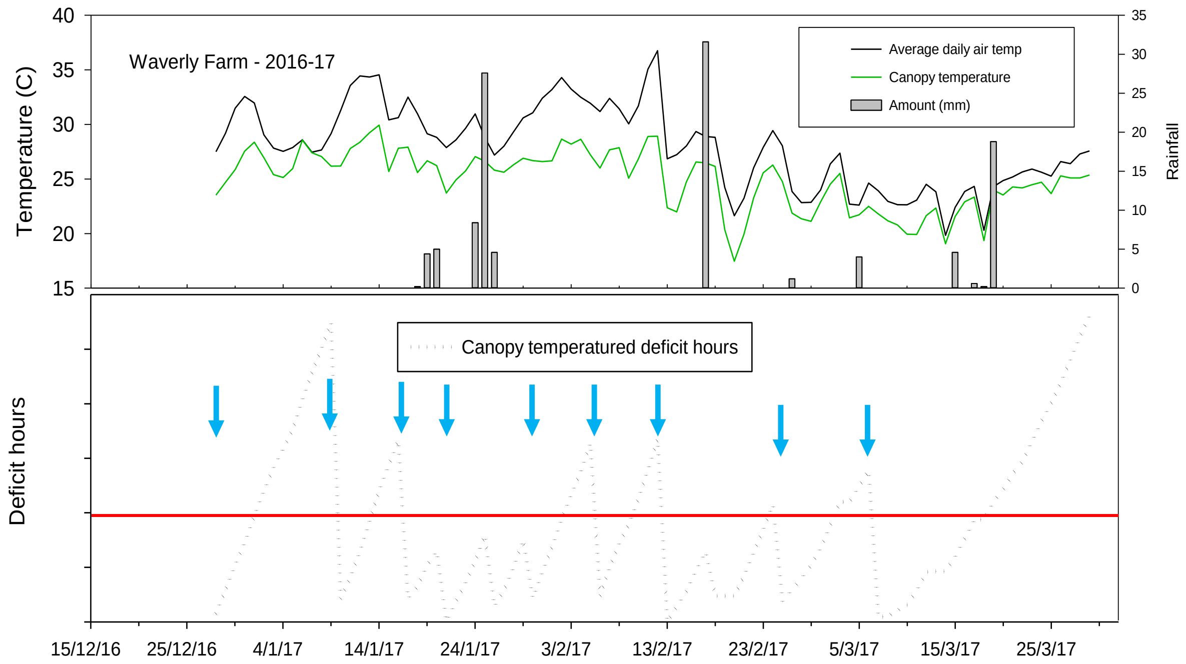

Figure 30: Canopy temperature and weather data collected at Waverly Farm during 2016-17 season; blue arrows show the timing of irrigation

2017-18 Limited water trial at Rowena

Although all irrigations were applied using roughly similar soil moisture deficits, canopy temperature deficit hours progressively decreased with season for similar soil water deficits (Fig. 31). This pattern was consistent in both the fields and may be explained by plants having access to a larger amount of water later in the season because of larger root mass. These results highlight the importance of monitoring plant stress directly alongside the soil moisture probes when scheduling irrigations.

There was also variability in canopy temperature and deficit hours between eastern and western fields (Fig. 31). Higher canopy temperature and cumulative deficit hours between irrigations were observed in eastern field compared with western field although both fields received irrigations at similar interval in terms of days (except the first irrigation) but the eastern field showed higher plant stress. Lint yield in eastern and western field was approximately 8 and 8.1 bales ha^{-1} although ginning was yet to be carried out.

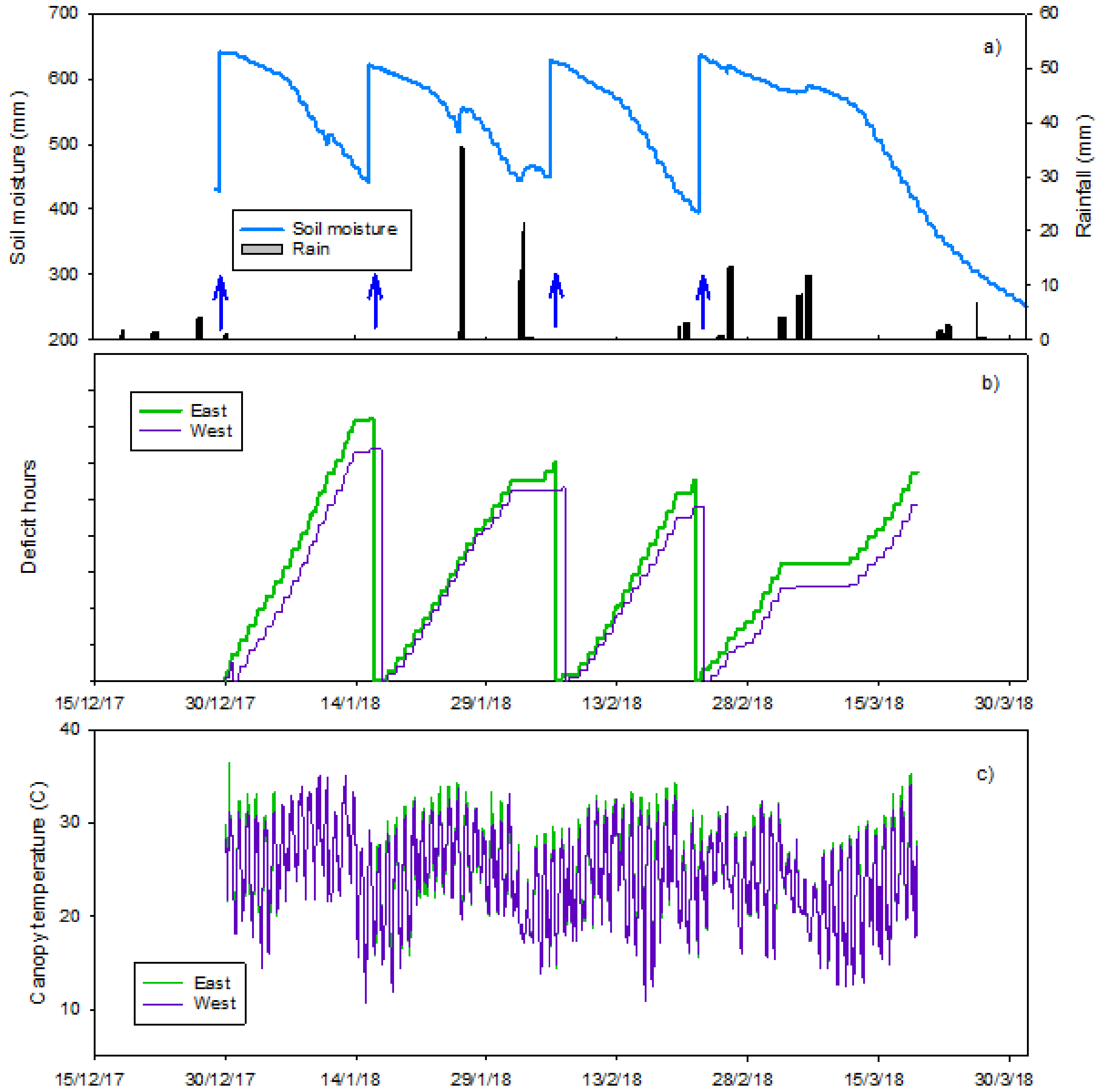

Figure 31: Limited water monitoring trial at Rowena showing: a) Soil moisture to 1m depth, rainfall and irrigation dates (arrows) in Eastern field; b) cumulative deficit hours based on canopy temperature, and c) canopy temperature

2017-18 Limited water trial at Walgett

The processing of canopy temperature and yield data was under way at the time of filing of this report.

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Brodrick R; Neilson, J; Bange MP; Hodgson D; Mundey RL (2012) Dynamic deficits for irrigated cotton - matching the soil water to plant requirements. *Proceedings of 16th Australian Agronomy Conference 2012, 14-18 October 2012, Armidale, New South Wales, Australia 2012 pp.203 ref.4*

Conaty, WC; Burke, JJ; Mahan, JR; Neilson, JE; Sutton, BG (2011) Determining the Optimum Plant Temperature of Cotton Physiology and Yield to Improve Plant-Based Irrigation Scheduling. *Crop Science* (52)

Mahan, JR; Burke, JJ; Wanjura, DF; Upchurch, DR (2005) Determination of temperature and time thresholds for BIOTIC irrigation of peanut on the Southern High Plains of Texas. *Irrigation Science* 23 (4).

○ Project level achievements

Provide a description of project achievements against the activities, KPIs and outputs as specified in sections B and C of the grant agreement.

Include an assessment of the extent to which the activity achieved the project objective, drawing on the project evaluation report.

KPI no.	KPI description	Status against KPIs	Date	Progress achieved against KPI	Outputs
1.1	Three experiments that measure early node development, leaf expansion, canopy temperature, and root development.	☒ Achieved ☐ Partially achieved ☐ Not achieved	30/04/2018	Three experiments were completed at ACRI during 2015-16 and 2016-17 seasons. One experiment compared the effect of normal first irrigation and early first irrigation on crop development. Two experiments assessed utility of thermal camera to measure canopy temperature at 15 minute intervals in the pre-flowering crop development phases.	Identify the optimum time for first irrigation, contributing towards the first objective of the Rural R&D for Profit program, i.e. generating knowledge, technologies, products or processes that benefit primary producers.
1.2	Using data collected identify whether canopy temperature, early node development, leaf expansion or root assessments can be used as a tool for scheduling the first irrigation	☒ Achieved ☐ Partially achieved ☐ Not achieved	30/04/2018	We refocused to increase efforts on estimating plant stress directly by using tools such as thermal cameras for early season irrigation decision making.	This research identified thermal camera as the best tool for early season irrigation decision making. This research will contribute towards first objective of the Rural R&D for Profit program, i.e. generating knowledge, technologies, products or processes that benefit primary producers.
2.1	Two experiments in two different soil types and two regions monitoring crop establishment and early growth comparing pre-irrigated and watered up crops.	☐ Achieved ☒ Partially achieved ☐ Not achieved	30/04/18	One detailed experiment was completed at ACRI during 2015-16 cotton season which compared the effect of watering up and pre-irrigation on crop establishment and early growth.	Definitive data on the response of crop establishment to pre-irrigation and watering up. This research will contribute towards the first objective i.e. generating knowledge, technologies, products or processes that benefit primary producers.
3.1	Using data from irrigation experiments in previous project determine whether changes in canopy temperature can be	☒ Achieved ☐ Partially achieved ☐ Not achieved	30/04/2016	Canopy temperature data collected in previous projects and historic climate data was analyzed to determine an average value for expected daily stress hours which was	Establish which parameters in the forecast can be used to predict canopy temperature and how this approach would compare to

	predicted using the short-term forecast			used to predict future canopy temperatures and schedule an irrigation five days in advance.	outcomes of the dynamic deficits scheduling. This research will contribute towards the first objective i.e. generating knowledge, technologies, products or processes that benefit primary producers.
3.2	Two experiments testing the refined integrated approach measuring water use, yield and quality	☒ Achieved ☐ Partially achieved ☐ Not achieved	30/04/2018	One experiment completed at ACRI during 2015-16 which investigated two different approaches of planning an irrigation five days in advance by integrating canopy temperature and dynamic deficit approach utilizing short term weather forecast. One experiment completed at a commercial farm in Emerald where grower practice irrigation scheduling was compared with irrigation scheduling based on canopy temperature approach and dynamic deficit approach.	These experiments highlighted the need to predict canopy temperature from forecasted weather data and integrate with dynamic deficit approach. This research will contribute towards the first objective i.e. generating knowledge, technologies, products or processes that benefit primary producers.
4.1	Two experiments manipulating timing of last irrigations to assess optimal water use yield and quality and relating to measures of crop development, soil water, and canopy temperature.	☒ Achieved ☐ Partially achieved ☐ Not achieved	30/4/2018	Two detailed experiments have been completed at ACRI during 2016-17 and 2017-18 seasons where three canopy temperature stress hour treatments were used to apply the last irrigation.	The trials identified thresholds based on canopy temperature that may be used to manage late season irrigations. This research will contribute towards the first objective i.e. generating knowledge, technologies, products or processes that benefit primary producers.
4.2	Using data from experiments in previous project determine whether canopy temperature can be used to predict water	☐ Achieved ☐ Partially achieved ☒ Not achieved	30/04/2018	This objective could not be achieved because of uncertainty in the 3-4 week forecasted weather data and the complex relationship between canopy temperature and crop water use.	

	use during this period using the 3-4 week forecast				
5.1	Identify irrigation agronomy research questions in at least two cotton growing regions through workshop/meetings with grower groups and Cottoninfo staff.	☒ Achieved ☐ Partially achieved ☐ Not achieved	30/04/2016	Research team engaged with cotton growers through field days, grower group meetings and visits to individual farms to identify grower issues regarding irrigation management which were addressed through grower trials.	Regionally specific irrigation agronomy issues investigated and latest irrigation strategies tested in different regions. This research will contribute towards the third objective i.e. establishing and fostering industry and research collaborations that form the basis for ongoing innovation and growth of Australian agriculture.
5.2	Protocols to test priority questions developed.	☒ Achieved ☐ Partially achieved ☐ Not achieved	30/11/2017	Protocols were developed to test the research priorities highlighted by growers.	Enabling growers to test a research question using scientific methods. These experiments will contribute towards second (strengthening pathways to extend the results of rural R&D, including understanding the barriers to adoption) and third (establishing and fostering industry and research collaborations that form the basis for ongoing innovation and growth of Australian agriculture) objectives of the program.
5.3	Scientific oversight and assistance provided to successfully complete grower-led experiments in at least two regions	☒ Achieved ☐ Partially achieved ☐ Not achieved	30/04/2018	Overall eight grower trials were conducted in different cotton growing valleys including Emerald, St. George, Wee Waa, Rowena and Walgett. Technical support was also provided to consultants using canopy temperature sensors.	Growers exposed to new tools for irrigation scheduling. These experiments will contribute towards second (strengthening pathways to extend the results of rural R&D, including understanding the barriers to adoption) and third (establishing and fostering industry and research collaborations that

					form the basis for ongoing innovation and growth of Australian agriculture) objectives of the program.
6.1	Two detailed experiments conducted using canopy temperature to schedule irrigation in partially irrigated cotton grown under different row configurations.	☒ Achieved ☐ Partially achieved ☐ Not achieved	30/04/2018	Four experiments were conducted at ACRI with different partial irrigation treatments using three row configurations. New relationships between yield and canopy temperature stress hours for different row configurations were developed. These relationships were tested to understand the utility of canopy temperature sensors in limited water environments.	Definitive data on establishing thresholds for different irrigation amounts and row configurations. This research will contribute towards the first objective i.e. generating knowledge, technologies, products or processes that benefit primary producers.
6.2	Test the use of OZCOT model to characterize risk (variability) with short-term or seasonal outlook for partially irrigated situations	☐ Achieved ☐ Partially achieved ☒ Not achieved	30/04/2018	This activity was not be carried out as results were not as expected, and increased focus on limited water trials and grower trials.	
7.1	Publish articles, participate in conference and/or industry presentations	☒ Achieved ☐ Partially achieved ☐ Not achieved	30/04/2018	Hiz Jamali (HJ) and Michael Bange (MB) attended the Australian Cotton Conference held at Gold Coast 2016) where MB presented the research highlights from canopy temperature work. HJ gave two presentations at the Australian Cotton Research Conference at Canberra (2017) and a presentation at the Irrigation Australia Conference in Sydney (2018). MB presented at the Burdekin Water Forum (2017) and at the Beltwide Cotton Conference (2017), USA about utility of	Research findings shared with stakeholders in cotton industry and wider research community which contributes towards third objective, i.e. establishing and fostering industry and research collaborations that form the basis for ongoing innovation and growth of Australian agriculture.

				plant-based sensing in cotton irrigation scheduling.	
7.2	Contribute to the Smarter Irrigation extension plan by end date of the project	☐ Achieved ☐ Partially achieved ☐ Not achieved	30/04/2018	In progress	
7.3	Contribute data to the Smarter Irrigation M&E plan by end date of the project	☐ Achieved ☐ Partially achieved ☐ Not achieved	30/04/2018	In progress	
8.1	Preliminary final report submitted to the Department of Agriculture	☒ Achieved ☐ Partially achieved ☐ Not achieved	30/04/2018	Final report submitted	Results of all experiments reported to the CRDC and the Department of Agriculture for future use by industry and researchers.
8.2	Final report submitted to CRDC	☒ Achieved ☐ Partially achieved ☐ Not achieved	30/06/2018	Final report submitted	Results of all experiments reported to the CRDC and the Department of Agriculture for future use by industry and researchers.

○ Contribution to programme objectives

The overall aim of the this project was to optimize irrigation management by taking guess work out of irrigation decisions, enabling growers to adapt and tailor their irrigations to an uncertain future climate and water availability. This research generated new knowledge based on definitive data using new technologies that will benefit primary producers through optimizing irrigations and identified the areas which need further research. A major focus of this research project has been on developing and extending a plant-based approach of irrigation scheduling in cotton by using proximal canopy temperature infrared sensors. Trials have demonstrated that utilizing the canopy temperature sensing technology resulted in water savings on multiple occasions by optimizing the timing of irrigations without losing yield. Building on previous research the canopy temperature method was further refined for fully irrigated cotton systems and its utility tested in partial irrigated systems to manage risk.

On-farm trials in a number of cotton growing regions enabled growers integrating new technologies such as canopy temperature with their existing tools to improve water productivity in an increasingly water limited environment. These trials have shown that integrating canopy temperature into irrigation decision making helped save at least one irrigation without losing yield on two farms. These trials helped identify potential barriers to adoption which will be considered when this technology is extended to cotton industry at a commercial scale in near future. A commercial partner has been identified to extend the canopy temperature approach of irrigation scheduling which will enable growers to integrate a new plant-based tool that may help cotton growers optimize water use and manage risk.

5. Collaboration

The long-term collaboration between CSIRO researchers working on canopy temperature research and Dr James Mahan from the USDA, Texas, USA who originally developed the BIOTIC protocol of irrigation scheduling continued through this project. This collaboration enabled exchange of scientific ideas assisting us implement the BIOTIC approach for a broader range of Australian cotton systems, supported by a CSIRO McMaster Fellowship. A preliminary study on using thermal images for early season crop water stress was conducted at ACRI during the visit of Dr Mahan to Australia in 2016. This collaboration will continue in future with likely more visits for scientific exchange between the two research groups.

A new collaboration opportunity to work with the University of Southern Queensland on use of thermal imagery in irrigation scheduling has been identified for future research. This research will specifically help address the challenge of quantifying plant stress at the start of season when canopy temperature sensors cannot be used because of smaller cotton canopy.

6. Extension and adoption activities

Figure 32: Field day at limited water trial near Walgett, NSW during 2017-18 cotton season (photo credit: Lori Nemec)

The extension and adoption activities included trials at commercial farms in collaboration with the growers and extension team, field days, grower meetings and presentations at conferences and industry forums. Several articles were contributed in the industry magazines and research presented at conferences and industry forums which are listed under "Media and Communications Material" in section 8 below.

During the course of this project eight field trials were conducted at commercial farms in Emerald, St. George, Wee Waa, Rowena and Walgett to optimize irrigation strategies in both fully irrigated as well as partially irrigated systems. These trials enabled integrating the canopy temperature approach with existing tools that growers use for irrigation decision making, and provided important insights into growers' perspective of integrating different tools in making difficult irrigation decisions. Below are a few comments from the grower who used canopy temperature at his farm in St. George:

"We need better data for better scheduling"… "the bigger the farm the more data you want"

"You have to integrate different types of information. You can't ask the plant."

"You can measure the soil water, which is an indirect measurement. I can check them every 5 minutes if I wanted to. These are the most common tools and the most affordable ones at the moment.

"Then you have canopy temperature which is the most direct measurement. I receive this output once a week, but hopefully it will become something that I can access to all the time. That would be really helpful. I receive a graph. It is understandable. I just need it all the time. I would be happy to pay a fee for it, as long as it is not excessive. I send it to the manager in my farm and he is ok with it."

"Who knows, it might reduce the number of irrigations. Or on the contrary, people might realise that they should be irrigating more often."

"Even if I start using canopy temperature all the time, I would still continue with soil moisture probes. I would still need to get used to the canopy temperature and be confident with it."

"Being able to have a line, considering soil moisture and canopy temperature to know when to irrigate would be very handy."

The process of commercialization of the canopy temperature approach for irrigation scheduling has significantly progressed and a commercial partner with significant presence in Australian cotton industry has been identified and negotiations for an agreement are underway. The engagement with growers in utilizing canopy temperature approach for their irrigation decision making under this project will help the adoption of this approach as these trails demonstrated water savings using canopy temperature approach on multiple occasions. It is important to continue on-farm trials as an integral part of all research projects as growers relate to these trials better than the trials using smaller plots although latter are also important in many ways.

Michael Bange, Rose Brodrick and Hiz Jamali attended a field day organized by CottonInfo extension team in Macquarie Valley (2016) to discuss with growers their experience of using canopy temperature sensors. Another field day was organized at the site of limited water trial near Walgett at the end of 2017-18 cotton season (Fig. 32) where the irrigation strategies for different water availability situations were discussed including how plant-based techniques such as canopy temperature may assist in such scenarios. A grower meeting was attended by James Mahan (USDA) and Hiz Jamali, at CSD (Wee Waa) in collaboration with CottonInfo team to discuss basic principles of canopy temperature approach, its utility in irrigated cotton and its limitations. A delegation of irrigated cotton farmers from the southern NSW was hosted at the ACRI during 2016-17 cotton season to visit different irrigation trial sites.

Lack of fundamental understanding of any new method of irrigation decision making can be a significant barrier to adoption. It is important to continue to engage with the end-users (farmers) directly through grower trials and indirectly through generating extension material.

7. Lessons learnt

Most researchers focus on a specific crop or cropping system as such research is funded by a specific funding body, e.g. CRDC funds research in cotton only which is logical. This project and the Rural R & D for Profit Program in general provided a unique platform for researchers generally working in a cropping system to share, learn and apply such knowledge across industries. The project was coordinated and run smoothly in a collaborative spirit.

One of the key outcomes of this project was cross industry learnings which initiated development of new collaborations. It is important that such collaborations are harvested by continuing this or similar cross industry research initiatives.

There remains some uncertainty on continuation of such research through new projects under the Rural R & D for Profit program which, given the number of agencies involved, can add to the challenges in developing collaborative projects across industries. More clarity on timelines for different stages of funding process might help researchers develop new project ideas through coordination with researchers funded by different RDCs. Streamlining the differences in the funding process of involved RDCs and aligning it with the timelines of Rural R & D for Profit program is also important.

8. Appendix - additional project information

2.1 Project material and intellectual property

○ Equipment and assets

No new assets were purchased during this project.

○ Media and communications material

Conference/industry presentations

Hiz Jamali, Rose Brodrick Tracey May, Victoria Smith and Michael Bange (2017) Irrigation scheduling with canopy temperature sensors, Australian Cotton Research Conference, Canberra.

Hamlyn Jones, Paul Hutchinson, Dave Deery, Tracey May and Hiz Jamali (2017) A practical method for estimating crop canopy conductance and evaporation rate, Australian Cotton Research Conference, Canberra.

Rose Brodrick, O Coast, H Jamali, M Bange (2017) Smarter Irrigation, The Beltwide Cotton Conference, January 2017, Dallas, USA.

Michael Bange (2017) New Approaches to Precision and Smarter Irrigation. Burdekin Water Forum, Townsville

Hiz Jamali, R Brodrick, O Coast, T May, V Smith and M Bange (2018) Canopy temperature: A plant-based method for irrigation scheduling in cotton, Irrigation Australia International Conference and Exhibition, Sydney (June 2018)

Industry articles

Hiz Jamali, Rose Brodrick and Michael Bange (2017) Irrigation scheduling using canopy temperature: let the plants do the talking. CottonInfo (published online)

Hiz Jamali, Michael Bange (2018) Sensing crop needs. SPOTLIGHT (in press)

Hiz Jamali, Michael Bange (2018) Canopy temperature – plant based method for irrigation scheduling. Irrigation Scheduling Technologies Booklet (under review)

Field days and grower meetings

Field day, Walgett (2018): Utility of canopy temperature sensors in partially irrigated cotton

Field Day, Macquarie Valley (2016): Utility of canopy temperature sensors in cotton

Grower meeting at CSD, Wee Waa (2017): Utility of canopy temperature sensors in cotton

IREC Maximising Irrigation Profitability Tour to ACRI (07 February 2017)

○ Evaluation report

Final project evaluation report is attached.

○ Budget

The statement of funds and contributions will be submitted as part of the final financial report due by 31st July 2018. The budget for the life of the project will be fully expended by the end of the project.