Smarter Irrigation for Profit 2

RRDP 2006 Plant based sensing for cotton irrigation

Final Report

Australian Government
Department of Agriculture, Fisheries and Forestry

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CRDC

CSIRO

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Plain English summary

BACKGROUND

Water is considered the most uncertain and limiting factor for cotton production in Australia, which is reflected in the variability in total lint production over the past 15 years - ranging from less than 150 kilo tonnes to more than 1200 kilo tonnes per year. Australia's cotton industry has achieved significant gains in water use efficiency in recent decades through improvements in yield and more efficient irrigation systems including the utility of irrigation scheduling tools. Good irrigation scheduling practices ensure that water is available in sufficient quantity when crop needs it. Irrigation scheduling methods can be based on monitoring soil water content, measured and predicted rates of evapotranspiration, plant water potential, and plant temperature. In Australia, soil water deficit is frequently used as an irrigation scheduling tool in cotton systems where a field is flood irrigated once soil water is depleted to a pre-determined deficit. Soil water availability can vary between years and within a season due to factors including sub-soil constraints, weather and root development. These factors make it challenging to schedule irrigations based on soil water data only. Building on CSIRO's research in the last 15 years, this project aims to improve irrigation scheduling in both fully irrigated and partially irrigated systems by developing plant-based sensing tools to complement the existing tools such as soil water sensors. CSIRO has developed an irrigation scheduling tool based on continuous monitoring of canopy temperature which is an indicator of crop water stress.

EARLY SEASON IRRIGATION

The existing canopy temperature sensors are single pixel and see the sensor field of view as a single unit. This means the data from these sensors is only accurate with a closed canopy which occurs closer to flowering, as the difference between soil and plant in the field of view during early-stage cotton causes errors in the canopy temperature readings. This research reviewed the suitability of commercially available multipixel sensors for early season stress monitoring and selected a low-cost thermal sensor array. Detailed field trials were conducted in NSW and QLD to collected data using a range of sensors including the point sensors, multipixel sensors array, and RGB images. Machine vision approaches were used to develop thermal segmentation algorithm that did not require colour camera images. The developed algorithm tracked the location of plant pixels in a time series of thermal images over the previous 24-hour period. A

significant outcome of this research is that the cotton farmers can now monitor canopy temperature from the start of the season.

MANAGING LIMITED WATER

When water is limited, farmers look for strategies to maximize yield per drop. We investigated the optimum time to apply a single irrigation in a cotton crop. Field experiments were conducted over three seasons at the Australian Cotton Research Institute, Narrabri. ACRI. We identified an optimum time to apply the single irrigation and irrigating earlier or later resulted in yield penalties. We investigated different methods to optimize the timing of a single irrigation using modelling. Using stress time derived from the continuous measurements of canopy temperature provided the narrowest window of two days to apply the irrigation for best yield. In cases where canopy temperature data is not available, we provide the recommendations based on actual days since first flower, degree days since first flower and soil water deficit; however, the recommended time window is wider compared with the canopy temperature approach. The identified stress threshold based on canopy temperature appears to be the most accurate method for scheduling an irrigation in limited water. This research will significantly increase farm profitability in limited water situations as we observed up to 56% loss in yield in 2020-21 cotton season when the single available irrigation was not applied at the recommended time during flowering.

SPATIAL VARIABILITY

Cotton farms are often spread over large areas with multiple soil types represented within a farm boundary. Soils with variable water holding capacity can have implications for irrigation management. In this project we evaluated the utility of lightweight uncooled UAV thermal cameras in assessing spatial variability in canopy temperature. The accuracy of thermal data was tested against a blackbody calibration source in controlled and outdoor conditions which identified several sources of error including a period of instability for the first 30 minutes, effect of battery swapping, vignetting around edges of the thermal image, and camera body temperature. We provide recommendations on addressing the above-mentioned issues to generate more accurate imagery using uncooled thermal cameras. Spatial variability was assessed on a large commercial farm in southern NSW by installing sixteen canopy temperature sensors in different parts of the field. Large spatial variability was observed in cumulative crop water stress. For example, there was a difference of up to seven days in recommended irrigation

dates for different parts of field. These results highlight the opportunities for optimising irrigations based on spatial and temporal variability in crop stress. This information can also be used by farmers to decide the location of canopy temperature sensors. In Australia, cotton is mostly grown using surface flood irrigation methods which often do not have the flexibility to change irrigation regime for different parts of the field. Nonetheless, the knowledge about spatial variability can help growers understand the opportunities to improve water productivity by adopting more flexible irrigations systems and layouts.

ON-FARM RESEARCH

The project team worked closely with a number of cotton growers which was facilitated by the cotton industry's extension wing – CottonInfo. A grower focus group was established to explore strategies for managing water in partially irrigated cotton systems. This focus group participated in trials conducted at seven locations during the 2020-21 cotton season to demonstrate the utility of canopy temperature sensors in optimizing the timing of irrigations in fully irrigated and limited water situations. Growers were provided feedback during weekly virtual meetings to help interpret the data collected from their crops. These engagements are important for increasing grower awareness about new crop sensing tools and reduce barriers for their adoptions. Project team has provided technical support to the commercial partner in designing their platform and integrating the CSIRO-developed irrigation scheduling algorithms based on canopy temperature data into their platform. This product is now commercially available to cotton growers on desktop and as mobile app to help optimize their irrigation decisions.

FUNDING

This project was supported by funding from the Cotton Research and Development Corporation and the Australian Government Department of Agriculture, Fisheries and Forestry under the Rural R&D for Profit program.

Abbreviations

ACRI – Australian Cotton Research Institute

CSD – Cotton Seed Distributors

CRDC – Cotton Research & Development Corporation

CSIRO – Commonwealth Scientific & Industrial Research Organization

FOV – Field of View

GVIA – Gwydir Valley Irrigators Association

IR – Infrared

HVI – High Volume Instrument

UAV – Unmanned Aerial Vehicle

USQ – University of Southern Queensland

1 Project rationale and objectives

Developing strategies for optimising water use, yield and quality in both fully irrigated and partially irrigated systems, will contribute to long term sustainability of the Australian cotton industry. By maintaining best practices in water use Australian growers will continue to lead the world in producing highest yields in an environmentally sustainable manner. Uncertainty around availability of water in different years has made irrigation management challenging. New tools and approached are required to help farmers make informed irrigation decisions according to their farming situation especially water availability in a season. Plant-based methods of irrigation scheduling can help improve irrigation decision making as plants integrate the effect of both soil and aerial environments. CSIRO researchers at Narrabri have developed a plant-based method of irrigation scheduling for fully irrigated cotton using canopy temperature sensors. This project helped progress the adoption of this canopy temperature method of irrigation by the cotton industry and enable further refinement and testing the methodology in both fully and partially irrigated systems. There is great value in improved water use efficiency enabling a greater area of cotton production or higher yield of the planted area. The marginal return on one mega litre water is more than $500 (one bale of lint). If the industry was at approximately 472,000 ha of cotton production in 2016-17, and if 25% of the industry saved one mega litre per hectare, that value would be increased production worth $58 million.

More specific to CRDC's strategy the outcomes of this project will contribute to the "farmers' program themes **1.2 "productive resource efficiencies**" and theme **1.3 "profitable futures**" and strategy **1.2.3 "development of new systems and tools to support farm decision making processes**". Developing new irrigation strategies will take the guesswork out of irrigation decisions, enabling growers to adapt and tailor their irrigation to a future water limited environment. This will ultimately assist growers in closing the significant gap between the yield and water use efficiency of the highest achievers and the industry average. Development of new systems and tools is a key focus of theme 1.2 and the development of new strategies particularly for limited water scenarios will assist in theme 1.3's goal of achieving the longer-term profitability in a changing environment.

2 Method, activities, and project locations

5.1a Conduct research to develop sensing techniques to complement the BIOTIC approach based on canopy temperature for early-season irrigation scheduling.

- KPI 1.7 Identify plant-based- sensing techniques suitable for early-season irrigation scheduling (Activity output 5.1a).
- KPI 2.4 Conduct research to test the performance of at least one initially identified plant-based sensing technique and develop relevant calibration and analytics to extract canopy temperature (Activity output 5.1a)
- KPI 3.3 Develop a proof-of-concept early-season plant-based sensing system with automated online data processing system for imagery sensing techniques (Activity output 5.1a).

Commercial in confidence

5.1b Conduct two experiments and meta-analysis to evaluate the usefulness of canopy temperature thresholds in fully and partially irrigated cotton.

- KPI 1.8 Evaluate different canopy temperature thresholds using historic canopy temperature data with a focus on the accuracy of irrigation dates based on predicted canopy temperature. (Activity output 5.1b).
- KPI 2.5 Commence two experiments to optimise stress time thresholds in partially and fully irrigated cotton (Activity output 5.1b).
- KPI 3.4 Develop a method of incorporating rainfall events into canopy temperature stress time calculations and report on experiments to optimise stress time thresholds in partially and fully irrigated cotton (Activity output 5.1b).

Commercial in confidence

5.1c Conduct two experiments to determine the spatial variability in canopy temperatures using infrared canopy sensors and UAVs under full and partial irrigation of cotton.

- KPI 1.9 Evaluate the effectiveness of UAVs for capturing the spatial variability in canopy temperature on larger farms using thermal imagery (Activity output 5.1c).

Commercial in confidence

Activity 5.1c Conduct two experiments to determine the spatial variability in canopy temperatures using infrared canopy sensors and UAVs under full and partial irrigation of cotton.

- KPI 2.6 Determine the spatial variability in canopy temperatures using infrared canopy sensors in two field experiments to determine the minimum number of canopy temperature sensors required for irrigation scheduling (Activity output 5.1c).

- KPI 3.5 Determine the spatial variability in canopy temperatures using infrared canopy sensors and UAVs in two field experiments. Process and analyse UAV imagery and canopy temperature data and share recommendations on minimum number of sensors required for irrigation scheduling with the commercial partner (Activity output 5.1c).

- Final report. Provide a brief and final report on the utility and effectiveness of the canopy temperature approach of irrigation scheduling under full and partial irrigation of cotton (Activity output 5.1c).

5.1d Engage with cotton industry and private sector partners to demonstrate the value of using canopy temperature sensing to inform irrigation scheduling.

Engagement with the commercial partner

CSIRO's project team has provided technical support to the commercial partner, Goanna Ag, in designing their platform. Goanna Ag has integrated the CSIRO-developed irrigation scheduling algorithms based on canopy temperature data into their GoApp platform. This product is now commercially available to cotton growers on desktop and as mobile app and provides soil water and crop stress data in real-time. Technical support is being provided to Goanna Ag on ongoing basis to help design and/or improve their hardware and software to deliver canopy temperature technology to the Australian cotton industry.

Engagement with farmers

A grower focus group was established in collaboration with the CottonInfo to investigate strategies for managing water in partially irrigated cotton systems. This focus group participated in trials conducted at seven locations during the 2020-21 cotton season to demonstrate the utility of canopy temperature sensors in optimizing the timing of irrigations in fully irrigated and limited water situations. Growers were provided feedback during weekly virtual meetings to help interpret the data collected from their crops. A grower demonstration trial was conducted at Keytah farm near Moree, NSW where canopy temperature and soil water sensors were installed in 10 different fields. Access to real-time data was provided to farm manager through Goanna Ag's online platform to help manage irrigation decisions.

Project team

Name	Organisation/Business	Role
Hizbullah Jamali	CSIRO	Project Leader and research scientist
Christopher Nunn	CSIRO	Digital Agronomist
Darin Hodgson	CSIRO	Research technician & UAV pilot
Victoria Smith	CSIRO	Research Assistant
David Deery	CSIRO	Research Scientist
Quanxi Shao	CSIRO	Data Scientist
Andrea Powell	CSIRO	Data Scientist
Tom Dowling	Goanna Ag Pty Ltd	Commercial partner
Alison McCarthy	University of Southern Queensland	Research scientist

Locations of all project activities

Name & type of site (field site, laboratory, project partner sites, RDC headquarters)	**Street Address**	**State**	**Postcode**
ACRI (field site)	Kamilaroi Highway, Narrabri	NSW	2390
Caroale	Carnarvon Highway, Moree	NSW	2400
Auscott Narrabri	Kamilaroi Hwy, Narrabri	NSW	2390
Warilea, Maules Creek	Maules Creek Road, Narrabri	NSW	2390
Battery Hill	Gunnedah	NSW	2380
Walma	Walgett	NSW	2832
Towri	Burren Junction	NSW	2386
Strathguyle	Gwydir	NSW	2400
Cleveland	Gwydir	NSW	2400
Midkin	Gwydir	NSW	2400

3 Project Outcomes

This should be a summary of the project achievements detailed in your technical report.

3.1 Project level achievements

Provide a description of the project achievements against Outputs 5.1a, 5.1b, 5.1c, 5.1d. The italics is additional KPI information required in the final report. Include graphs, tables and/or images where applicable.

Output and KPI numbers and description	**Summary of achievements**
5.1a Conduct research to develop sensing techniques to complement the BIOTIC approach based on canopy temperature for early-season irrigation scheduling.	Existing IRT sensors used are typically single-point and only accurate with a closed canopy, as the temperature reading is inaccurate during early-stage cotton when there is also soil in the sensor's field of view. Low-cost multipixel sensor arrays have become available in recent years that allow diving the FOV into several hundred pixels. This research reviewed the suitability of commercially available multipixel sensors for early season stress monitoring and selected a low-cost thermal sensor array. Detailed field trials were conducted in NSW and QLD to collected data using a range of sensors including the point sensors, multipixel sensors array, and RGB images. Machine vision approaches were used to develop thermal segmentation algorithm that did not require colour camera images. The developed algorithm tracked the location of plant pixels in a time series of thermal images over the previous 24-hour period. The plant temperature using the developed segmentation algorithm had RMSE=0.20°C and R^2=0.804 compared with manual ground truth segmented temperature.
5.1b Conduct two experiments and meta-analysis to evaluate the usefulness of canopy temperature thresholds in fully and partially irrigated cotton.	Research was conducted to achieve three milestones under this activity: **Activity 1**: The accuracy of CSIRO's published canopy temperature prediction model was investigated. The analysis showed high level of accuracy for irrigation events based on predicted Tc.

	Out of 40 irrigation events, 75% (30 events) matched to the day of irrigation. Of the remaining 10 irrigation events, 10% were out by one day, 12.5 % by two days and 2.5% (i.e., one event) by 3 days compared with the irrigation dates based on measured Tc. **Activity 2:** When water is limited, farmers look for strategies to maximize yield per drop. We investigated the optimum time to apply a single irrigation in a cotton crop. Trials were conducted over three seasons at ACRI where the timing of a single irrigation was changed to investigate its effect on yield. In all three seasons (2018-19, 2019-20 and 2020-21) and in the simulated season of 2020-21 with flush irrigation there was a yield response to the timing of the single irrigation. In the first two seasons delaying irrigation resulted in an increase in yield. In 2020-21, yield increased with delayed irrigation, but the most delayed irrigation resulted in a relative yield loss. We assessed utility of different parameters as indicators of irrigation timing by fitting curves. A second-degree polynomial curve was fitted to determine the best time to apply an irrigation in terms of days after first flower, degree days after flower, soil water deficit at the time of irrigation, and cumulative stress time since first flower. In further analysis, we explored if the peak of the curves is consistent across seasons in all parameters (i.e., days, degree days, soil water deficit and stress hours). Results showed that peak of the curves was variable across seasons for days, degree days, and

	soil water deficit. This outcome was not unexpected. For example, days do not consider the variability in weather, especially thermal length of the days, between seasons. Degree days normalises the days according to thermal intensity; however, it does not consider the variability in soil moisture between seasons. This is the reason curve peak between flush and non-flush treatments during 2020-21 season is different despite same degree days. Soil water deficit does not consider the variability in weather especially temperature between the years, hence different shape, and peak of the curve. In contrast, the accumulative stress time from firs flower showed a consistent peak at 115-117 stress hours. Thus, using stress time derived from the continuous measurements of canopy temperature provided the narrowest window of two days to apply the irrigation for best yield. In cases where canopy temperature data is not available, we also provide the recommendations based on actual days since first flower, degree days since flower and soil water deficit; however, the recommended time window is wider compared with the canopy temperature approach. **Activity 3:** In the current irrigation scheduling methodology based on canopy temperature algorithms, rainfall is not adequately considered. In terms of irrigation scheduling, rainfall can potentially delay the irrigation timing and improve water use efficiency; however, extent of the potential delay is not clear. We investigated how rainfall affects the accumulative stress time which is used to guide irrigation scheduling. In this research, we

	proposed a resting factor which is used to adjust the value of original accumulative stress hours following rainfall events. We proposed a framework to introduce rainfall effect in the stress resting by determining a discount factor as the function of effective rainfall. we assume that the discount factor is a segmented linear function of soil water refill, with zero discount (i.e., original accumulative stress time is applied) for the soil water refill below a low threshold, full reset (equivalent to irrigation, i.e., complete reset) for the soil water refill above an upper threshold and linear function between the low and upper threshold. Under a continuity constraint, we derived the discount factor. Under continuity constraint, we derived the discount factor (see **Error! Reference source not found.**). The proposed inclusion of partial stress reset to reflect the impact of watering events into the *periodiCT* model (background IP) shows potential to use the *periodiCT* model to test reset criteria in predicting canopy temperature for non-well-watered crops. We have demonstrated that incorporating the partial reset factor into the *periodiCT* model does not degrade the model performance for well-watered cotton, meaning the linear discount factor is potentially applicable to partially reset the accumulate stress hours in planning irrigation schedule. .
Final report. Provide a brief final report on optimizing stress time thresholds for irrigation scheduling in partially and fully irrigated cotton. Include commentary on the accuracy of irrigation dates based on canopy temperature. (Activity output 5.1b).	A detailed technical report is included in Appendix 1.

5.1c Conduct two experiments to determine the spatial variability in canopy temperatures using infrared canopy sensors and UAVs under full and partial irrigation of cotton.	Cotton farms are often spread over large areas with multiple soil types represented within farm boundary. In this project we evaluated the utility of lightweight thermal cameras in assessing spatial variability. The accuracy of thermal data was tested against a blackbody calibration source in controlled and outdoor conditions which identified several sources of error. Thermal data was impacted by period of instability for first 30 minutes, few minutes before and after replacing a battery, vignetting around edges of thermal image, and camera body temperature. We discuss and provide recommendations on addressing the above-mentioned issues to generate more accurate imagery using uncooled thermal cameras. Spatial variability was assessed on a large commercial farm in southern NSW by installing sixteen canopy temperature sensors in different parts of the field. It was observed that irrigation schedule adopted by growers did not match with that recommended by canopy temperature approach on most occasions. During early flowering (mid-Dec – mid-Jan) irrigations were often applied later than the recommended date. There are two possible explanations to this delay in irrigation: 1) farmers delay irrigations during early season to increase root development which helps access water from deeper soil layers later in the season; 2) error in canopy temperature data due to smaller crop canopy and presence of 'warmer' soil in the sensor field of view. During interval 4-7, irrigations were applied up to six days earlier than recommended and highlight opportunities to delay and potentially save irrigations.

	Large spatial variability was observed in cumulative stress. For example, there was a difference of up to seven and five days in recommended irrigation dates during internal 5 and 6, respectively. These results highlight the opportunities for optimising irrigations based on spatial and temporal variability in crop stress. In Australia, cotton is mostly grown using surface flood irrigation. Unlike pressurised systems, flood irrigation systems do not have the flexibility to change irrigation regime for different parts of the field. Nonetheless, the knowledge about spatial variability can help growers adjust irrigation layouts in future.
Final report. Provide a brief and final report on the utility and effectiveness of the canopy temperature approach of irrigation scheduling under full and partial irrigation of cotton (Activity output 5.1c).	A detailed technical report is included in Appendix 1.
5.1d Engage with cotton industry and private sector partners to demonstrate the value of using canopy temperature sensing to inform irrigation scheduling.	CSIRO's project team has provided technical support to the commercial partner, Goanna Ag, in designing their platform. Goanna Ag has integrated the CSIRO-developed irrigation scheduling algorithms based on canopy temperature data into their GoApp platform. This product is now commercially available to cotton growers on desktop and as mobile app and provides soil water and crop stress data in real-time. Technical support is being provided to Goanna Ag on ongoing basis to help design and/or improve their hardware and software to deliver canopy

	temperature technology to the Australian cotton industry. A grower focus group was established in collaboration with the CottonInfo to investigate strategies for managing water in partially irrigated cotton systems. This focus group participated in trials conducted at seven locations during the 2020-21 cotton season to demonstrate the utility of canopy temperature sensors in optimizing the timing of irrigations in fully irrigated and limited water situations. Growers were provided feedback duirng weekly virtual meetings to help interpret the data collected from their crops. A grower demonstration trial was conducted at Keytah farm near Moree, NSW where canopy temperature and soil water sensors were installed in 10 different fields. Access to realtime data was provided to farm manager through Goanna Ag's online platform to help manage irrigation decisions.

Please include information from any project specific evaluations you may have conducted.

3.2 Contribution to SIP2 program outcomes

1. Improved on farm water productivity/water use efficiency through use optimised irrigation practices, precision irrigation technologies and autonomous irrigation systems on participating farms.
Indicators:

- *20% increase in water productivity on SIP2 optimisation and key learning sites.*
- *20% improvement in irrigation water productivity through use of autonomous irrigation and/or autonomous components on SIP2 research and demonstration sites.*
- *80% of participating producers adopt or intend to adopt precision irrigation strategies and technologies.*

5. Increase in the number of cost-effective precision irrigation technologies able to be integrated into autonomous irrigation systems/platforms.
Indicator

- *Number and type of new precision irrigation technologies and/or fully automated irrigation systems developed/refined as a result of your projects research activities.*

This sub-project most closely aligns with the outcome 1 and 5 listed above. A new digital tool based on canopy temperature measurements has been added to farmer toolbox to help improve irrigation decisions and improve water productivity. This low-cost tool is now available to growers on commercial scale with uptake of technology increasing every season. Through this project, algorithms have also been developed to measure canopy temperature using a multipixel array which will significantly expand the use of this technology to early cotton season and reduce labour costs associated with sensor maintenance during the season. An economic analysis [Link] showed that using canopy temperature for irrigation scheduling can increase farm profitability by $152 per ha per season in a fully irrigated cotton system by improving yield and reducing cost of water and labour. A similar economic analysis is being conducted for the partial irrigated systems.

4 Collaboration

4.1 Project collaborations

This project delivered industry outcomes through developing effective multifaceted collaborations as described below:

1. Research

The project team collaborated with researchers from other business units within CSIRO and with external organizations. Within CSIRO collaboration included working with the data scientists from CSIRO's Data61 based in Perth who helped perform complex analyses in incorporating the rainfall events in the irrigation scheduling algorithm based on canopy temperature. The external collaboration included working with researchers (Drs Alison McCarthy and Derek Long) University of Southern Queensland (USQ) to develop tools for assessing crop water stress during early season. Despite COVID-19 related travel restrictions, the CSIRO and the USQ teams worked closely to design and implement field trials at Toowoomba and Narrabri. Nominating key members of the project team to liaise with partners has helped achieve effective communication. This collaboration with USQ has successfully delivered development of machine learning algorithms for extracting canopy temperature of younger plants and is being evaluated for commercial exploitation. The next steps for this collaboration have been identified and discussions for research funding are in progress.

2. Commercial

Goanna Ag Pty Ltd was commercial partner for this project who the project team also worked with during phase 1 of the Smarter Irrigation for Profit project. Goanna Ag have entered into a commercial agreement with CRDC and CSIRO to deliver the canopy temperature method of irrigation scheduling to cotton growers at commercial scale. CSIRO researchers and the Goanna team have established a good working relationship and are communicating frequently to resolve any issues that may arise during the adoption phase. Technical support to Goanna team is being provided on ongoing basis to help implement the irrigation scheduling algorithms developed by CSIRO.

3. Extension

The project team worked closely with CottonInfo, the extension wing of cotton industry, to leverage their networks in all cotton growing valleys. The support from CottonInfo was key to deliver a range of extension activities including development of YouTube videos, webinars,

podcasts, and industry articles. CottonInfo provided significant support in establishing a focus group of farmers who collaborated with the research team to investigate strategies for managing limited water.

4. Farmers

Project team collaborated with several growers to conduct detailed field trials to help answer their questions and explore the utility of canopy temperature in managing their irrigation decisions. Farmers were provided feedback on data collected from their farms through weekly reports that were discussed in more detail through weekly virtual meetings. This close engagement was critical to ensure farmers were getting valuable information in return to their time investment in these extension activities. The effective collaboration helped identify any issues (e.g., hardware failure on a farm) and address in a timely manner which resulted in collection of quality data on most farms involved in these trials.

4.2 Recommendations for activities to support future collaborations.

The commercial-in-confidence nature of research limited collaboration opportunities with other industries and research organizations. Having a commercial partner from the start of project helps bring the service provider and end-user perspective which is key to deliver research impact.

5 Extension and adoption activities

5.1 Project extension & adoption activities

A complete list of extension materials created under this sub-project is presented in section 6 below. Hiz Jamali and Chris Nunn presented the research findings at several prominent industry events including the Cotton Seed Distributors (CSD) field day, Gwydir Valley Irrigators Association (GVIA) field day, and the Australian Cotton Researchers Conference. In collaboration with the CottonInfo, cotton industry's extension wing, two YouTube videos were created that demonstrated the utility of canopy temperature sensors in irrigation decision making. Several articles were published in prominent national and international cotton industry magazines including the Spotlight, Cotton Growers Magazine, and the International Cotton Researchers' Association newsletter.

In collaboration with the CottonInfo, a focus group of growers was formed to share the knowledge between growers and the project team with the aim to develop strategies for managing irrigation in limited water cotton systems. Canopy temperature sensors were installed on the seven participating farms located in Namoi and Gwydir valleys. A farm report was sent to each grower weekly showing a series of graphs based on data collected from their farms. The focus group held weekly virtual meetings where the project team and the growers exchanged ideas.

A grower demonstration trial was conducted at Keytah farm near Moree, NSW where canopy temperature and soil water sensors were installed in 10 different fields . Access to realtime data was provided to the farm manager through Goanna Ag's online platform to help manage irrigation decisions. CSIRO's project team has provided technical support to Goanna Ag in designing their platform. Goanna Ag Pty Ltd has integrated the CSIRO-developed irrigation scheduling algorithms based on canopy temperature data into their GoApp platform. This product is now commercially available to cotton growers on desktop and as mobile app and provides soil water and crop stress in real-time.

5.2 Lessons learnt and recommendations for future extension.

COVID-19 related disruptions underscored the importance of diversifying extension activities. Conventionally, field days have been the most popular extension method in cotton industry providing the opportunity for face-to-face interaction; however, such events were severely disrupted due to COVID-19. Many farmers are also not able to attend face-to-face field days due to farming activities that can be unpredictable at times.

COVID-19 necessitated significant shift to virtual events requiring farmers, presenters and organizers getting used to of new technology or new ways of using the existing technology which will benefit the industry in the longer run. Some farmers were disadvantaged due to lack of telecommunication coverage in their area which has also been highlighted as the single most important barrier in the adoption of digital technologies. The reach of extension activities might be broadened by providing multiple options of participating due to the barriers mentioned above. For example, live broadcasting as well as recording of industry events such as field days will likely increase the audience significantly as it will give the option to participate in person, remotely through video call, and in their own time by watching the recording if a participant is busy at the time of event.

It can be a challenge to continue extension activities beyond the life of project as participating in such events requires time and financial resources which are usually funded by projects. Researchers can continue these activities if new projects are funded by the industry that are a continuation of or build on existing research; for example, SIP phase 1 and phase 2. This issue might partially be addressed by training the industry extension teams (e.g., CottonInfo) who might be able to step in where researchers are not able to continue the extension activities beyond the life of project.

6 Appendix 1 - additional project information

6.1 Sub-project, media and communications material and intellectual property

Include a summary of all material including research papers, journals and/or extension materials and all intellectual property created or arising during the period covered by the project.

Update your list of media, communications, and activities. For the purposes of the report, you may wish to list journal papers, extension resources and activities under separate headings e.g.

6.1.1 Journal and conference papers published/in preparation

1. Jamali, Nunn, Hodgson, May, Deery & Roche (*under review*) Utility of plant-based sensing for optimizing irrigation decisions in limited water cotton systems, *International Conference on Irrigation and Drainage*, Australia (Conference paper)

2. McCarthy, Long, Jamali, Nunn and Hodgson (*commercial-in-confidence manuscript*) Infield canopy temperature assessment of early-stage crops using thermal sensing array

3. Jamali, Nunn, May, Smith, Hodgson and Bange (2019) Growing cotton with limited water, Australian Cotton Research Conference, 28th October 2019, Armidale (Conference paper)

4. Jamali, Nunn, Hodgson, Smith, Deery, Roche and Bange (*journal paper in preparation*) Optimising irrigation scheduling in limiter water cotton systems

6.1.2 **Extension materials** (guidelines, websites, videos, podcasts, reports, tools, economic case studies, fact sheets etc – *please provide links)*

1. Correctly optimizing limited water means big things for yield, Spotlight Summer 2021 edition, Summer21-22.pdf (crdc.com.au)

2. Jamali, Nunn, Roche & Bange (2021) Optimizing irrigation scheduling in cotton using canopy temperature monitoring – A new addition to farmer toolbox, *International Cotton Researchers Association* (ICRA), Volume 1, Issue 5 [Link]

3. Hiz Jamali, Michael Bange, and James Quinn (CSD) delivered a webinar on strategies to optimise water productivity in limited water situations in a webinar organized by CottonInfo: https://www.youtube.com/watch?v=dOeM-Fl4Cjg

4. Hiz Jamali and Peter Lennox (grower) discuss the irrigations trial under the SIP2 project: Plant based sensing – optimising irrigation timing in limited water (smarterirrigation.com.au)

5. Hiz Jamali explains the utility of canopy temperature sensors for irrigation scheduling in cotton systems in this video developed in collaboration with CottonInfo: https://www.youtube.com/watch?v=i2fPMCVG9dU&t=26s

6. Hiz Jamali explains how to install canopy temperature sensors in field in this YouTube video developed in collaboration with CottonInfo: https://www.youtube.com/watch?v=pg1SxzOubHk

7. Michael Bange and Hiz Jamali discuss how canopy temperature sensors can benefit irrigation decision making in the article published by Farmonline on 19th June 2019: https://www.farmonline.com.au/story/6224931/letting-the-plants-do-the-talking/

8. Hiz Jamali and Chris Nunn discuss their research under SIP2 in this YouTube video GVIA Field Day 2021 Hiz Jamali & Chris Nunn talk Canopy Temperature Sensors - YouTube

6.1.3 **Extension activities** (workshops, field days, forums etc)

Project team proactively engaged in extension activities which were severely impacted by COVID-19 related restrictions. Main extension activities are list below:

1. Presentation by Hiz Jamali on annual field day organized by Cotton Seed Distributors (CSD) and Lower Namoi Cotton Grower Association on 2nd March 2021 at Wee Waa, NSW

2. Presentation by Hiz Jamali on annual field day organized by Cotton Seed Distributors (CSD) and Lower Namoi Cotton Grower Association on 20th February 2020 at Wee Waa, NSW

3. Talk by Hiz Jamali and Chris Nunn (Fig. 1) at Gwydir Valley Irrigators Association (GVIA) field day on 19th February 2021 at Keytah farm near Moree, NSW

Figure 1: A twitter post about the talk delivered by Hiz Jamali and Chris Nunn at the GVIA field day

Grower workshop at Moree

6.1.4 Media/social media activities

Project related posts on social media registered more than 35,000 impressions on Twitter and more than 4,000 impressions on LinkedIn. Some examples of these social media posts are shown below:

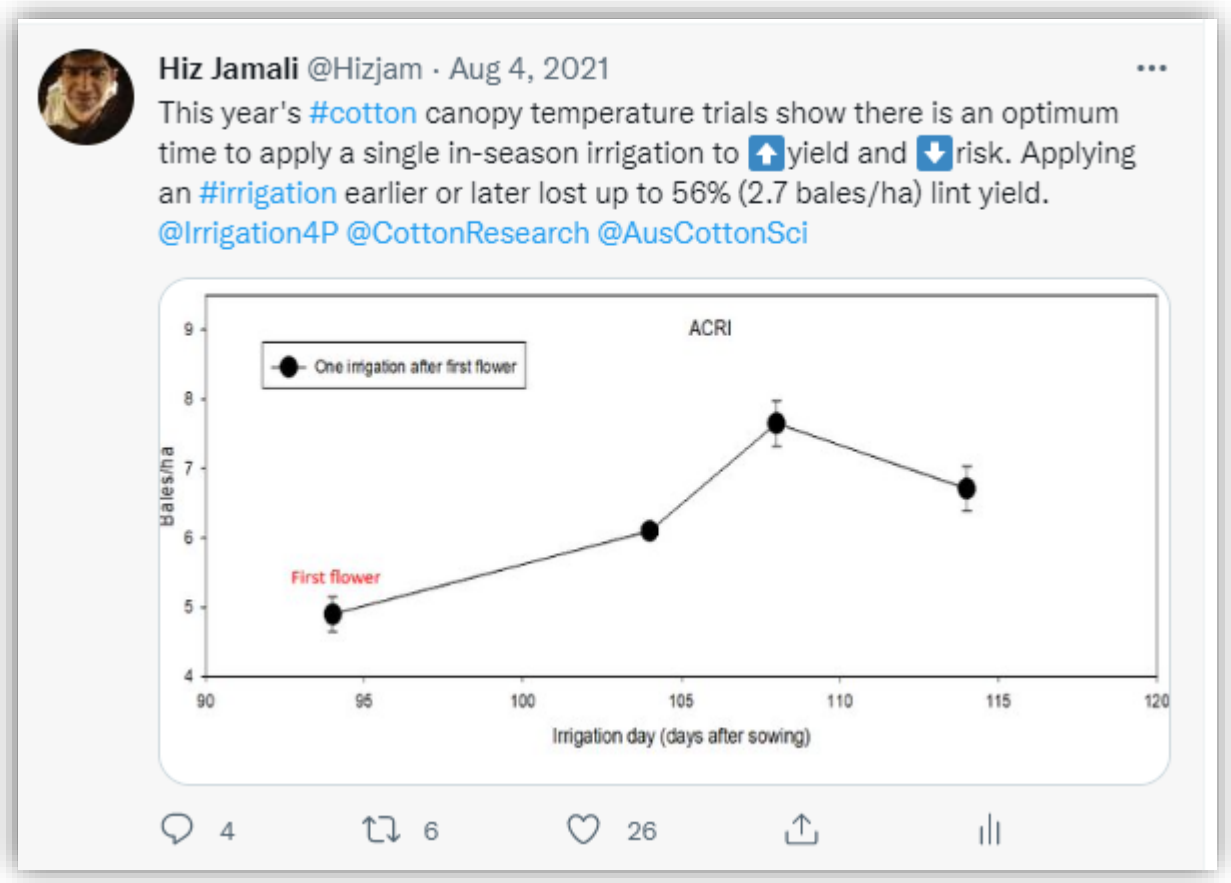

Figure 1: Twitter post sharing results from recent field trials to optimize timing of irrigation in partially irrigated systems

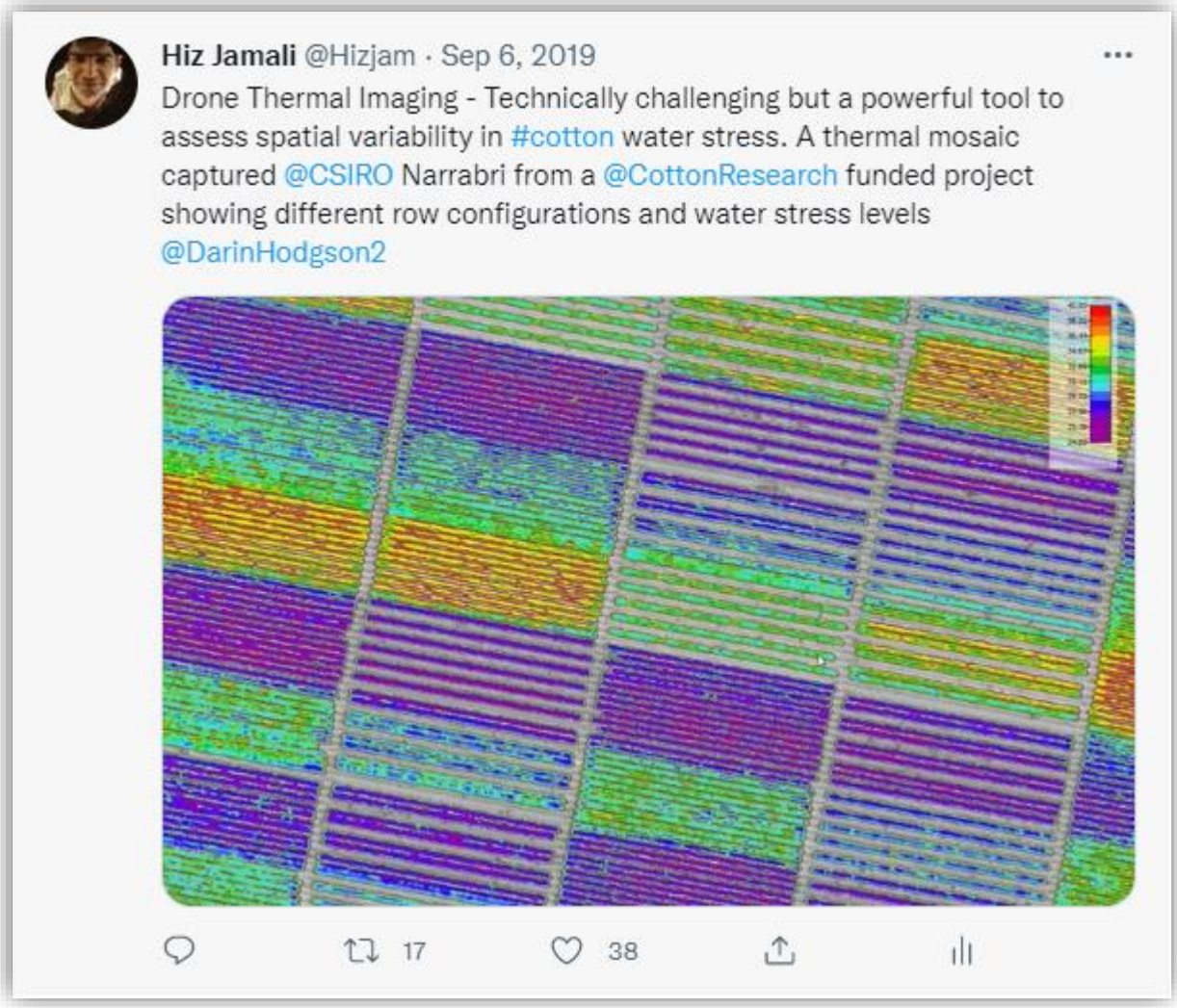

Figure 2: Twitter post about utility of UAV thermal imaging in assessing spatial variability in cotton crops

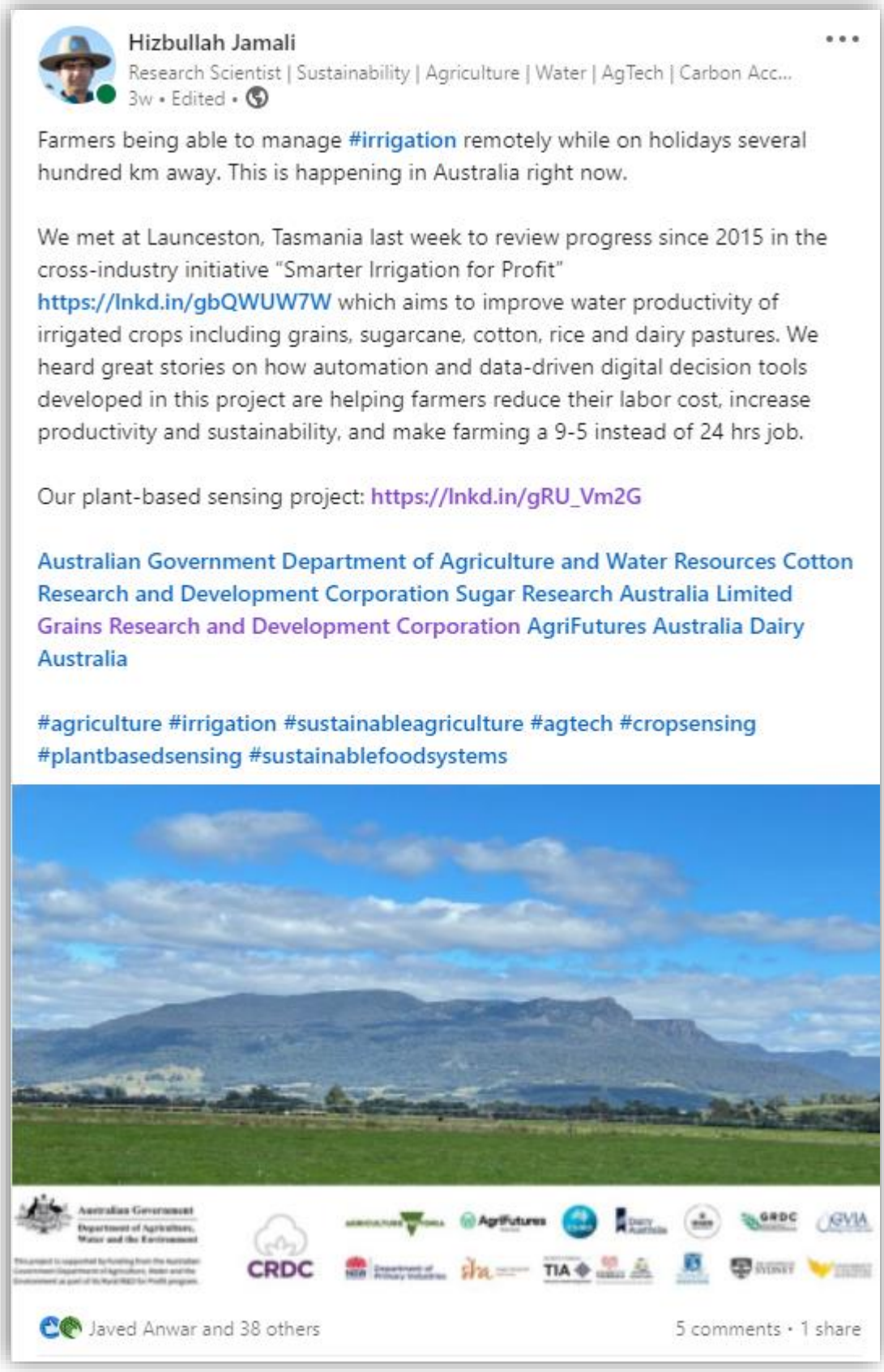

Figure 3: LinkedIn post about final face to face project meeting held at Launceston, Tasmania

Nature of materials / activities	**Number**	**Details** (Please provide details if appropriate (eg links to publicly available documents)
Press releases		
Media appearances – press and TV	1	Interview with Farmonline
Brochures, fact sheets, posters and newsletters	6	YouTube videos, podcast, ICRA newsletter, Spotlight article
Web page	1	SIP2 website
Field days, expos, field walks	3	GVIA field day 2021, CSD field day 2020 CSD field day 2021
Stakeholder forums, meetings, presentations, workshops, webinars	2	Limited water webinar Cotton growers focus group – weekly virtual catch ups with growers during 2020-21 cotton season
Social media presence	~40,000 impressions	Several project related posts on Twitter and LinkedIN
Scientific conference presentations	1	Australian Cotton Research Conference

6.2 Monitoring and evaluation

An economic analysis was conducted by AgEcon to evaluate the benefit of monitoring crop stress using canopy temperature technology to improve irrigation scheduling in partially irrigated and fully irrigated systems.

Economic Analysis for Fully Irrigated Cotton

KEY MESSAGES

- Through water limited trials, where cotton received only one irrigation, CSIRO showed that canopy temperature stress (CTS) technology provides a mechanism by which growers can have increased confidence in deciding when to apply an irrigation in water limited cotton thereby reducing both yield risk and associated economic risk.
- Using CTS technology, the yield-optimising irrigation timing could be narrowed down to within a 1-day window. This compares to a 3-day window when considering *days after first*

flower and *soil moisture deficit*, and an 8-day window when considering *cumulative degree days*.

- The reduced irrigation uncertainty helps to keep the yield and gross margin (GM) within 1% of the maximum. In contrast, the wider 3-day window risks reducing yield by <1% and GM by <1% ($6/ha) on average, but with GM losses of 3.9% ($42/ha) in some years depending on relative lint and water prices; while a 8-day window risks reducing yield by 11% and GM by 16% (326/ha) on average, with GM losses up to 11.5% ($124/ha) in some years.

ABOUT THE RESEARCH

A key challenge in limited water cotton production is deciding when to irrigate to maximise yield. As part of Smarter Irrigation for Profit Phase 2 (SIP2) the CSIRO compared canopy temperature stress (CTS) monitoring to other measures of crop stress and irrigation timing: cumulative degree days, soil moisture deficit, and days after first flower.

A MORE CONSISTENT GUIDE TO OPTIMISE YIELD WITH LIMITED WATER

The research found that CTS was a more consistent indicator of maximum yield across different seasons compared to the other metrics. This in turn allows a more reliable and precise guideline for optimising yield with limited water. For CTS, optimum yield was found to occur within a 1-day window. In comparison, maximum yield occurred within a 3-day window when considering *days after first flower* and *soil moisture deficit*, and within an 8 day window when considering *cumulative degree days*. As a result, there is higher uncertainty when using these methods to apply limited irrigation water to achieve optimum yield.

This uncertainty is shown in Figure 1, where the yield potential decreases with every day the irrigation application moves away from the optimum timing.

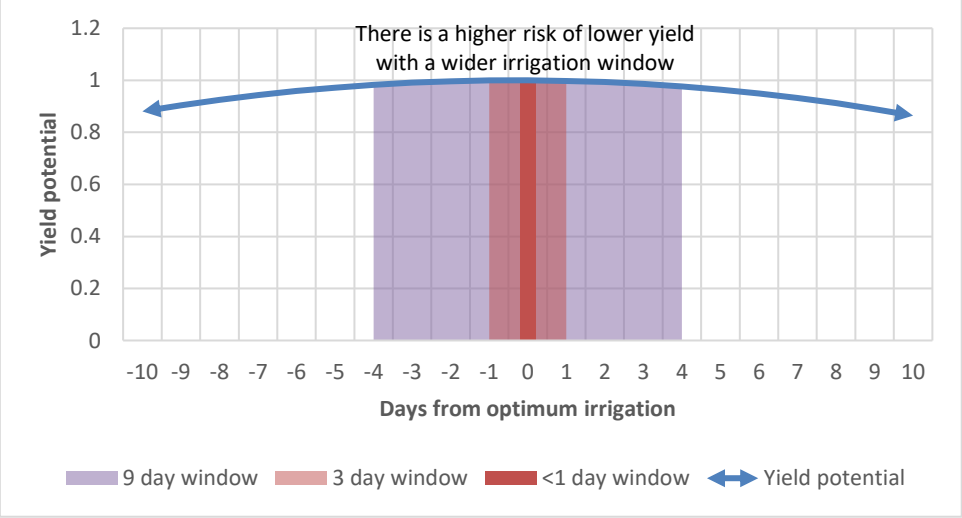

Figure 1. Yield impact from uncertainty in irrigation timing

From Figure 1, we can see that within a 1-day irrigation window using CTS, the yield losses are close to 0% from the maximum. Within a 3-day window using days after first flower or soil moisture deficit the yield losses are still less than 1% of the yield potential, and with a 8-day

irrigation window using cumulative degree days the yield losses are up to 2% of the maximum yield potential.

ECONOMIC COST OF UNCERTAINTY AROUND IRRIGATION TIMING

Applying gross margin data (GM) to the yield curve, the economic cost of these differing levels of uncertainty can be seen (*Figure 2*), with a greater risk of GM losses associated with a wider irrigation window. Figure 2 applies the trial average of 6.7 bales/ha with corresponding water application of 1ML/ha, and uses the 10-year average inflation adjusted prices of $604/bale, and $194/ML. All other GM costs were drawn from the 2021-22 CottonInfo semi-irrigated cotton GM[1].

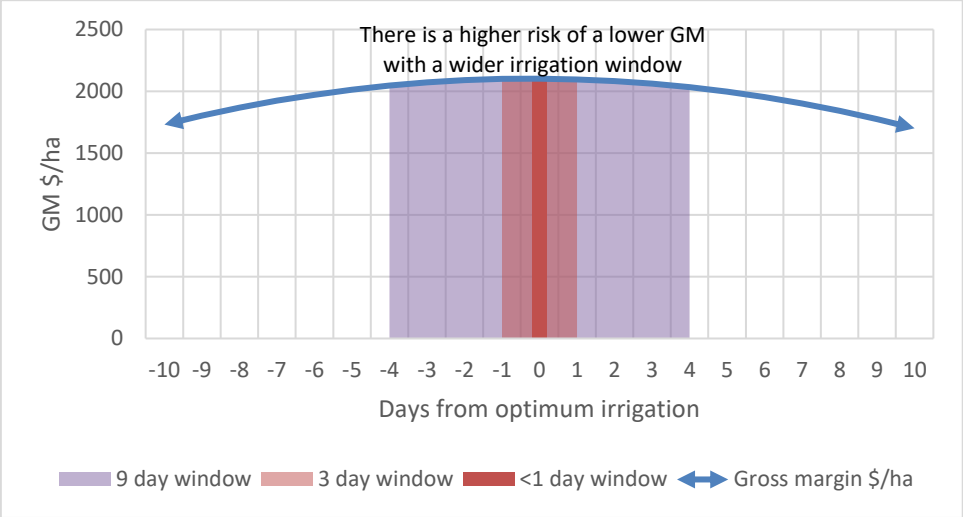

Figure 2. Gross margin impact from uncertainty in irrigation timing

Within a 1-day irrigation window using CTS, the GM is maximised at $2154/ha. Within a 3-day window using days after first flower or soil moisture deficit the GM losses are up to $6/ha (<1% of the maximum potential GM), and with an 8-day irrigation window using cumulative degree days the GM losses are up to $70/ha (3.8% of the maximum potential GM).

While these figures reflect average cotton lint and water prices, varying prices for water or cotton could result in greater GM risk. Applying the 10-year historic price ranges for water and lint shows higher potential GM loss of $41/ha with a 3-day irrigation window, and $124/ha for a 8-day window.

From the CSIRO SIP2 research and the above analysis, it can be seen that the CTS technology provides a mechanism by which growers can have increased confidence in deciding when to apply an irrigation in water limited cotton thereby reducing both yield risk and associated economic risk.

Economic Analysis for Partially Irrigated Cotton

A summary of the economic analysis for fully irrigated cotton systems is give below and full report can be found on this link:

[1] CottonInfo, 2021, Australian cotton industry gross margin budgets

Smarter Irrigation for Profit
PHASE II CASE STUDIES

Responsive irrigation management with Canopy Temperature Stress technology

- By supporting more accurate monitoring of a crop's stress levels and need for water, canopy temperature stress (CTS) technology can increase cotton yields while reducing labour and water costs.
- **Incorporating CTS technology into irrigation management has the potential to generate an additional $152/ha/season.**
- Due to long water supply lead times, some growers may find it harder to adapt irrigation management unless there is sufficient on-farm storage or bore water supply.

ABOUT THE RESEARCH

As part of ***Smarter Irrigation for Profit phase 1*** (SIP1), the CSIRO conducted on-farm trials of canopy temperature stress (CTS) technology in different cotton growing valleys in New South Wales (Wee Waa, Rowena, Walgett) and Queensland (Emerald, St. George).

The overarching philosophy of the trials was to provide farmers the opportunity to use an irrigation scheduling tool that is based on real-time monitoring of a crop's stress levels and need for water.

CONCLUSIONS

Drawing on the SIP1 research and other industry research and data, this case study has evaluated the economic viability of CTS in cotton production, with the potential to generate an additional $152/ha/season. The Costs of $25/ha/season may vary depending on field dynamics such as field size and differing soil types. The benefits of $177/ha/season were driven by the potential for improved irrigation management with regards to crop stress and water availability, generating yield savings one in two years and irrigation savings one in three years. It has, however, been identified that where growers are faced with long water supply lead times, they may find it harder to adapt irrigation management unless there is sufficient on-farm storage or bore water supply[14]. As such, when considering incorporating CTS technology into irrigation management, producers should undertake individual investment analysis while considering specific farm and market dynamics.

Smarter Irrigation for Profit Phases I (SIP1) was led by the Cotton Research and Development Corporation (CRDC) in conjunction with Dairy Australia, Agrifutures, Sugar Research Australia. SIP1 was supported by funding from the Australian Government Department of Agriculture, Water and the Environment as part of its Rural R&D for Profit program. For information on the SIP1 research, including the CSIRO project underlying this case study, visit https://www.crdc.com.au/smarter-irrigation-phase-1.

For more information on the SIP2 visit https://smarterirrigation.com.au/. CTS technology was developed by CSIRO and CRDC funded projects and tested in SIP1 and SIP2.

For more information on this economic analysis, please contact George Revell, Principal Economist at Ag Econ, through george@agecon.com.au.