Australian Government

Cotton Research and Development Corporation

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Part 1 - Summary Details

Please use your TAB key to complete Parts 1 & 2.

CRDC Project Number: UTS1301

Project Title: Assessing climate change impacts and adaption options in the cotton industry

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CRDC Research Program: 1 Farmers

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Part 3 – Final Report

(The points below are to be used as a guideline when completing your final report.)

Background

1. Outline the background to the project.

A warmer and drier climate has been projected in Australia especially for the inner part of Australia (CSIRO, 2007) which covers the cotton production regions. This change will have significant implications for the sustainable development of the cotton industry, as it is highly sensitive to climate and relies heavily on water for irrigation. To better address the challenges and opportunities of future climate change in the cotton industry, local climate change including changes in the mean climate, climate variability, and resultant water availability needs to be understood, its impacts need to be quantified, and effective and economical adaptation options need to be identified. Given the resilience of cotton production to current climate variability, the context of this existing resilience also needs to be assessed in a changing climate.

Atmospheric CO_2 and water are fundamental substances for crops to synthesise carbohydrate. Climate is the major driving force of crop production systems. Even though most cotton production in Australia is under irrigated conditions, water is a precious and costly resource for irrigated farming system and dependent on rainfall amount and pattern. Greenhouse gas induced climate change will inevitably impact on cotton production. It has been projected that annual temperature over inland Australian including the cotton production regions will increase 1~1.2°C and annual rainfall will decrease 2~5% for the period 2020-2040 (CSIRO, 2007). This will have significant implications for the cotton industry. For example, increase in temperature will increase water use and the frequency of exceeding critical temperature thresholds, which will adversely impact on cotton growth, boll production, fibre quality and resultant farm profitability. A drier environment means less rainfall on average or more frequent and severe droughts placing increased pressure on precious water resources. Even though increased atmospheric CO_2 concentration have some positive effects on cotton production, these effects are constrained or impacted by high temperature, soil water and nutrient conditions (Bange et al., 2009). For cotton industry to continue to thrive into the future, there is a strategic need to quantify the combined impacts of changes in temperature, rainfall, water availability and atmospheric CO_2 concentration on cotton production, and to identify and evaluate existing and potential adaptation options in dealing with projected negative impacts and in capitalising the potential growth opportunities of climate change.

Objectives

2: List the project objectives and the extent to which these have been achieved

Obj. 1 Understand local climate change including changes in the mean climate and in climate variability for key cotton production areas in Australia for the period 2020 – 2040

Local climate change information was derived and understood and applied to the LARS-WG to construct robust local climate change scenarios for impact and adaptation studies. This objective has been achieved.

Obj. 2 Define extreme climate events and characterise their occurrence at key stages of cotton growth

Typical extreme climate events in relation to cotton production were identified and defined, and their occurrence within cotton growing season (GS) was quantified under climate change. This objective has been achieved.

Obj. 3 Investigate the impact of future climate change and water availability on cotton water use, water use efficiency (WUE), lint yield and fibre quality

Climate change impacts on cotton lint yield, water use and WUE under irrigated and rain-fed conditions were investigated. The effects of future temperature change on cotton fibre quality such as micronaire were examined across sowing times. The potential effects of future rainfall change on fibre grade at harvest stage were analysed. This objective has been achieved.

Obj. 4 Identify and evaluate the effectiveness of a range of on-farm adaptation options in dealing with negative impacts and taking advantage of positive impact

On-farm adaptation options such as changing sowing time, irrigation schedules, row configurations and rotation patterns were identified as the key management strategies in the face of future climate change. Their effects on cotton lint yield, water use and WUE were evaluated in a changing climate. This objective has been achieved.

Obj. 5 Quantify the cost and benefit of adaptation options

The average gross margin and risk distribution across adaptation options (changing sowing time, irrigation schedules, row configurations and rotation patterns) in a changing climate at key cotton production areas under irrigated and rain-fed conditions were quantified. This objective has been achieved.

Obj. 6 Inform relevant stakeholders of future climate change, its risks and opportunities, and identified and prioritised effective and economical adaptation options in managing the risks and in capitalising the potential growth opportunities of climate change

Research information from this project was communicated to scientific and industry communities through journal paper publication, conference and workshop presentation and delivery of project progress report to funding body-CRDC. This objective has been achieved.

Methods

3. Detail the methodology and justify the methodology used. Include any discoveries in methods that may benefit other related research.

Obj. 1 Understand local climate change in 2020-2040

Daily outputs of CSIRO Conformal Cubic Atmospheric Model (CCAM) for the periods 1980-1999 and 2020-2039 were used by a stochastic weather generator – LARS-WG to derive monthly changes in the mean climate (mean temperature, mean rainfall and mean solar radiation) and in climate variability (the average length of wet/dry spells, variability of mean temperature and mean rainfall) and to construct robust local climate change scenarios (CCSs) for nine key cotton production areas in eastern Australia (Figure 1). The CCAM was driven by four general circulation models (GCMs): MarK3.5, GFDL, MPI and MIROC under the Special Report on Emission Scenarios (Nakicenovic and Swart, 2000) A2 scenario, which is a high emission scenario with atmospheric CO_2 concentration of 440 ppm in 2030. The CCAM is a dynamical downscaling approach, which was widely applied to climate change impact assessment and adaptation evaluation. More details on the construction of climate scenarios can be found in Luo et al. (2014 & 2015), which were attached to this report.

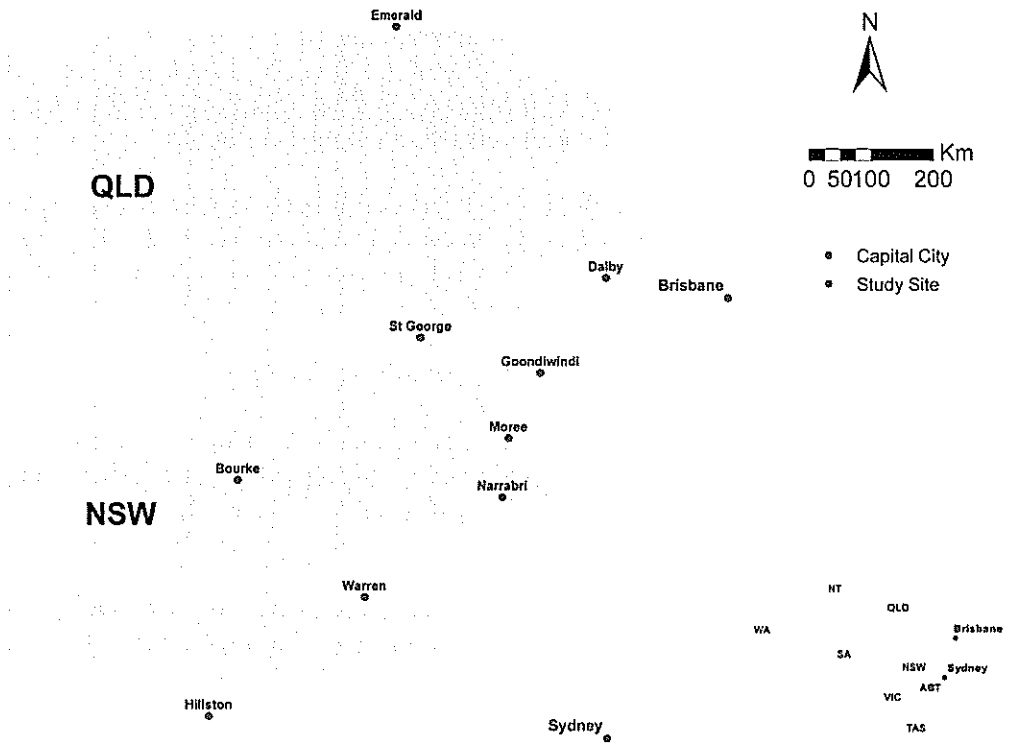


Figure 1 Study Locations

Obj. 2 Define extreme climate events (ECEs) and characterise their occurrence at key stages of cotton growth

Cold shocks and heat stress within cotton GS are identified as key extreme climate events for cotton production. A 'cold shock' is defined as an event when daily Tmin falls to 11°C or less. A heat stress event occurs when daily Tmax is ≥35°C. A program was edited to quantify the occurrence of cold shocks and heat stress on a monthly basis within cotton GS (1 Oct. - 31 May). The nine production areas as described in Obj.1 were considered in this analysis. Furthermore, the effects of future climate change on crop phenology were quantified. The CottASSIST on-line Day Degree Calculator and Last Effective Flower tool (http://cottassist.com.au), were modified to be used with constructed temperature scenarios including baseline and future period. Cotton crop phenology stages considered in this study include the date of emergence, 1st square (flower bud), 1st flower, 1st open boll, last effective square (LES), last effective flower (LEF), and last harvestable boll (LHB). For the early phenological events we considered three sowing times: 21st Sep., 1st Oct. and 11th Oct. We then defined the GS as the period from these sowing dates until 21st May, 31st May and 10th Jun. respectively. More information on the research methodology of this analysis can be found in Luo et al. (2014).

Obj. 3 Investigate the impact of climate change on water use, WUE, lint yield and fibre quality

Climate change impacts on cotton lint yield, water use and WUE

Climate scenarios constructed in Obj. 1 along with elevated atmospheric carbon dioxide concentration (eCO_2) were then linked to a process-oriented cotton model (CSIRO OZCOT) to quantify their potential impacts on cotton lint yield, water use, and WUE under irrigated and rain-fed conditions in 2030. For irrigated cotton, we considered four water supply levels (2, 4, 6 and 8 ML/ha) at nine cotton production locations (Emerald, Dalby, St George, Goondiwindi, Moree, Bourke, Narrabri, Warren and Hillston). For rain-fed cotton, we considered three planting configurations (solid, single skip and double skip) at four locations (Emerald, Dalby, Moree and Narrabri). The OZCOT external parameter used to capture the physiological effects of eCO_2 on cotton production was modified based on Reddy et al. (2008). A photosynthetic rate scalar value of 1.065 was considered in the OZCOT (representing an increase of 6.5% in canopy photosynthesis rate in 2030 compared with current situation). Atmospheric CO_2 concentration was set to 400 ppm and 450 ppm for baseline and 2030 respectively. More information on the modification and parameterisation of the OZCOT can be found in Luo et al. (2015).

Climate change impacts on cotton fibre quality

This analysis is based on the nine cotton production areas as described earlier. Local climate scenarios as detailed in Obj.1 were used by established crop-level empirical relationships that firstly estimated the time and average daily temperature when the majority of cotton bolls in a crop are thickening their fibres, and secondly related this estimate of temperature to fibre micronaire. Briefly, the approach estimates the crop boll filling period during which the majority bolls that contribute to yield and quality are thickening their fibres. Estimates of the period are based on a high yielding crop with 10 fruiting branches. An enhanced function beyond that used in Bange et al. (2010) was used in this analysis to transform estimated average daily temperature to micronaire value. Included in the micronaire impact assessment, we considered four sowing times: normal sowing (varies across locations), 15 d earlier and later than normal sowing, and 30 d later than normal sowing. Monthly mean rainfall and average wet spells for autumn months (i.e. March, April and May) were also analysed to examine their potential impact on cotton fibre grade (e.g. colour). More details on research methods can be found in Luo et al. (unpublished a).

Obj. 4 Identify and evaluate the effectiveness of a range of on-farm adaptation options

Effects of changing sowing times and irrigation schedules on cotton lint yield, water use and WUE

Once again, climate scenarios constructed in Obj.1 were linked to the modified OZCOT to quantify the effects of changing sowing times and irrigation triggers on cotton lint yield, water use, and WUE in 2030. We considered four sowing times: specifically, normal sowing, 15 d early sowing, 15 d and 30 d late sowings. This was applied to both irrigated cotton and rain-fed cotton. For irrigated cotton, we considered two available soil water deficits (50 mm and 70 mm) below which an irrigation event was triggered with a water supply level of 8 ML/ha and nine cotton production areas (Emerald, Dalby, St George, Goondiwindi, Moree, Bourke, Narrabri, Warren and Hillston). For rain-fed cotton, we considered three planting configurations (solid, single skip and double skip) and four production areas (Emerald, Dalby, Moree and Narrabri). Please direct to Luo et al. (unpublished b) for details.

Effects of rotation patterns on crop yields

Climate scenarios were linked to the Agricultural Production System sIMulator (APSIM) to quantify the effects of various rotation patterns on crop (i.e. cotton and wheat) production under irrigated and rain-fed conditions in a changing climate in 2030. For irrigated cotton, we considered three rotation patterns (cotton rotation with wheat followed by a short fallow, specifically, cotton 3 yrs in and 1 yr out, cotton 2 yrs in and 1 yr out, and continuous cotton) and nine production areas (Emerald, Dalby, St George, Goondiwindi, Moree, Bourke, Narrabri, Warren and Hillston) spanning the current industry. For rain-fed cotton, we considered two rotation patterns (cotton-wheat-long fallow and cotton-long fallow) with three cotton row configurations (solid, single skip and double skip) and four production areas (Emerald, Dalby, Moree and Narrabri). Soil water and nutrients were carried over between rotation phases. More information on simulation design can be found in Luo et al. (unpublished c).

Obj. 5 Quantify the cost and benefit of adaptation options

Based on the two adaptation evaluation studies as detailed in Obj. 4, this study quantified the costs and benefits of implementing adaptation options (changing sowing times, irrigation schedules and rotation patterns) under irrigated and rain-fed conditions. Both gross margin analysis and risk distribution analysis were conducted. For gross margin analysis, we considered Dalby, Narrabri and Hillston for irrigated cotton and the first two sites for rain-fed cotton. Risk distribution analysis was based on Narrabri. Enterprises budget information can be found in Luo et al. (unpublished d). Risk analysis was implemented with the @Risk package. Monte Carlo simulation, with 1000 iterations was conducted to determine the economic return at a whole farm level. Economic return was measured through return on assets, which shows the effect of adaptation strategies and climate on farm business profitability and risk.

Obj. 6 Inform relevant stakeholders of research information

Research information was communicated to scientific and industry communities and to funding body through journal paper publication, conference and workshop presentations and bi-annual project progress reports. We will also get the drafted papers published and produce a range of cotton grower/spotlight articles that highlight key findings of this research project. In addition, we will present research results at the Australian Agronomy conference.

Results

4. Detail and discuss the results for each objective including the statistical analysis of results.

Obj. 1 Understand local climate change including changes in the mean climate and in climate variability for key cotton production areas in Australia for the period 2020 – 2040;

Figure 2 shows the multimodel ensemble mean changes between future period (2020-2039) and baseline period (1980-1999) in GS (1st Oct – 31st May) mean rainfall, rainfall variability, wet spells, dry spells, solar radiation, mean temperature and its variability. From this figure it can be seen that mean rainfall increased 2~16% across locations with southern areas increasing more (Figure 2a). The variability of rainfall increased from 4 to 17% across locations with Warren increased most (although the variability across the models was greatest) and Emerald increased least (Figure 2b). The average length of wet spells increased 1~6% with southern areas increasing the most (Figure 2c). The average length of dry spells decreased 2~5% except for Dalby where a 2% increase was found (Figure 2d). Solar radiation uniformly decreased (1%) across locations (Figure 2e). Mean temperature variability increased 5~9% across locations with the exception of Emerald where a 2% decrease was found (Figure 2f). Mean seasonal temperatures increased 1~1.2°C across locations (Figure 2g) with the largest increase at Dalby and the smallest at Hillston. More detailed results can be found in Luo et al. (2014, 2015).

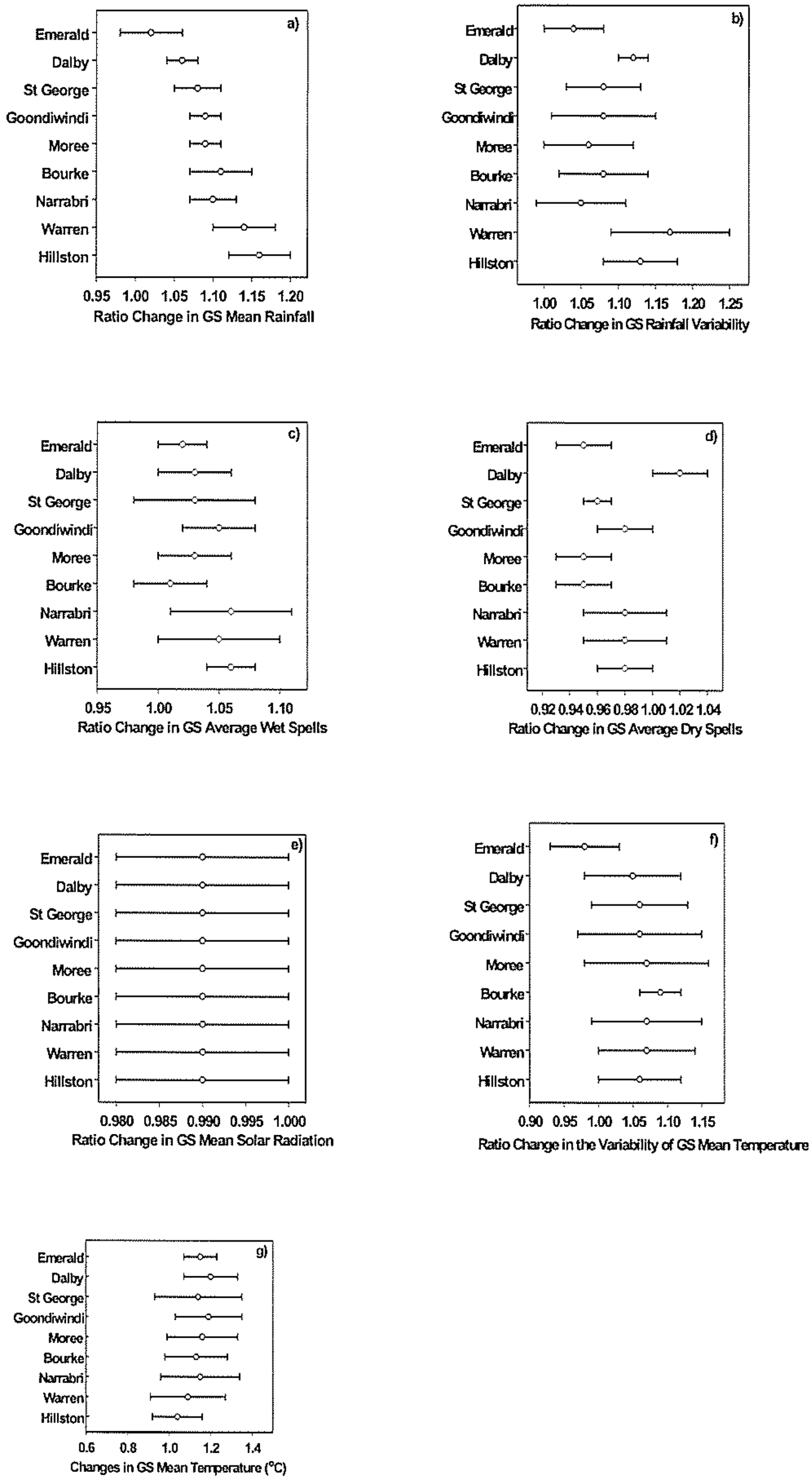


Figure 2 Growing season (Oct.-May) changes in mean climate and in climate variability in comparison with baseline. *The horizontal lines are the error bars, which were calculated as the standard deviation from the four climate models, divided by root mean square of the sample size. The empty circles are the multi-climate model ensemble mean. a) rainfall, b) rainfall variability, c) average length of wet spells, d) average length of dry*

spells, e) solar radiation, f) variability of mean temperature, g) mean temperature. A spell is defined as three or more consecutive days with wet (a daily rainfall total of at least 0.2 mm) or dry condition. Variability is associated with growing season mean temperature and rainfall intensity and was calculated as standard deviation of these variables.

Obj. 2 Define extreme climate events and characterise their occurrence at key stages of cotton growth

Emergence, first square, first flower and first open boll individually were advanced 1~9, 2~8, 1~2, and 1~5 days, respectively (Figure 3a). The largest changes were projected in the period from sowing to emergence, especially for the locations further south. In general the smallest effect across all phases was associated with the most northern growing region of Emerald while the largest change for all phases was associated with the most southern growing areas of Warren and Hillston. This translated into the smallest overall cumulative change for Emerald (mean change of 8 days) and greatest change for Hillston and Warren (mean change 16 days).

For the end of season, the timing of the phenological stages of the LES, LEF and LHB were delayed 0.3~3, 1.8~6.8 and 2.5~9 days respectively across all locations (Figure 3b). The greatest variability in delays was associated with LHB (at T≤2°C) with the largest changes projected for Warren (mean change 9d), Dalby (mean change 7d) and Narrabri (mean change 6d). The smallest changes for LHB were for St George (mean change -0.3d) and Bourke (mean change 2.5d). Across all locations, LES and LEF were also later as the periods between LHB to LEF, and LEF to LES were shorter. Overall, this meant that the smallest overall delays in season end were for Bourke (mean change 6.5d), Hillston (mean change 7.3d) and St George (mean change 7.5d). The projected longest delays in season end was for Dalby (mean change 11.8d) followed by Moree (mean change 10d).

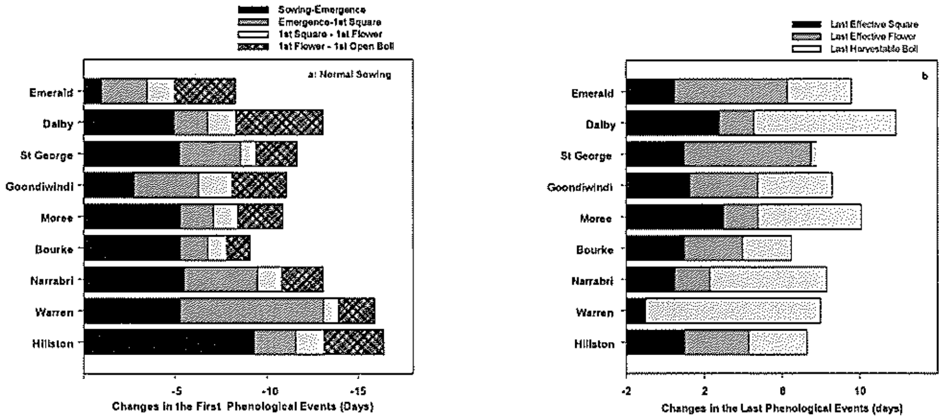


***Figure 3 Cumulative contribution of each phenophases to cotton crop phenology in 2030** in comparison with baseline; a) earlier phenological stages associated with normal sowing (sown on the 1st of Oct.), b) later phenological stages.*

With earlier sowing (21st Sept.), emergence advanced by 1~3d or was unchanged across locations except for St George where a 3d delay was found. First square was advanced by 1~4d in northern cotton production areas (with warmer climate) but was delayed ~1d in southern areas (with colder climate). In general there was little effect on the 1st open boll as advancement or delay was no more than 1d (Table 1). With later sowing (11th Oct.) in comparison with 1st Oct. sowing, emergence delayed 1~4d except at Hillston where a 0.3d advancement was found. First square was advanced by 1~2d in warmer locations while delayed 0.3~3d in colder locations. First flower and 1st open boll were advanced or delayed in the range of 0~1.5d depending on locations (Table 1).

The fruit development period in 2030 would increase up to two to three weeks compared with baseline associated with normal sowing (Table 2). The number of hot days would increase across all locations and GS months except May with the warmer months (Dec., Jan. and Feb.) and locations increased more. The number of cold shocks would decrease or remain the same across locations and GS months except Jan. and Feb. with cold months and places decreased more under climate change condition. Detailed results can be found in Luo et al. (2014).

Table 1 Changes (in days) in early phenological events of an earlier (21 Sep.) and later sowing (11 Oct) in comparison with 1 Oct. sowing in a changing climate

Locations	Emergence		1st Square		1st Flower		1st Open Boll	
	ES[1]	LS[2]	ES	LS	ES	LS	ES	LS
Hillston	-1.5	-0.3	0.8	0.3	0.5	1.3	-0.5	-1.5
Warren	-1.0	0.0	0.0	2.8	0.3	0.8	-0.3	-0.8
Narrabri	-1.5	2.8	0.8	0.3	0.5	-0.5	0.0	0.0
Bourke	-3.0	2.3	0.5	-1.0	-0.5	-0.5	0.5	-0.3
Moree	-2.3	4.0	0.8	-1.5	0.3	0.3	0.0	-0.3
Goondiwindi	0.0	0.5	-2.0	0.5	0.5	-0.5	0.5	1.0
St George	3.0	2.3	-3.8	0.0	-0.8	-0.5	1.0	0.5
Dalby	-1.5	3.3	-0.5	-1.5	0.5	-0.5	0.5	0.0
Emerald	0.0	0.5	-0.8	-0.5	0.8	0.5	-0.3	-0.3

1: early sowing, 2: late sowing

Table 2 Changes in the length of fruiting period across sowing times*

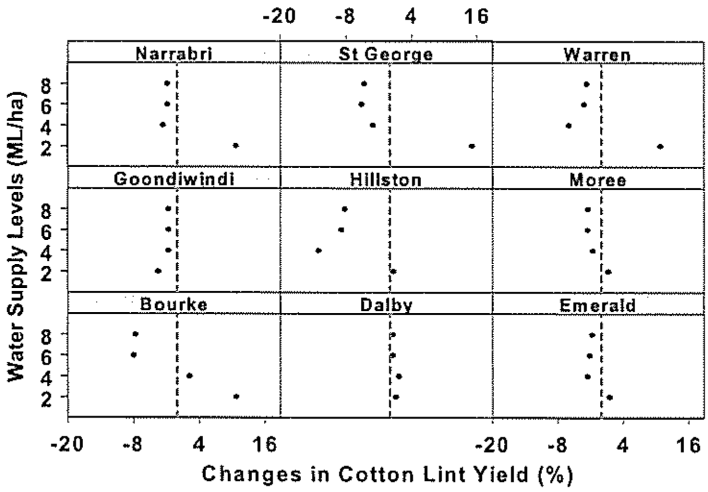
Locations	Earlier	Normal	Later
Hillston	19.5	18.8	18.8
Warren	22.0	21.0	18.3
Narrabri	18.5	17.8	14.8
Bourke	15.8	13.3	12.0
Moree	18.5	17.0	14.5
Goondiwindi	16.8	14.8	13.8
St George	16.8	16.0	13.8
Dalby	20.5	18.5	16.8
Emerald	13.8	13.0	13.0

*the difference in days between the first square to last effective square

Obj. 3 Investigate the impact of future climate change and water availability on cotton water use, water use efficiency (WUE), lint yield and fibre quality

Climate Change impacts on cotton water use, WUE and lint yield

For irrigated cotton (assuming full access to water and nitrogen), cotton lint yield would decrease -13 ~ -2% in 24 out of 36 cases (the combinations of four water supply levels and nine locations) under climate change conditions (Figure 4). Future climate scenarios would decrease cotton crop water use (-6~0%) in 28 out of 36 cases (Figure 5). WUE would decrease -11 ~ -2% in 20 out of 36 cases due to the combined effects of eCO_2 and future climate, which are location- and water supply-specific (Figure 6).



Figures 4 Multi-model ensemble mean changes in cotton lint yield (%) for irrigated cotton for the period centred on 2030 across locations and irrigation water supply levels under future climate scenarios [both enhanced CO_2 concentration (eCO_2) and future climate were considered]. The dashed vertical line represents no change.

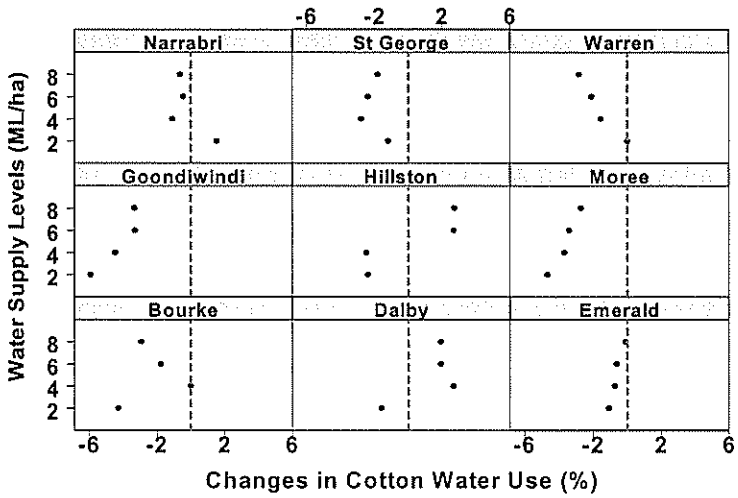


*Figure 5 **Multi-model ensemble mean changes in cotton water use (%) for irrigated cotton for the period centred on 2030** across locations and irrigation water supply levels under future climate scenarios (both eCO_2 and future climate were considered). The dashed vertical line represents no change.*

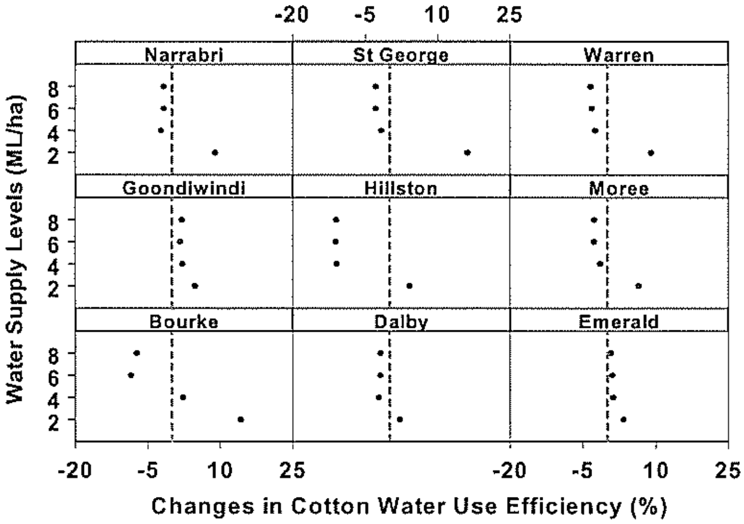


*Figure 6 **Multi-model ensemble mean changes in cotton water use efficiency (%) for irrigated cotton for the period centred on 2030** across locations and irrigation water supply levels under future climate scenarios (both eCO_2 and future climate were considered). The dashed vertical line represents no change.*

This simulation analysis also demonstrated the ability of the OZCOT in capturing the interactive effects of eCO_2 and future climate, indicating the usefulness of this tool in this important research area (Figure 7). Positive interactive effects (within 4%) of eCO_2 and future climate on lint yield were found in 27 out of 36 cases (Figure 7). Negative interactive effects (-2%~0%) were found at some locations mainly associated with lower water supply levels. The same as cotton lint yield, the interactive effects of eCO_2 and future climate on water use were positive in 27 out of 36 cases and negative in the rest of cases. However, the magnitude of interactive effects of eCO_2 and future climate on cotton water use (within 2%) was smaller than those on cotton lint yield (Figure 7). Similar to cotton lint yield and water use, the interactive effects of eCO_2 and future climate on WUE were positive in 28 out of 36 cases and negative in 8 cases (Figure 7). The magnitude of the interactive effects was within 2% including both increase and decrease.

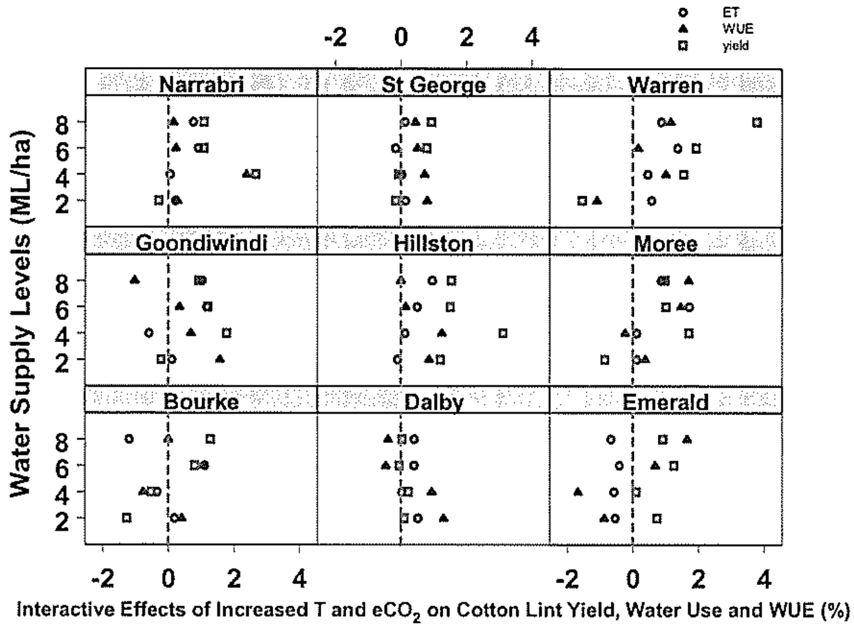
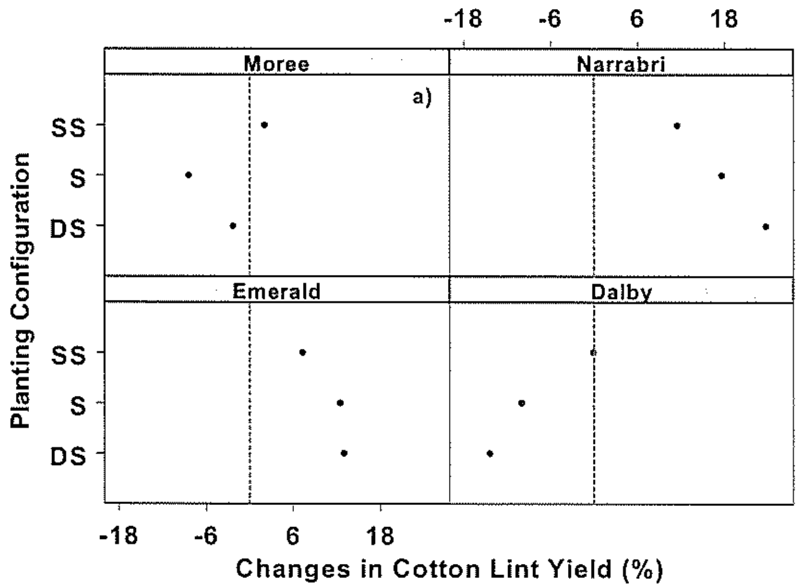


Figure 7 Interactive effects of eCO_2 and climate change on cotton lint yield, water use and WUE for the period centred on 2030 under irrigated condition across locations. Results shown were multi-model ensemble mean changes in percentage, which was quantified by adding the singular effects of eCO_2 and future climate together, and then subtracting this result from the combined effects of eCO_2 and future climate. The dashed vertical line represents no change.

Figure 8 shows multi-model ensemble mean changes of cotton lint yield, water use and WUE across planting configurations and study locations for the period centred on 2030 under rain-fed condition (assuming full initial soil profile). Cotton lint yield would increase 2~24% in 7 out of 12 cases (the combinations of three plant configurations and four locations) in 2030 (Figure 8a). Future climate scenarios would increase cotton water use of 3~6% at Emerald and Narrabri and decrease cotton water use in the range of -9 ~ -5% at Dalby and Moree (Figure 8b). WUE would increase 0~15% except at Dalby associated with double skip in a changing climate (Figure 8c).



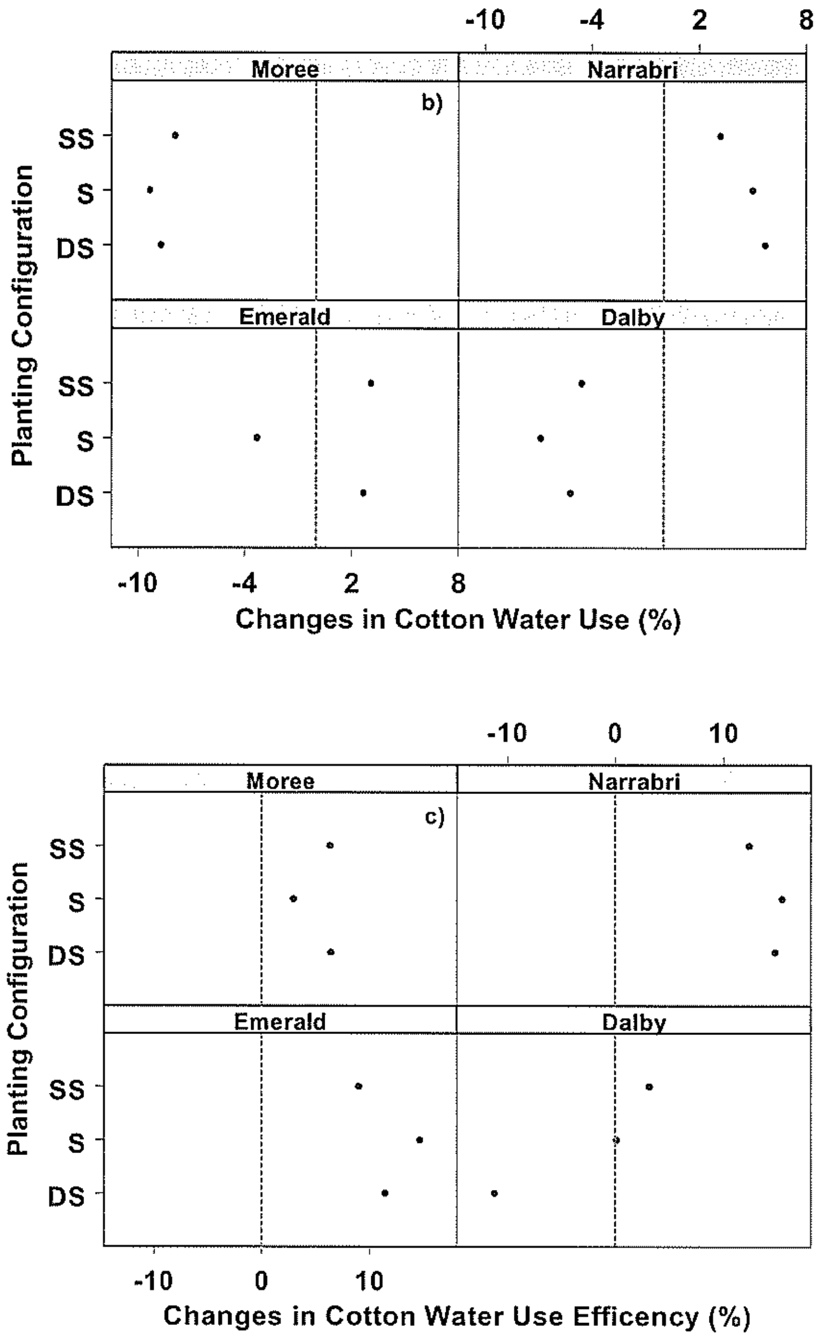


Figure 8 Multi-model ensemble mean change in percentage for rain-fed cotton for the period centred on 2030 across locations and planting configurations under future climate scenarios (both eCO_2 and future climate were considered): (a) cotton lint yield, (b) cotton water use and (c) water use efficiency. S: solid; SS: single skip; DS: double skip. The dashed vertical line represents no change.

Climate change impact on cotton fibre quality

When compared to the baseline climate scenario, mean micronaire in 2030 would increase 0.04~0.34 in 2030 across all locations with Hillston increased most while St George and Bourke increased least (Table 3). The chances of attaining optimum micronaire (3.8 to 4.5) would decrease in 2030 at most of the locations and increase slightly at Hillston (Table 3).

Table 3 Multi-model ensemble mean changes in the first flower, fibre thickening period (FTP), micronaire and the frequency of achieving optimum micronaire range (3.8 ~ 4.5) for the period centred on 2030 associated with normal sowing in comparison with baseline climate.

Locations	First Flower (days)	FTP (days)	Micronaire	Freqency_2030 (%)

Emerald	-5.3	-1.8	0.10	-100
Dalby	-7.8	-3.3	0.24	0
St George	-7.8	-0.8	0.04	-100
Goondiwindi	-8.5	-2.0	0.09	-97
Moree	-9.3	-1.8	0.09	-47
Bourke	-7.5	-0.5	0.04	-100
Narrabri	-9.3	-1.8	0.08	-16
Warren	-11.3	-3.0	0.15	-14
Hillston	-11.8	-5.0	0.34	3

Compared with normal sowing, **earlier sowing** (15 d) would result in (1) small increases (0.01-0.02) in mean micronaire at Dalby, Narrabri, Warren and Hillston and slight decreases in mean micronaire (-0.01) at St George and Bourke; and (2) increases, decreases or no change in the chances for micronaire falling in the optimum range depending on specific locations (Table 4). In comparison with normal sowing, **later sowings** would (1) decrease the mean micronaire at four and eight out of nine locations for 15 d and 30 d later sowing respectively and (2) increase the chances for optimum micronaire in five out of nine locations with 30 d later sowing increasing more (Table 4) through decreasing micronaire (Table 5). This implies that late sowing may be an effective management strategy to maintain optimum micronaire.

Table 4 Multi-model ensemble mean changes in the occurrence of first flower, fibre thickening period, micronaire, frequency of (number of years within 100 years with) micronaire falling in the optimum range *(3.8 ~ 4.5) for the period centred on 2030 across sowing times. Data shown are the difference between the earlier/later sowings and normal sowing in a changing climate.*

Locations	First Flower (days)			MFP (days)			Micronaire			Frequency Change (%)		
	15 d earlier	15 d later	30 d later	15 d earlier	15 d later	30 d later	15 d earlier	15 d later	30 d later	15 d earlier	15 d later	30 d later
Emerald	-1.0	0.5	1.3	-0.3	-0.3	-0.3	0.00	0.00	-0.02	0	0	0
Dalby	-1.8	1.3	2.3	-0.3	-0.8	-2.0	0.02	-0.05	-0.15	0	0	0
St George	-2.0	1.3	2.3	0.3	-0.3	-0.8	-0.01	0.00	0.00	0	0	0
Goondiwindi	-1.8	1.5	3.3	0.3	0.0	-0.3	0.00	0.00	-0.01	67	33	300
Moree	-2.0	1.5	3.0	0.0	-0.3	-1.0	0.00	0.00	-0.01	-10	10	24
Bourke	-2.3	1.8	2.8	0.3	-0.5	-1.0	-0.01	0.00	-0.01	0	0	0
Narrabri	-2.5	2.3	3.8	0.0	-0.5	-1.0	0.01	-0.02	-0.06	-6	8	19
Warren	-1.8	2.0	4.5	0.3	0.0	-0.5	0.01	-0.03	-0.07	-10	8	15
Hillston	-1.0	2.3	4.0	-0.3	-0.3	-1.0	0.01	-0.02	-0.07	0	1	3

Table 5 Number of years with micronaire entering and leaving the optimal range across sowing times in *comparison with normal sowing in a changing climate. Data shown also include the way optimal micronaire was affected through increase and/or decrease in micronaire.*

Locations	15 d earlier sowing			15 d later sowing			30 d later sowing		
	Entering Range	Out of Range	Net Change	Entering Range	Out of Range	Net Change	Entering Range	Out of Range	Net Change
Goondiwindi	2 decrease	0	2	3 decrease	2 increase	1	12 decrease	3 increase	9
Moree	6 decrease	11 increase	-5	13 decrease	8 increase	5	20 decrease	8 increase	12
Narrabri	5 decrease	10 increase	-5	9 decrease	2 increase	7	16 decrease	0	16
Warren	2 decrease	10 increase	-8	8 decrease	1increase	7	13 decrease	0	13
Hillston	1 decrease	1 increase	0	1 decrease	0	1	3 decrease	0	3

Increases in monthly mean rainfall and the average length of wet spells in autumn were found indicating negative impacts on fibre quality with greater risk found at Hillston and Narrabri, followed by Goondiwindi and then the others. However, when the risks of rainfall were investigated on a monthly basis, there would be less chance of increased rainfall and wet spells associated with the month of May. This may assist with crops potentially grown for longer under the warmer conditions in Australian. More detailed results of this study can be found in Luo et al. (unpublished a)

Obj. 4 Identify and evaluate the effectiveness of a range of on-farm adaptation options in dealing with negative impacts and taking advantage of positive impact

Effects of changing sowing time and irrigation schedule on cotton production in a changing climate

For irrigated cotton (assuming access to full water, no nitrogen limitation), lint yield, water use and WUE would change -6.9%~5.2%, -2.1%~3.6% and -10%~2.4% respectively, associated with normal sowing and irrigation trigger 50 mm across locations when compared with baseline (Table 6). These three production components would change -8.2%~0.5%, -3.3%~2.7% and -11%~2.1% respectively, associated with normal sowing and irrigation trigger 70mm in comparison with baseline (Table 6). The impacts of changing sowing times on cotton lint yield would be generally small (within 3%) across locations and irrigation triggers except at Hillston associated with early sowing (Figure 9). Where increases in cotton lint yield would be found due to changed sowing times, the magnitude of these increases could not offset the negative effects of future climate scenarios on cotton lint yield indicating other management strategies are needed to maintain current cotton production level.

Table 6 Percentage changes in irrigated cotton lint yield, water use and water use efficiency between future period (2020-2039) and baseline period (1980-1999) associated with normal sowing

Locations	Lint Yield		ET[1]		WUE[2]	
	[3]ASW70mm	ASW50 mm	ASW70 mm	ASW50 mm	ASW70 mm	ASW50 mm
Emerald	-1.7	0.0	-0.1	-0.3	0.8	0.4
Dalby	0.5	5.2	1.9	3.6	-1.9	0.1
St George	-4.6	-2.6	-1.8	-1.8	-2.9	-1.9
Goondiwindi	-1.6	0.6	-3.3	-1.7	2.1	2.4
Moree	-2.5	-1.8	-2.7	-2.1	-2.7	-1.6
Bourke	-7.6	-6.9	-2.9	0.3	-7.3	-6.6
Narrabri	-1.8	-1.9	-0.6	-0.1	-1.7	-2.5
Warren	-2.7	-1.5	-2.8	-0.4	-3.4	-0.9
Hillston	-8.2	-6.4	2.7	2.6	-11.0	-10.0

1: evapotranspiration, 2: water use efficiency, 3: available soil water deficit

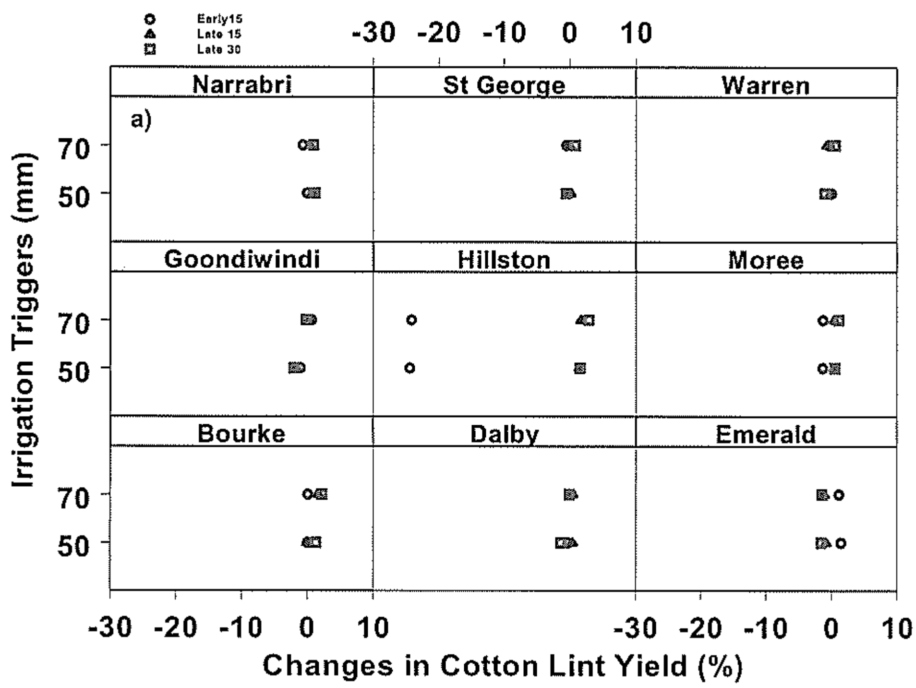


Figure 9 Multi-model ensemble mean change (%) in cotton lint yield under irrigated condition for the period centred on 2030 when compared with normal sowing across locations, planting times and irrigation triggers.

For rain-fed cotton (assuming starting full soil profile), lint yield would increase 7.4~23.7% at Emerald and Narrabri and decrease -14.4~0% at Dalby and Moree across the three row configurations. Water use would increase 2.7~5.7% at Emerald and Narrabri and decrease -9.3 ~ -4.6% at Dalby and Moree across row configurations. WUE would increase 0~15.5% in most of cases (combinations of locations and row configurations) under future climate scenarios associated with normal sowing (Table 7).

Table 7 Percentage changes in rain-fed cotton lint yield, water use and water use efficiency between future period (2020-2039) and baseline period (1980-1999) associated with normal sowing

Locations	Lint Yield			ET[1]			WUE[2]		
	S[3]	SS[4]	DS[5]	S	SS	DS	S	SS	DS
Emerald	12.5	7.4	13.1	-3.3	3.1	2.7	14.7	9.0	11.5
Dalby	-10.0	-0.1	-14.4	-6.9	-4.6	-5.2	0.2	3.2	-11.2
Moree	-8.4	2.1	-2.3	-9.3	-7.9	-8.7	2.9	6.3	6.4
Narrabri	17.6	11.5	23.7	5.0	3.2	5.7	15.5	12.4	14.8

1: water use, 2: water use efficiency, 3: solid, 4: single skip, 5: double skip

For rain-fed cotton, early sowing would decrease lint yield -10 ~ -5% in most of the cases while late sowings would increase lint yield (up to 25%, Figure 10). The magnitude of increase due to later sowings could compensate for the negative effects of future climate scenarios on cotton lint yield at Dalby and Moree and further enhanced lint yield at Emerald and Narrabri; the later the sowing, the more the lint yield at Emerald, Dalby and Moree (Figure 10). For detailed results please direct to Luo et al. (unpublished b).

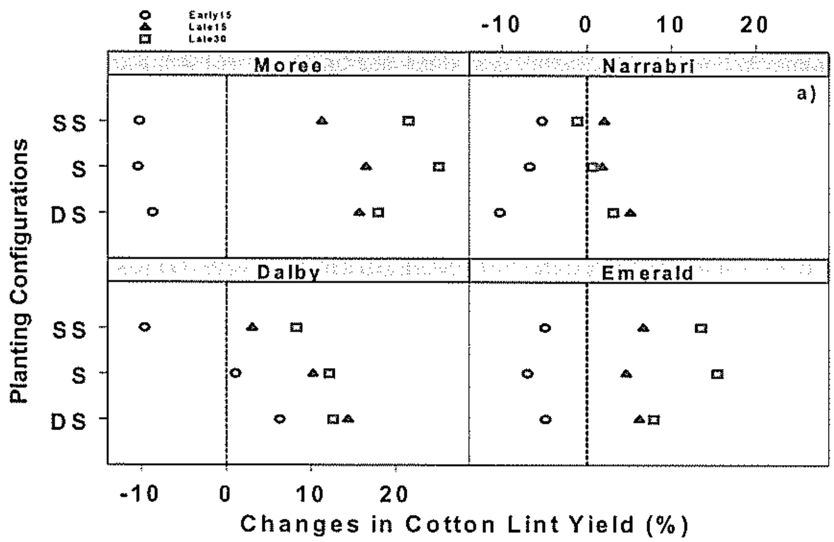


***Figure 10 Multi-model ensemble mean changes in cotton lint yield (%) under rain-fed condition for the period centred on 2030 when compared with normal sowing** across locations, sowing times and row configurations. S: solid; SS: single skip; DS: double skip. The dashed vertical line represents no change.*

Effects of rotation patterns on cotton production in a changing climate

Under irrigated condition it was found that the performance of the three rotation sequences would vary across production areas in terms of cotton lint yield. Crop yields would decrease in a changing climate across rotation patterns at most of the locations with wheat yields decreasing more. The rotation pattern of cotton 2 yrs in and 1 yr out would outperform the rotation pattern of cotton 3 yrs in and 1 yr out in terms of wheat yields (Table 8).

***Table 8 Multi-model ensemble mean changes (%) in crop yields** across locations and rotation sequences under irrigated condition*

	Cotton 3 in 1 out		Cotton 2 in 1 out		Continuous Cotton
Locations	Cotton	Wheat	Cotton	Wheat	Cotton
Emerald	-7.1	-17.9	-7.1	-12.9	-10.0
Dalby	-2.1	-23.9	-3.5	-16.6	-2.9
St George	-1.4	-2.7	-0.7	-3.0	-0.7
Goondiwindi	-1.0	-12.9	1.3	-10.4	-1.7

Moree	-6.5	-23.0	-4.3	-22.3	-8.9
Bourke	-4.8	2.1	-6.3	-15.2	-3.2
Narrabri	-3.6	-18.3	-4.4	-9.4	-5.1
Warren	-4.8	-20.1	-5.8	-11.3	-3.5
Hillston	-4.4	-1.7	-7.6	3.1	-4.8

Under rain-fed condition, a rotation pattern of cotton-long fallow would perform better in terms of cotton lint yields at Emerald, Dalby and/or Narrabri associated with solid and single skip while the rotation pattern of cotton-wheat-long fallow would outperform cotton-long fallow in terms of cotton lint yields associated with double skip at Emerald, Moree and Narrabri (Table 9). Luo et al. (unpublished c) provides more details on this work.

***Table 9 Multi-model ensemble mean changes (%) in crop yields** across locations, rotation sequences and row configurations under rain-fed condition*

Locations	Cotton-wheat-fallow						Cotton-fallow		
	S[1]		SS[2]		DS[3]		S	SS	DS
	Cotton	Wheat	Cotton	Wheat	Cotton	Wheat	Cotton	Cotton	Cotton
Emerald	-8.8	-14.7	-7.0	-14.7	-3.8	-11.7	-1.9	-2.3	-7.1
Dalby	-3.9	-12.3	-12.5	-12.6	-17.3	-12.8	3.2	-8.9	-11.4
Moree	-7.9	-21.7	1.6	-21.7	-16.8	-21.9	-13.0	-1.6	-20.8
Narrabri	8.0	-13.1	7.4	-13.3	22.0	-13.4	12.6	-2.0	-21.1

1: solid, 2: single skip, 3: double skip

Obj. 5 Quantify the cost and benefit of adaptation options

Irrigated cropping systems

Gross margin (GM) would increase 1.2 ~13.8% at Dalby and decrease at Narrabri (-4%) and Hillston (-17 ~ -14%) across irrigation triggers associated with normal sowing under future climate change (Figure 11). Late sowing +15 d would further enhance GM 1% across irrigation triggers at Dalby while late sowings (+15 d, +30 d) would partially compensate for the negative impacts of future climate change on cotton GM at Narrabri (0.6~2.5%) and Hillston (3.5~6.7%) across irrigation triggers (Figure 11). Rotation pattern: cotton three years in and one year out would perform better in terms of GM [less decreases (-6.7 ~ -4.7%) compared with other rotation patterns (-10.4 ~ -4.4%)] across locations in a changing climate (Table 10).

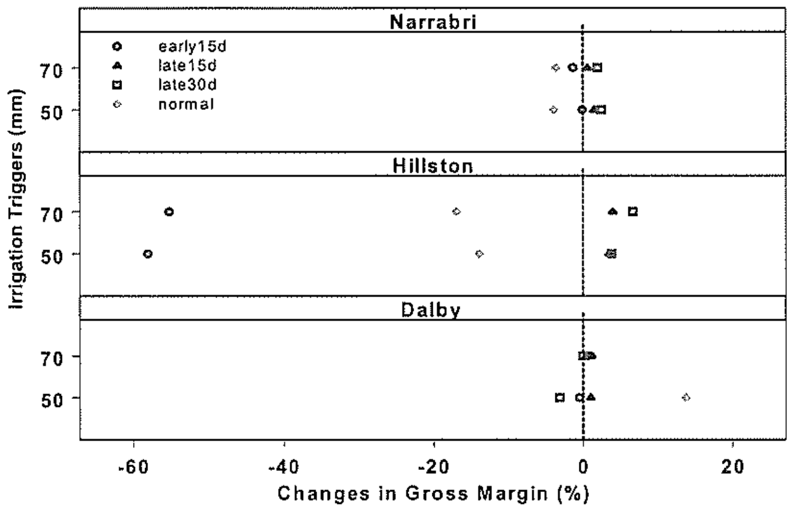


***Figure 11 Percentage changes in irrigated cotton gross margin (GM) between changed sowing times and normal sowing across irrigation triggers in a changing climate.** Changes in average GM under normal sowing were derived from future period and baseline. The dashed vertical line represents no change.*

***Table 10 Changes in cotton farm gross margin under irrigated condition** between future period and baseline across rotation patterns*

Locations	Rotation Patterns		
	Cotton 3 yrs in 1 yr out	Cotton 2 yrs in 1 yr out	Continuous cotton

Dalby	-4.7	-6.7	-4.4
Narrabri	-7.3	-7.7	-8.0
Hillston	-6.7	-10.4	-7.5

Farm profitability (% return on assets invested) in 2030 would decrease (from 9.8% to 9.0%, 10.3% to 9.4 for 50 mm and 70 mm irrigation triggers, respectively) compared with that of baseline situation associated with normal sowing at Narrabri. Both 15 d and 30 d later sowings would maintain or increase farm profitability while 15 d earlier sowing would decrease farm profitability under future climate when compared with normal sowing across the two irrigation triggers (Table 11). Compared with baseline, future climate would have negative impacts on cotton farm profitability across the three rotation patterns at this location (Table 11).

***Table 11** **Whole farm profitability (Return on Assets: ROA) and risk (coefficient of variation of ROA shown in parentheses) of irrigated cropping systems** under future and baseline climate across irrigation triggers, sowing times and rotation patterns at Narrabri*

		Climate	
		Baseline	**Future**
Irrigation trigger	**Sowing time**		
50mm	Normal sowing	9.8% (16%)	**9.0% (22%)**
	15 d later		9.2% (20%)
	30 d later		9.2% (19%)
	15 d earlier		8.6% (29%)
70 mm	normal sowing	10.3% (16%)	**9.4% (21%)**
	15 d later		9.4% (19%)
	30 d later		9.5% (19%)
	15 d earlier		8.9% (28%)
Rotation system			
Continuous cotton		13.4% (21%)	12.2% (28%)
Cotton 3 yrs in 1 yr out-Cotton/wheat		12.3% (25%)	10.7% (33%)
Cotton 2 yrs in 1 yr out-Cotton/wheat		10.8% (34%)	10.1% (36%)

Rain-fed cropping systems

GM would decrease -19.8 ~ -0.2% at Dalby and increase 19.8~41.2% at Narrabri across row configurations associated with normal sowing under future climate change (Figure 12). Late sowings could compensate for the negative impacts of future climate change on cotton GM at Dalby (4.5~21.1%) and would further enhance cotton GM at Narrabri (1.1~7.9%) in most of the cases (the combination of late sowings and row configurations) in a changing climate (Figure 12). Solid configuration would outperform other row configurations at Dalby across rotation patterns in a changing climate while double skip would perform the best associated with rotation pattern cotton-long fallow-wheat, and solid would perform the best associated with cotton-long fallow at Narrabri under climate change (Table 12). Further details of this analysis can be found in Luo et al. (unpublished d).

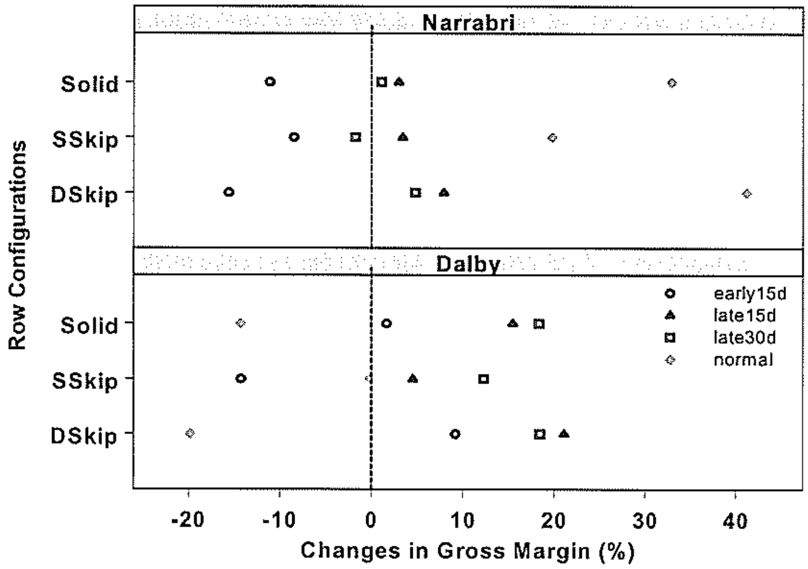


Figure 12 ***Percentage changes in rain-fed cotton gross margin (GM) between changed sowing times and normal sowing across row configurations in a changing climate.*** *Changes in average GM under normal sowing were derived from future period and baseline. SSkip: single skip, DSkip: double skip. The dashed vertical line represents no change.*

Table 12 Changes in cotton farm gross margin under rain-fed condition between future period and baseline across plant configurations and rotation patterns

Locations	Rotation Patterns					
	Cotton-Long Fallow-Wheat			Cotton-Long Fallow		
	S[1]	SS[2]	DS[3]	S	SS	DS
Dalby	-10.7	-21.0	-27.1	6.9	-16.8	-21.3
Narrabri	0.6	-1.0	11.7	36.1	-4.6	-42.6

1: solid; 2: single skip; 3: double skip

Farm profitability (% return on assets invested) in 2030 would increase (from 6.5% to 6.9%, from 7.0% to 7.2% for double skip and solid, respectively) or maintain the same level (6.9% for single skip) compared with baseline situation. Both 15 d and 30 d later sowings would increase or maintain cotton farm profitability associated with double skip and solid compared with normal sowing (Table 13). Later sowing 15 d would increase farm profitability while later sowing 30 d would decrease farm profitability in relation to single skip compared with normal sowing. Earlier sowing 15 d would decrease cotton farm profitability across row configurations in comparison with normal sowing (Table 13). Future climate change would have negative impacts on farm profitability across row configurations and rotation patterns considered (Table 13).

Table 13 Whole farm profitability (Return on Assets, ROA) and risk (coefficient of variation of ROA shown in parentheses) *of rain-fed cropping systems under future and baseline climate across planting configurations, sowing times and rotation patterns at Narrabri*

		Climate	
Planting configuration	Sowing time	Baseline	Future
Double Skip	Normal sowing	6.5% (28%)	**6.9% (30%)**
	15 d later		7.1% (27%)
	30d later		7.0% (28%)
	15 d earlier		6.3% (34%)
Single Skip	Normal sowing	6.9% (27%)	**6.9% (31%)**
	15 d later		7.0% (29%)
	30 d later		6.8% (29%)
	15 d earlier		6.6% (34%)

Solid	Normal sowing	7.0% (29%)	**7.2% (33%)**
	15 d later		7.3% (31%)
	30 d later		7.2% (31%)
	15 d earlier		6.8% (37%)
Rotation system			
Cotton-Long fallow	Solid	5.6% (35%)	5.5% (41%)
	Single Skip	5.8% (31%)	5.3% (36%)
	Double Skip	5.9% (30%)	4.9% (39%)
Cotton-wheat-Long fallow	Solid	5.4% (44%)	4.9% (45%)
	Single Skip	5.3% (40%)	4.8% (41%)
	Double Skip	5.1% (40%)	4.7% (43%)

Outcomes

5. Describe how the project's outputs will contribute to the planned outcomes identified in the project application. Describe the planned outcomes achieved to date.

Outputs 1: Cotton Crop Phenology in a New Temperature Regime
This work, published in *Ecological Modelling* in 2014 and presented in Cotton Scientist Conference and MODSIM 2013, constructed robust local climate change scenarios (CCSs) by adopting a stochastic weather generator: LARS-WG, understood the impact mechanism of future climate change on cotton phenology and characterised the occurrence of extreme climate events (i.e. cold shocks and heat stress) within cotton growing season. This output has contributed to the 1st and 2nd scientific outcomes as listed in Part C of the full research proposal: "Enhanced understanding of local climate change and the way local CCSs were constructed" and "Understanding the impact of future climate change on the occurrence of extreme climate events". This work was also communicated to cotton growers through workshop presentation. This has contributed to the 1st and 2nd industry/applied outcomes "Cotton growers will have better understanding of what future climate change looks like on their cotton farms" and "Increased industry awareness and knowledge base of the occurrence of extreme climate events in a changing climate and their potential impacts on cotton production".

Output 2: Cotton Crop Water Use and Water Use Efficiency in a Changing Climate
Output 3: Climate Change and Cotton Fibre Quality
The work associated with Output 2 was published in *Agriculture, Ecosystems and Environment* in 2015. This work investigated the potential impacts of future climate change on cotton lint yield, water use and WUE under irrigated and rain-fed conditions. For irrigated cotton, four water supply levels were considered. For rain-fed cotton, three row configurations were taken into account. Output 3 (revised version re-submitted to *Climatic Change*) examined the potential impacts of future climate on cotton fibre quality. These two outputs have contributed to the 3rd scientific outcome "Understanding the impact mechanism of future climate change and water availability on cotton lint yield (from the perspective of cotton water use and WUE) and on cotton fibre quality (i.e. micronaire and fibre grade: colour)" as given in Part C of the CRDC full research proposal. Research output 2 was presented in a workshop in which researchers, cotton growers and CRDC representative participated. This has contributed to the 3rd industry outcome: "Increased industry awareness and knowledge base of the potential impacts of future climate change and water availability on cotton production processes and lint yield".

Output 4: Effects of Changing Sowing Times and Irrigation Schedules on Cotton Production in a Changing Climate
Output 5: Effects of Rotation Patterns on Crop Production in a Changing Climate
The work associated with Output 4 (submitted to *Mitigation and Adaptation Strategies for Global Change*) quantified the effects of changing sowing times and irrigation schedules on irrigated cotton production and of changing sowing times on rain-fed cotton production from the perspective of cotton water use and WUE in a changing climate. Output 5 (under internal review) evaluated the effectiveness of various rotation patterns on crop (cotton and wheat) production in a changing climate in terms of crop yields. Publication and communication of these outputs with relevant scientific and industry stakeholders will contribute to achieving the 4th scientific outcome "Understanding of available adaptation options and their effectiveness in responding to future climate change at a local scale" and the 4th industry outcome "Cotton growers will have access to new cotton industry information packages and new best practice recommendations" as described in Part C of the full

CRDC research proposal. These outcomes will be achieved when this final report is released or published on the CRDC website. As mentioned previously we will also look to take the papers published as a result of this study and produce a range of cotton grower/spotlight articles that highlight key findings of this research project. In addition, we will look to present outcomes at the Australian Agronomy conference.

Output 6: Economics of Adaptation Options in Australian Cotton Industry
This work quantified (1) the economic impact of future CC on cotton production and (2) the costs and benefits of undertaking specific adaptation options through gross margin analysis and whole farm profitability and risk analysis. This work will contribute to achieve the last scientific outcome (Understanding the economic impact of CC on cotton production and the cost and benefit of implementing a specific adaptation option) and the last industry outcome (Cotton growers will have access to economical adaptation options in facing the challenge of CC) as detailed in Part C of the full research proposal. Release and/or publication of this final report on CRDC website will contribute to achieving this outcome.

6. Please describe any:-

a) technical advances achieved (eg commercially significant developments, patents applied for or granted licenses, etc.);

b) other information developed from research (eg discoveries in methodology, equipment design, etc.); and

c) required changes to the Intellectual Property register.

The CSIRO Day Degree Day calculator and the Last Effective Flower Tool were extended to accommodate the effects of future climate change on cotton phenology, which are available for any potential research. OZCOT model parameters were modified to capture the physiological effects of eCO_2 on cotton photosynthesis. In addition to reviewing the photosynthetic rate used in the OZCOT model, the transpiration efficiency in high CO_2 environments was considered, as water use was of particular interest in this project. In reviewing the literature it was noted that any effects of eCO_2 on the evapotranspiration of cotton were too small to be detected (Kimball et al., 1994). Even though a 13% increase in evapotranspiration was reported by Kimball et al. (1994), this magnitude was considered as insignificant due to uncertainties (in the order of 20%) in measuring net radiation. Reddy et al. (2005) reported that eCO_2 did not noticeably increase transpiration at the canopy level. The effect of decreased stomatal conductance on cotton water use at the leaf level is offset by the effect of increased leaf area resulting in the net effect being a negligible difference in canopy transpiration. Based on these findings and the lack of any reported findings to the contrary, we decided to leave the routines that determine transpiration efficiency in OZCOT unmodified.

Furthermore, a visual basic programming was edited to quantify the effects of future climate change on the occurrence of cold shocks and heat stress from CCSs generated. *In addition a python program was developed at the early stage of this project to extract daily climate projections from NetCDF format.*

Conclusion

7. Provide an assessment of the likely impact of the results and conclusions of the research project for the cotton industry. What are the take home messages?

By adopting a modelling approach, this project quantified the potential impacts of future climate change in 2030 on (1) cotton phenology, (2) the occurrence of extreme climate events within cotton season, (3) cotton lint yield, water use and WUE under irrigated and rain-fed conditions and cotton fibre quality. This project evaluated the effectiveness of a range of adaptation options (e.g. changing sowing time, irrigation schedules, water supply levels, row configurations and rotation patterns) on cotton phenology, cotton production quantity and fibre quality. Finally, this project quantified the costs and benefits of management options in dealing with the risks and/or in capitalising the opportunities of future climate change in 2030. Research results from this project will have significant impacts for the cotton industry such as increasing cotton growers' awareness of the potential impacts of future climate change on their cotton farms and informing them the most effective and economical management options in the face of future climate change. Adoption and implementation of identified best management practices will ensure profitable and sustainable development of the cotton industry into the future.

The cotton phenology and extreme climate events study found that there would be less impact of cold temperatures and a longer growing season that could be beneficial for cotton production. On the other hand, there would be more incidences of heat stress impacting growth, and more rapid crop development towards crop maturity that might limit the opportunities associated with increases in growing season length without adjustments in management.

The impact analysis of future climate change on cotton production found that for irrigated cotton, water supply level with 2ML/ha would generate the greatest positive effects to future climate scenarios in terms of cotton lint yield in most of the study locations. Increase in season rainfall would negatively impact on irrigated cotton lint yield due to possibly exacerbated waterlogging problems under higher water supply levels. On the other hand, an increase in season rainfall would benefit cotton lint yield under rain-fed condition. For rain-fed cotton, double skip planting would most positively respond to future climate scenarios at Emerald and Narrabri while single skip planting would perform the best in terms of lint yield at Dalby and Moree. This indicates that adaptation options in dealing with climate change issues are site- and farming system-specific.

The fibre quality study found that the chances for obtaining optimum micronaire would decrease in most of the study locations if current sowing time is to be maintained. Southern cotton production areas (from Goondiwindi) are sensitive to changes in sowing time except at Bourke. Early sowing would decrease the chances for meeting targeted optimum micronaire range while both late sowings would result in an increase in achieving optimum micronaire range compared with normal sowing: the later the sowing the higher chances for obtaining optimum micronaire indicating 30 d late sowing is the most effective strategy for achieving optimal micronaire in a warmer environment. Late sowing of 30 d could compensate for the negative effects of increased temperature on micronaire or further enhance the chances for optimum micronaire at four production areas (Goondiwindi, Narrabri, Warren and Hillston). Whereas other strategies such as breeding may also be needed to counteract the negative effects of increased temperature on micronaire at other production areas in addition to late sowings.

Adaptation evaluation study found the effects of changing sowing times and irrigation triggers are site-specific under irrigated condition. Early sowing would decrease cotton lint yield while late sowings would increase cotton lint yield in most of the cases. Where an increase in cotton lint yield would be found due to changing sowing times, the benefit gained could not compensate for the negative effects of future climate scenarios on cotton lint yield implying other management strategies are needed such as decreasing water supply level. However, some impact pattern could be found in cotton water use and WUE arising from the management strategies considered. Generally speaking, early sowing would result in an increase in cotton water use and a decrease in WUE. Late sowings would reduce cotton water use and increase WUE. For rain-fed cotton, early sowing would decrease cotton lint yield, water use and WUE while late sowings would increase cotton lint yield and WUE in most of the cases considered. Unlike irrigated cotton, the increase in rain-fed cotton lint yield resulting from late sowings could compensate for the negative effects of future climate scenarios.

The rotation sequence analysis found that the performance of the three rotation sequences would vary at different production areas in terms of cotton lint yields under irrigated condition. This implies that different production areas would have different rotation strategies in the face of future climate change. Crop yields would decrease in a changing climate across rotation patterns at most of the locations with wheat yields decreasing more. The rotation pattern of cotton 2 yrs in and 1 yr out would outperform cotton 3 yrs in and 1 yr out in terms of wheat yields. For rain-fed condition, rotation pattern of cotton-long fallow would perform better in terms of cotton lint yields at Emerald, Dalby and/or Narrabri associated with solid and single skip while the rotation pattern of cotton-wheat-long fallow would outperform cotton-long fallow in terms of cotton lint yields associated with double skip at Emerald, Moree and Narrabri. To maintain current production level, the better performance rotation patterns need to be combined with other adaptation options such as decreasing water supply level for irrigated cotton and changing sowing times for both irrigated and rain-fed cropping systems.

Extension Opportunities

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

(a) to further develop or to exploit the project technology.

(b) for the future presentation and dissemination of the project outcomes.

(c) for future research.

The modification of the OZCOT to represent the physiological effects of eCO_2 was based on experimental results conducted in the USA. As experimental results on the effects of changed production environment (i.e. temperature, soil moisture and CO_2 concentration) on cotton production under Australian environment become available, there is a future need to calibrate and validate the OZCOT and the APSIM-OZCOT models to refine the scaler adopted in these cotton models in representing the effects of eCO_2 on cotton production and to adjust other relevant parameters if required.

One of the research objectives of this project is to quantify the cost and benefits of adaptation options in a changing climate. This project had a focus on cotton even though wheat is involved in the rotation analyses. The economic analysis of this project is limited to cotton and wheat and did not consider other crops that are sometimes used concurrently in a typical farming system. Industry focused economic analysis adopted in this project also needs to be extended to whole farm analysis, which considers resources allocation among multiple enterprises in a typical farm in which cotton production is one of the key agribusinesses. Even though the risk analysis conducted in this project is a kind of whole farm analysis, it does have many assumptions which need consideration.

9. A. List the publications arising from the research project and/or a publication plan.

(NB: Where possible, please provide a copy of any publication/s):

Journal papers

1. Luo, Q., Bange, M. and Clancy, L.: 2014, Cotton Crop Phenology in a New Temperature Regime. *Ecological Modelling* 285 22-29.
2. Luo, Q., Bange, M., Johnston, D. and Braunack, M.: 2015, Cotton Water Use and Water Use Efficiency in a Changing Climate. *Agriculture, Ecosystems and Environment* 202 126-134.
3. Luo, Q., Bange, M., Johnston, D.: Climate Change and Cotton Fibre Quality. Revised version re-submitted to *Climatic Change*.
4. Luo, Q., Bange, M., Johnston, D. and Braunack, M.: Effects of Changing Planting Time and Irrigation Schedule on Cotton Production in a Changing Climate. Submitted to *Mitigation and Adaptation Strategies for Global Change*.
5. Luo, Q., Bange, M. and Devoil, P.: Effects of Rotation Patterns on Crop Production in a Changing Climate. Under internal review.
6. Luo, Q., Behrendt, K., Powell, J. and Bange, M.: Economics of Adaptation Options in Australian Cotton Industry. Submitted to *Agriculture, Ecosystems and Environment*.

Conference papers

1. Luo, Q., Bange, M., Braunack, M. and Hertzler, G.: 2012, Assessing Climate Change Impacts and Adaptation Options in the Cotton Industry. The Climate Change Research Strategies in Primary Industries Conference. 27-29 Nov 2012 Melbourne, Victoria.
2. Luo, Q., Bange, M. and Clancy, L.: 2013, Temperature Increase and Cotton Crop Phenology. 20th International Congress on Modelling and Simulation - Adapting to change: the multiple roles of modelling. 1-6 Dec 2013 Adelaide, Australia.
3. Luo, Q., Bange, M. and Clancy, L.: 2013, Irrigated Cotton Crop Phenology in a New Temperature Regime. 2013 Australian Cotton Research Conference - "Stimulating Science in Cotton". 8-11 Sep 2013 Narrabri, Australia.
4. Luo, Q., Bange, M., Johnston, D. and Braunack, M.: 2105, Cotton Production in a Changing Climate. 20-24 Sep 2015 Hobart, Tasmania, Australia.

Part 4 – Final Report Executive Summary

Provide a one page Summary of your research that is not commercial in confidence, and that can be published on the World Wide Web. Explain the main outcomes of the research and provide contact details for more information. It is important that the Executive Summary highlights concisely the key outputs from the project and, when they are adopted, what this will mean to the cotton industry.

This project aims to identify effective and economical on-farm adaptation options to deal with the risks and/or to capitalise the potential growth opportunities of future climate change in 2030 in the key cotton production areas of eastern Australia. To fulfil this aim, the outputs of dynamically downscaled outputs of four global climate models were fed into a stochastic weather generator to construct robust local climate scenarios. These climate scenarios were then used by various impact models to quantify the impact of future climate change on cotton phenology, cotton water use, water use efficiency (WUE) and lint yield, and to evaluate the effectiveness of a range of on-farm adaptation options in a changing climate. Based on the biophysical modelling results of adaptation evaluation the costs and benefits of implementing specific adaptation options were quantified by conducting gross margin and risk analyses.

The cotton phenology and extreme climate events analysis found that there would be less impact of cold temperatures and a longer growing season. On the other hand, there would be more incidences of heat stress and more rapid crop development towards crop maturity. There would be little effects of changing sowing times on cotton growing season length. This information will prompt cotton growers to identify and implement other management options to embrace the opportunity of increasing cotton growing season length which benefits cotton production.

The sensitivity analysis of cotton water use, WUE and lint yield to water supply levels and to row configurations identified management strategies that had less impacts associated with climate change for both irrigated and rain-fed cotton. Less effects was associated with lower water supplies in irrigated systems and use of skipped row systems in rain-fed cotton systems.

The fibre quality analysis found that a 30 d later than the current normal sowing time could compensate for the decreased frequency of achieving optimum micronaire, or actually led to further increases in the frequency of achieving optimum micronaire in four (Goondiwindi, Narrabri, Warren and Hillston) out of nine production areas. It was noted that there would be a need for other management strategies (i.e. breeding) to assist in overcoming challenges in achieving optimum micronaire in future climate change.

For irrigated cotton, changing sowing times could not offset the negative effects of future climate scenarios on cotton lint yield. Other management strategies are needed to maintain current cotton production levels. For rain-fed cotton, however, the magnitude of increase due to later sowings could compensate for the negative effects of future climate scenarios on cotton lint yield at Dalby and Moree and further enhanced lint yield at Emerald and Narrabri. Adoption of this research information will maintain or enhance cotton lint yield hence cotton farm profitability.

The rotation sequence analysis under climate change condition found that the identified better performance rotation patterns need to be combined with other adaptation options such as changing sowing times for both irrigated and rain-fed cropping systems to maintain or enhance cotton production levels. Adoption of this recommendation will ensure a sustainable and profitable cotton industry into the future.

Future climate change would not only bring negative impacts on gross margin (GM) but also opportunities as seen at Dalby under irrigated condition and at Narrabri under rain-fed condition. Climate change would have negative impacts on farm profitability under irrigated condition and positive impacts under rain-fed condition associated with normal sowing. Late sowing would be an effective strategy in maintaining or enhancing cotton GM and farm profitability under rain-fed condition in a changing climate whereas it would not be enough in offsetting the negative impacts of climate change on GM and farm profitability for irrigated cotton at Narrabri and/or Hillston. Future climate change would have negative impacts on farm profitability across rotation patterns considered. This research information will help cotton growers scoping and prioritising adaptation options and avoid maladaptation.

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