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Effects of a wheat rotation on cotton production in a changing climate: a simulation study

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ABSTRACT: There is mounting evidence that climate change could be threatening the viability of cotton production in regions of Australia. This study aims to evaluate the effectiveness of a cotton–wheat rotation system in dealing with climate change for the period centred on 2030 by linking the outputs of the CSIRO Conformal Cubic Atmospheric Model with the Agricultural Production System sIMulator (APSIM) through a stochastic weather generator, LARS-WG. For irrigated cotton, we considered 3 crop sequences and 9 production areas spanning the current industry. For rain-fed cotton, we considered 2 crop sequences with 3 cotton row configurations and 4 production areas. Simulation results show that (1) for irrigated cotton, cotton 3 yr in and 1 yr out would perform the best in terms of cotton lint yield; (2) crop yields would decrease in a changing climate across crop sequences at most of the locations with wheat yield decreasing more than cotton; (3) for rain-fed cotton, continuous cotton would perform better at Emerald, Dalby and/or Narrabri under solid and single skip row configurations, while a cotton–wheat sequence would out-perform continuous cotton in terms of cotton lint yields under double skip at Emerald, Moree and Narrabri; and (4) wheat yield would decrease across locations. To maintain current production levels, better performing crop sequence needs to be combined with other adaptation options.

KEY WORDS: Rotation pattern · Cotton and wheat yields · Modelling · Climate change

1. INTRODUCTION

Cotton is the most widely produced natural fibre in the world and represents about 46% of the global textile market (Bange et al. 2008). The potential impact of climate change (CC), including elevated atmospheric CO_2 concentration (eCO_2), on crop production has attracted attention since the 1990s. Both experimental and modelling studies have been conducted to address this important issue. Based on a free-air CO_2 enrichment experiment, Mauney et al. (1994) found that cotton water use efficiency (WUE) increased in a high CO_2 environment under different levels of irrigation, and the increase in WUE was due to increased biomass production rather than a reduction of water use. Based on a Soil Plant Atmosphere Research facility, Reddy et al. (2005) investigated the interactive effects of eCO_2 and temperature on cotton production and found that doubling CO_2 concentration did not ameliorate the adverse effect of high temperature on reproductive growth (boll abscission or boll size). Using a modelling approach, Reddy et al. (2002) quantified the effects of CC on cotton production in the Mississippi Delta, USA, taking eCO_2 into account. A more recent modelling study by Adhikari et al. (2016) quantified CC impacts on cotton yield in the Texas High Plains, USA. Overall they found that with the predicted increased productivity

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due to increased carbon dioxide levels, cotton productivity could be maintained in the region if current irrigation levels could be sustained, despite the increased rainfall variability predicted under future climate scenarios. Haim et al. (2008) extended biophysical impact assessment to economic impact assessment of cotton production in Israel under climate change. Yang et al. (2014) applied impact assessment (quantification of CC impact) to adaptation evaluation (i.e. cultivar selection) in the context of cotton lint yield and water use in Xinjiang province, China. Several studies have examined the potential impacts of future CC on crop rotation systems such as wheat–soybean–maize (Diaz et al. 1997), corn–soybean (El Maayar & Sonnentag 2009), barley–maize–wheat–rape (Hlavinka et al. 2015) and maize–legume crops (Mitter et al. 2015). However, to our best knowledge, no relevant studies in cotton rotation systems have been reported.

Cotton is one of Australia's largest agricultural exports, contributing more than $2 billion in export value (Cotton Research and Development Corporation [CRDC] 2013). The potential impacts of future CC on Australian cotton phenology and production have been reported by Luo et al. (2014) and Williams et al. (2015), respectively. From an adaptation perspective, Luo et al. (2015) investigated the effects of changing water supply levels on irrigated cotton and of row configurations on rain-fed cotton in Australia under CC conditions. The effects of changing sowing time on fibre quality and on cotton production in a changing climate have been reported by Luo et al. (2016a,b). A feature of these studies is that they only considered monoculture cotton production systems. Rotation is a very important measure for the sustainability of cropping systems. In Australia, cotton is rotated with many crops, such as wheat, maize and vetch, in order to improve soil conditions and reduce the occurrence of diseases and pests. Among these, cotton rotated with wheat is a common farm practice. The benefits of a cotton–wheat rotation in controlling soil-borne disease and improving soil structure have been reported in Australia (Hulugalle et al. 2005, 2007). Hence, the potential impacts of future CC on cotton–wheat rotation systems (with various sequences) need to be assessed. This will contribute to knowledge of CC impacts on crop rotation production systems and help to identify and prioritise adaptation strategies in responding to future CC (e.g. appropriate rotation sequences). Therefore, this research aims to quantify the effects of future CC on cotton–wheat production systems in Australia and identify the best rotation sequences in a changing climate.

2. MATERIALS AND METHODS

In this study, the outputs of the CSIRO Conformal Cubic Atmospheric Model (CCAM) driven by 4 general circulation models (GCMs) were used by the stochastic weather generator Long Ashton Research Station-Weather Generator (LARS-WG) to derive local CC information, including both the mean climate (rainfall, maximum/minimum temperature and solar radiation) and climate variability (average length of wet/dry spells, daily and inter-annual variability of mean temperature). This was then used by the LARS-WG to construct 100 yr climate change scenarios (CCSs), which were then fed into the Agricultural Production System sIMulator (APSIM) to evaluate the performance of cotton–wheat sequences in terms of cotton yield for the period centred on 2030.

2.1. Study locations

For irrigated cotton, we considered 9 major Australian cotton production areas in Queensland (Emerald, Dalby, St George and Goondiwindi) and New South Wales (Moree, Bourke, Narrabri, Warren and Hillston), as illustrated in Fig. 1. The irrigated cotton production areas represent different growing environments. Using the analysis of McMahon & Low (1972) based on growing degree days (GDD), Emerald, Bourke and St George are classified as hot; Dalby, Goondiwindi, Moree, Narrabri and Warren as mild; and Hillston as cool. This equates to approximated categories for GDD as defined by McMahon & Low (1972) for a 7 mo growing season of >3000 GDD for a hot area, between 3000 and 2500 GDD for a mild area and <2500 GDD for a cool area. These different environments have resulted in different crop management practices, such as different sowing dates. For rain-fed cotton we focused on 4 typical rain-fed cotton production areas, namely Emerald, Dalby, Moree and Narrabri.

2.2. Local climate change and climate change scenarios

The outputs of the CSIRO CCAM, a dynamic downscaling approach, for baseline 1980–1999 (a standard baseline for Australia) and future period (2020–2039) climates, were used by the stochastic weather generator LARS-WG to derive monthly local CC information, including changes in the mean and in variability, and to construct long time series (100 yr) of climate scenar-

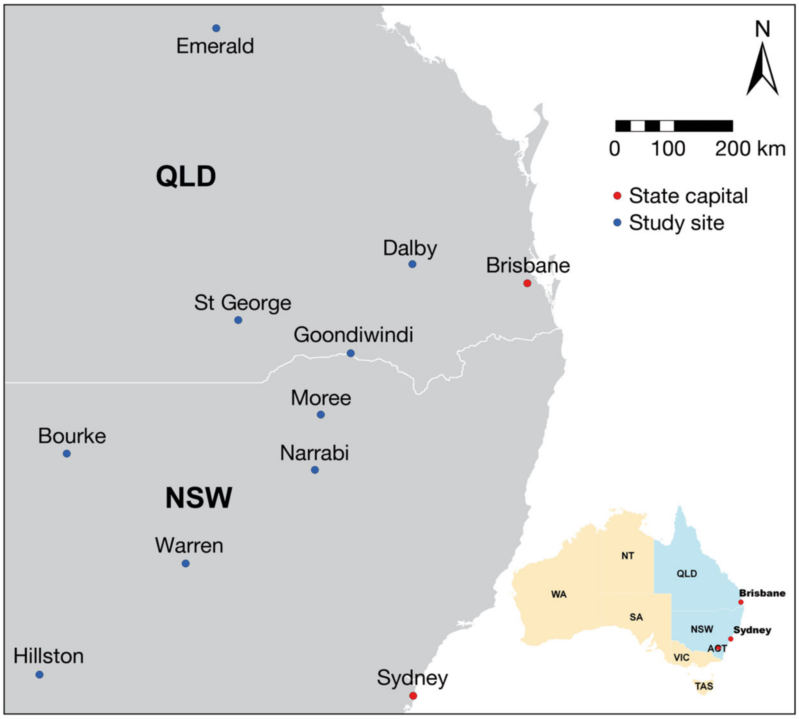

Fig. 1. Cotton production locations considered in the study. (●) Study locations, (●) reference locations

ios including baseline and future scenarios for impact assessment and adaptation evaluation. Three steps were involved in the construction of climate scenarios. In Step 1, the LARS-WG was calibrated using a historical daily climate dataset for the period 1980–1999 and used to produce daily baseline climate scenarios for each location. In Step 2, based on the daily outputs of CCAM for 1980–1999 (baseline) and 2020–2039 (future period), the LARS-WG was used to derive monthly local climate change information including changes in the mean and in variability. In Step 3, derived monthly climate change information from Step 2 along with historical climate parameters derived from Step 1 were then used by the LARS-WG to produce 100 yr daily climate scenarios for the future period. The CCAM model was driven by 4 GCMs: (1) Geophysical Fluid Dynamics Laboratory, (2) CSIRO Mark 3.5, (3) Max Planck Institute for Meteorology DKRZ, and (4) MIROC, all under the Special Report on Emission Scenarios (SRES) A2 emission scenario (IPCC 2000). More details on the CCAM model can be found in McGregor & Dix (2008) and in Luo et al. (2010, 2013). The A2 emission scenario is the only emission scenario considered by the CCAM due to the high computing resources needed. It is very similar to the Representation Concentration Pathways 8.5 emission scenario for the period centred on 2030 (Australian Climate Change ScienceProgram, http://s3.amazonaws.com/nca2014/low/NCA3_Full_Report_Appendix_5_Scenarios_Models_LowRes.pdf). The rationale of using the outputs of CCAM driven by 4 GCMs is that a multi-model ensemble is intrinsically more useful and skilful than sets of projections produced with any single model (Weigel et al. 2008). Further details concerning the construction of local CCSs can be found in Luo et al. (2014, 2015).

2.3. The APSIM crop models

APSIM is a farming systems modelling framework. It contains interconnected models to simulate systems comprising soil, crop, tree, pasture and livestock biophysical processes (Holzworth et al. 2014). The APSIM with the Ozcot and Wheat crop modules were used in this simulation analysis. They are mechanistic models which simulate the growth, development and crop yield on an area basis at a daily time step. The APSIM-Ozcot model was developed for Australian cotton production systems (Hearn 1994). The central component of this model is the fruit production and survival subroutine (Hearn & Da Roza 1985). The rates of fruit production, fruit shedding and growth of the organs are governed by carbon supply. This model has been validated for both irrigated and rain-fed cotton across a range of environments (Bange et al. 2005, Richards et al. 2008). The APSIM-Wheat model was developed for Australian wheat production systems. It is a process-oriented crop model which simulates wheat phenology, photosynthesis, biomass partitioning and re-translocation, grain development, leaf and node appearance and crop leaf area (www.apsim.info/Documentation/Model,CropandSoil/CropModuleDocumentation/Wheat.aspx). The testing and performance of this model in Australian environments have been reported by Asseng et al. (1998) and Probert et al. (1998). The predictive ability of the model was found to be satisfactory in terms of soil water, evapotranspiration and wheat yield.

To represent the physiological effects of eCO_2, radiation use efficiency, transpiration efficiency and leaf critical nitrogen content have been modified in the

Table 1. Rotation sequences under irrigated and rain-fed conditions. FS: farming system; C: cotton; F: fallow; W: wheat

FS	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Rotation pattern
Irrigated	C	F	C	W	F	F	C	Cotton 2 yr in 1 yr out
	C	F	C	F	C	W	F	Cotton 3 yr in 1 yr out
	C	F	C	F	C	F	C	Continuous cotton
Rain-fed	C	F	F	W	F	F	C	Cotton–wheat
	C	F	F	F	C			Continuous cotton

APSIM-Wheat model (Reyenga et al. 1999), while canopy photosynthesis rate has been modified in the APSIM-Ozcot model (Luo et al. 2015). The modified APSIM-Wheat model has been validated against Australian Grain FACE datasets (O'Leary et al. 2015). However, no relevant experimental data are available to validate the APSIM-Ozcot under CC in Australia.

2.4. Simulation design

Most cotton crops in Australia are planted on a 1 m row spacing under irrigated systems and at varying row spacing under rain-fed systems. In rain-fed systems skipped rows (1 m rows [solid], 1 m rows with 2 rows planted and 1 row not planted [single skip] and 1 m rows with 2 rows planted and 2 rows not planted [double skip]) are important agronomic management tools to reduce climate risk (Bange et al. 2005). Skip row systems are used to increase the amount of soil water available for the crop, which can influence the potential lint yield, reduce the level of variability or risk associated with production, enhance fibre quality, and reduce input costs (Bange & Milroy 2004). In this simulation analysis for irrigated cotton, we considered 3 crop sequences: cotton 2 yr in and 1 yr out, cotton 3 yr in and 1 yr out and continuous cotton (Table 1). Cotton was rotated with wheat in the cotton out year. For rain-fed cotton, we considered 2 crop sequences: cotton with wheat and a continuous cotton (Table 1). For the cotton component, 3 row configurations (solid, single skip, double skip) were taken into account. The rationale of including continuous cotton under both irrigated and rain-fed condition is to compare the benefit of crop sequences on subsequent cotton production. The impact of cropping sequences under future CC is indicated as yield change generated from these systems which contribute to the performance of whole farm profitability.

Details on sowing rules, crop cultivars and other sowing information used in this simulation analysis are presented in Table 2. Soil profile details used by the APSIM were obtained from APSOIL, a soil database within the APSIM package. Initial soil water was set to the full plant-available water-holding capacity of the soil. Of particular importance in these simulations was the plant-available water capacity of typical soils used to grow crops in each region. This information can be found in Luo et al. (2015). Information on nitrogen and furrow irrigation water management is given in Table 3. It should be noted that wheat is grown under rain-fed conditions following both rain-fed cotton and irrigated cotton, using a solid row configuration with a 0.25 m row spacing. Soil water and nutrients were carried over from year to year within the rotation cycle in this simulation analysis. Two levels of atmospheric CO_2 concentration (400 and 450 ppm) representing current and future (2030) conditions, respectively, were considered in this study. The level of atmospheric CO_2 for 2030 was based on the SRES A2 scenario (IPCC 2000).

Table 2. Crop sowing information. N/A: not applicable

Crops	Sowing rules	Sowing window	Cultivars	Sowing density (plants m^{-2})	Sowing depth (mm)	Row spacing (m)
Rain-fed cotton	10 mm rainfall over 3 consecutive days	25 Sep–25 Nov	S71BR	10	30	1
Irrigated cotton	N/A	Fixed sowing[a]	S71BR	10	30	1
Rain-fed wheat	25 mm over 3 consecutive days	31 Mar–31 May	Sunvale	100	30	0.25
		1 Jun–15 Jul	Hartog	100	30	0.25

[a]For fixed sowing time of each cotton production area please refer to Luo et al. (2015)

Table 3. Fertiliser and water management information

Crops	Fertiliser Timing	Fertiliser Amount (kg ha^{-1})	Fertiliser Type	Irrigation[a] Timing	Irrigation[a] Irrigation trigger[b]	Irrigation[a] Allocation (Ml ha^{-1})
Cotton	Sowing, 1st flower	200 50	Urea_N	Pre-irrigation on sowing day, furrow irrigation between sowing and 25 Mar	0.8	8
Wheat	Sowing	150	Urea_N	–	–	–

[a]Applies to irrigated cotton only
[b]Fraction of available soil water below which an irrigation event is triggered

3. RESULTS

3.1. Growing season climate changes in 2030

Multi-model ensemble mean changes (derived from the 4 climate models) in key climate variables (absolute change for maximum/minimum temperature and ratio change for the others) for cotton and wheat growing seasons (GS) are given in Table 4. A ratio change of 0.98 represents a 2% decrease, while a ratio change of 1.02 stands for a 2% increase compared with a ratio value of 1.00 (no change). It should be noted that cotton is a summer crop with a GS in the period from October to May, while wheat is a winter crop with a GS in the period from May to October. Cotton GS mean rainfall was projected to increase by 2 to 16%, while wheat GS mean rainfall was projected to decrease by 2 to 5% across locations. The average length of wet spells for cotton GS was projected to increase by 1 to 6%, while it was projected to decrease by 1 to 5% for wheat GS except at Emerald. The change direction of the average length of dry spells is opposite to that of wet spells for both cotton and wheat GSs. For example, the average length of wet spells would increase while the average length of dry spells would decrease for the cotton GS at most of the locations. The average length of dry spells for cotton GS would decrease by 2 to 5% across locations except for Dalby, where an increase of 2% would be found. The average length of dry spells for wheat GS would increase by 1 to 5% across locations except for Emerald, where a decrease of 1% would be found. Cotton GS minimum temperature would increase by 1.14 to 1.30°C and maximum temperature would increase by 0.94 to 1.13°C. Wheat GS minimum temperature would increase by 1.02 to 1.37°C and maximum temperature would increase by 1.15 to 1.40°C. Mean temperature variability for both cotton and wheat GS would increase by up to 9%, with that of the cotton season increasing more across most of the locations.

Table 4. Multi-model ensemble mean changes of growing season climatic variables for the period centred on 2030. GSR: growing season mean rainfall; ratio: ratio of future to baseline; wet and dry spells: mean length of spells (a spell is defined as ≥3 consecutive days with wet [daily rainfall of ≥0.2 mm] or dry conditions); T_{min} and T_{max}: future minus baseline; T_{var}: mean temperature variability

Locations	GSR (ratio)	Wet spells (ratio)	Dry spells (ratio)	T_{min} (°C)	T_{max} (°C)	T_{var} (ratio)
Cotton growing season (Oct–May)						
Emerald	1.02	1.02	0.95	1.23	1.07	0.98
Dalby	1.06	1.03	1.02	1.27	1.13	1.05
St George	1.08	1.03	0.96	1.29	0.99	1.06
Goondiwindi	1.09	1.05	0.98	1.30	1.08	1.06
Moree	1.09	1.03	0.95	1.27	1.05	1.07
Bourke	1.11	1.01	0.95	1.21	1.05	1.09
Narrabri	1.10	1.06	0.98	1.26	1.04	1.07
Warren	1.14	1.05	0.98	1.22	0.96	1.07
Hillston	1.16	1.06	0.98	1.14	0.94	1.06
Wheat growing season (May–Oct)						
Emerald	0.98	1.02	0.99	1.35	1.24	0.96
Dalby	0.96	0.96	1.02	1.31	1.27	1.01
St George	0.96	0.99	1.01	1.36	1.40	0.97
Goondiwindi	0.95	0.96	1.02	1.37	1.28	1.01
Moree	0.96	0.97	1.00	1.32	1.30	1.02
Bourke	0.96	0.95	1.03	1.33	1.32	1.01
Narrabri	0.97	0.96	1.00	1.31	1.30	1.03
Warren	0.96	0.96	1.03	1.19	1.25	1.02
Hillston	0.97	0.97	1.05	1.02	1.15	1.04

3.2. Irrigated farming systems

3.2.1. Effects of wheat in rotation on subsequent cotton lint yield. Multi-model ensemble mean changes (derived from the 4 climate models and calculated as future yield – baseline yield/baseline yield × 100) in cotton lint yield across locations and crop sequences are given in Table 5. The beneficial effects of wheat on cotton lint yield can be found at 6 out of 9 locations (i.e. Emerald, Dalby, Goondiwindi, Moree, Narrabri and Hillston) with cotton 3 yr in and 1 yr out and at 4 locations (i.e. Emerald, Goondiwindi, Moree, Narrabri) with cotton 2 yr in and 1 yr out in comparison with continuous cotton (Table 5).

3.2.2. Effects of cropping sequences on cotton lint yield. Cotton lint yield would decrease by 1.0 to 7.1% across locations with cotton 3 yr in 1 yr out under future climatic conditions. Similarly, cotton lint yield would change by −7.6 to 1.3% with cotton 2 yr in 1 yr out, with most of the locations showing a decrease. Cotton lint yield would decrease by 10% with continuous cotton across locations in a changing climate. These 3 rotation patterns would perform differently at different production areas. For example, cotton 2 yr in 1 yr out would perform the best (positive impact or less negative impact compared with other 2 rotation patterns) at Emerald, St George, Goondiwindi and Moree. Cotton 3 yr in 1 yr out would perform the best at Dalby, Narrabri and Hillston, while continuous cotton would perform the best at Bourke and Warren (Table 5).

3.2.3. Effects of cropping sequences on wheat yield. Under CC conditions, wheat yield would change by −23.9 to 2.1% under cotton 3 yr in 1 yr out and by −22.3 to 3.1% under cotton 2 yr in 1 yr out. Wheat yield would be positively impacted or less negatively impacted by future CC under cotton 2 yr in 1 yr out at most of the study locations considered compared with cotton 3 yr in and 1 yr out (Table 5).

Table 5. Multi-model ensemble mean changes (%) in crop yields in 2030 across locations and crop sequences under irrigated conditions (irrigation was applied to cotton only)

	Cotton 3 yr in 1 yr out		Cotton 2 yr in 1 yr out		Continuous cotton
	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

3.3. Rain-fed farming systems

3.3.1. Effects of wheat rotation on subsequent cotton lint yield. Positive effects of wheat on subsequent cotton lint yield would be found in 6 out of 12 cases (specifically Moree with solid; Moree and Narrabri with single skip; Emerald, Moree and Narrabri with double skip) with cotton–wheat sequence compared to continuous cotton (Table 6).

3.3.2. Effects of cropping sequences associated with solid row configuration. Cotton lint yield would change by −8.8 to 8.0% with Narrabri being positive compared with the baseline situation under cotton–wheat. Cotton lint yield would decrease by 1.9 to 13.0% at Emerald and Moree but increase by 3.2 to 12.6% at Dalby and Narrabri in comparison with the baseline situation under continuous cotton. Cotton lint yield would be more positively or less negatively impacted with continuous cotton across locations except at Moree when compared with cotton–wheat (Table 6).

3.3.3. Effects of cropping sequences associated with single skip row configuration. Cotton lint yield would decrease by 6.9 to 12.5% at Emerald and Dalby while it would increase by 1.6 to 7.4% at Moree and Narrabri under future CC and cotton–wheat. Cotton lint yield would decrease by 1.6 to 8.9% across all locations with the largest decrease being found at Dalby in a changing climate under

Table 6. Multi-model ensemble mean changes (%) in crop yields in 2030 across locations, crop sequences and planting configurations under rain-fed condition. Row configurations only apply to cotton. Parentheses: baseline crop yields (t ha^{-1}). Row configurations: S: solid; SS: single skip; DS: double skip; a, b, c: wheat rotating with solid cotton, single skip cotton and double skip cotton, respectively

Sites	Cotton–wheat						Continuous cotton		
	Cotton			Wheat			Cotton		
	S	SS	DS	a	b	c	S	SS	DS
Emerald	−8.8 (1.0)	−6.9 (0.9)	−3.8 (0.8)	−14.7	−14.7	−11.7	−1.9 (1.0)	−2.3 (0.9)	−7.1 (0.9)
Dalby	−3.9 (1.3)	−12.5 (1.3)	−17.3 (1.1)	−12.3	−12.6	−12.8	3.2 (1.2)	−8.9 (1.2)	−11.4 (1.1)
Moree	−7.9 (1.0)	1.6 (0.9)	−16.8 (0.9)	−21.7	−21.7	−21.9	−13.0 (1.1)	−1.6 (1.0)	−20.8 (1.0)
Narrabri	8.0 (1.0)	7.4 (0.9)	22.0 (0.7)	−13.1	−13.3	−13.4	12.6 (1.0)	−2.0 (1.0)	−21.1 (1.0)

continuous cotton. Cotton lint yield would be less negatively impacted by future CC at Emerald and Moree, while it would be negatively impacted rather than positively impacted at the other 2 locations under continuous cotton in comparison with cotton–wheat (Table 6).

3.3.4. Effects of cropping sequences associated with double skip row configuration. Cotton lint yield would change by −17.3 to 22.0% with Narrabri being positive under cotton–wheat and CC conditions. Cotton lint yield would decrease by 7.1 to 21.1% across all locations with the largest decreases being found at Moree and Narrabri under continuous cotton. Cotton lint yield would decrease more under continuous cotton in comparison with cotton–wheat except at Dalby (Table 6).

3.3.5. Effects of cropping sequences and row configurations on wheat yield. Wheat yield would decrease by 11.7 to 21.9% across locations with the largest decrease being found at Moree under cotton–wheat. This indicates that the negative effects of increased temperature and reduced wheat GS rainfall would outweigh the positive effects of eCO2. There were slight differences in wheat yield following the 3 cotton row configurations in these simulation analyses (Table 6).

4. DISCUSSION

The APSIM-Ozcot and -Wheat models were used in this study to investigate the effects of wheat on subsequent cotton production with various rotation patterns under both irrigated and rain-fed conditions. It should be noted that some of the benefits of wheat on cotton production (e.g. reduced occurrence of pests, disease and weed) cannot be captured by these models as the impact mechanisms of pests, disease and weed on crop production have not been considered in these crop models.

4.1. Irrigated farming systems

The performance of the 3 rotations varied at different production areas in terms of cotton lint yield under CC (Table 5). This implies that different production areas would have different rotation strategies in the face of future CC. The benefit of wheat crop to subsequent cotton lint yield can be ascribed to better soil structure compared to continuous cotton. Crop yield would decrease in a changing climate across rotation patterns at most of the locations with a larger decrease being found with wheat yield (Table 5) due to the fact that wheat is grown under rain-fed conditions and a decrease in wheat GS rainfall for the period from May to October is predicted (Table 4). This is in contrast to cotton production, which is grown under irrigated conditions with an increase in cotton GS rainfall (October to May) (Table 4). In addition to the negative effects of increased temperature on cotton lint yield due to shortened crop GS and heat stress, waterlogging arising from irrigation with a water supply level of 8 megalitres (Ml) ha^{-1}, and an increase in cotton seasonal rainfall would also have contributed to the decrease in cotton lint yield (similarly reported by Luo et al. 2015 for continuous cotton under a range of water supply levels). This indicates that water management strategies are needed under future wetter conditions, such as decreasing the water supply level and adjusting irrigation scheduling triggers in response to current crop status and future weather conditions (Brodrick et al. 2012). It has been shown that the greatest benefits under CC conditions occur when irrigation of the crops is reduced (Luo et al. 2015). However, an increase of 6% in cotton lint yield in 2030 was reported under continuous cropping and CC by Williams et al. (2015). The discrepancy in the change in cotton lint yield between the present study and that of Williams et al. (2015) can be attributed to (1) the different baseline period used, (2) the different emission scenario considered, (3) the different approach to constructing CCSs, and (4) the different representation of the physiological effects of eCO_2 on cotton production. The smaller decrease in wheat yield under cotton 2 yr in and 1 yr out is due to the higher nutrient level (data not shown) available for wheat growing as a smaller number of crops is involved in this rotation cycle compared with cotton 3 yr in and 1 yr out. These findings are consistent with the finding of Howden et al. (1999) that wheat yield would decrease more when wheat was rotated with sorghum compared with continuous wheat.

4.2. Rain-fed farming systems

The decrease in cotton lint yield in most of the cases (combinations of locations, row configurations and rotation patterns) may be due to the reason that the negative impacts of shortened cotton GS length and heat stress arising from a warmer environment outweighed the positive impacts of increased GS rainfall and eCO_2. On the other hand, the increase in cotton lint yield at Dalby (with solid row configura-

Table 7. Multi-model ensemble mean changes (%) in initial soil water at sowing in 2030 across locations, crop sequences and planting configurations under rain-fed conditions. Row configurations: S: solid; SS: single skip; DS: double skip; a, b, c: wheat rotating with solid cotton, single skip cotton and double skip cotton, respectively; + (–): increase (decrease) in initial soil water at sowing

Locations	Cotton–wheat						Continuous cotton		
	Cotton			Wheat			Cotton		
	S	SS	DS	a	b	c	S	SS	DS
Emerald	−0.7	−0.5	−0.4	−1.4	−1.5	−1.2	−0.9	−0.7	−0.7
Dalby	−0.3	−0.3	−0.3	+0.5	+0.5	+0.5	+0.1	+0.1	+0.2
Moree	+0.7	+0.8	+0.8	+1.7	+1.6	+1.5	+0.9	+0.8	+0.7
Narrabri	−1.0	−1.0	−1.0	+0.4	+0.5	+0.5	−0.6	−0.6	−0.6

tion under continuous cotton), Moree (with single skip under cotton–wheat) and Narrabri (with all 3 row configurations under cotton–wheat, and with solid under continuous cotton) is due to the greater positive impacts of increased rainfall and eCO_2 compared with the negative impacts of decreased cotton GS length and heat stress. It should be noted that these locations have either the lowest baseline temperature (i.e. Dalby, data not shown) or the lowest increase in mean temperature in 2030 (Moree and Narrabri, Table 4).

Continuous cotton would perform better in terms of cotton lint yields at Emerald, Dalby and Narrabri under solid; at Emerald and Dalby under single skip; and at Dalby under double skip when compared with cotton–wheat (Table 6). This can be attributed to a higher level of available soil water resources (Table 7) and/or soil nutrients (data not shown) with continuous cotton, arising from the long fallow, which are available to subsequent cotton growth and development. This finding is in accordance with the findings of Hlavinka et al. (2015) who reported that in dry conditions, the use of some crop rotations may have negative impacts, exacerbating soil water deficit for subsequent crops. The better performance of solid configuration in terms of cotton lint yields at Emerald, Dalby and Moree in comparison with other 2 configurations in a changing climate was reported by Luo et al. (2015) in a continuous cotton cropping context. However, cotton–wheat would perform better in terms of cotton lint yields in half of the cases (the combination of locations and row configurations) compared with continuous cotton (Table 6). This may be due to the beneficial effects of wheat rotation on soil structure for subsequent cotton production as the available soil water (Table 7) under cotton–wheat is lower than that of continuous cotton in most of cases.

Consistent and decreased wheat yield when compared with cotton lint yield under cotton–wheat is due to the decrease in wheat GS rainfall (Table 4). The slight difference in wheat yield following the 3 row configurations of cotton can be attributed to similar resources status (i.e. soil water, Table 7). This indicates that there was little effect of cotton row configurations on the subsequent wheat yields.

5. CONCLUSIONS

This study, by adopting a modelling approach, evaluated the effects of cotton–wheat sequences on cotton and wheat yields under irrigated and rain-fed conditions. For irrigated cotton, both crop yields would decrease in a changing climate across crop sequences at most of the locations with wheat yield being decreased more. Cotton 3 yr in and 1 yr out would perform the best across most of the locations studied in terms of cotton lint yield. For rain-fed cotton, decreased crop yields would also be found in most of the cases (combinations of crop species, row configurations and locations). Consistent performance of the 2 crop sequences would not be found across row configurations and locations. Decreases in cotton lint yield from both irrigated and rain-fed cropping systems indicated that rotation strategy alone could not offset the negative impacts of future CC on cotton lint yield. To maintain current production levels under CC, the better crop sequences need to be combined with other adaptation options such as modifying irrigation trigger points for irrigated cotton and changing sowing times for both irrigated and rain-fed cropping systems. The variability in crop sequences across locations and/or row configurations implies that cotton growers will need to consider which crop sequence best suits their circumstances. The financial performance of these crop sequences along with other management options will be evaluated in a separate work.

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