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Cotton crop water use and water use efficiency in a changing climate

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ABSTRACT

Daily outputs from the CSIRO Conformal Cubic Atmospheric Model, driven by four general circulation models, were used in a stochastic weather generator, LARS-WG, to construct local climate scenarios for key cotton production areas in eastern Australia. These scenarios along with elevated atmospheric carbon dioxide concentration were then linked to a process-oriented cotton model (CSIRO OZCOT) to quantify their potential impacts on cotton lint yield, water use, and water use efficiency (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). Simulation results show that (1) season temperatures will increase 1–1.2 °C and rainfall will increase 2–16% across locations; (2) for irrigated cotton (assuming full access to water and nitrogen), cotton crop water use will increase 0–4% in more than half of the cases (the combinations of the number of locations and water supply levels); cotton lint yield will increase 0–26% and WUE will increase 0–24% in most of the cases due to counteractive effects of elevated CO_2 and future climate, which are location- and water supply-specific; (3) for rain-fed cotton (assuming full initial soil profile), cotton water use will increase 2–8% at Emerald and Narrabri and decrease by −5 to −2% at Dalby and Moree; cotton lint yield will increase 4–26% in most of the cases and WUE will increase 2–22% in all cases. For irrigated cotton, it was found that water supply level with 2 ML/ha generated the greatest positive effects to future climate scenarios across locations except at Dalby where 4 ML/ha was greatest. For rain-fed cotton, a solid planting configuration had the greatest positive response to future climate scenarios at Emerald, Dalby and Moree while double skip planting generated the maximum benefit in lint yield at Narrabri. This simulation analysis also demonstrated the ability of the OZCOT in capturing the interactive effects of elevated CO_2 and future climate, indicating the usefulness of this tool in this important research area.

1. Introduction

The impact of climate change including elevated CO_2 concentration (eCO_2) on cotton production has attracted people's attention since the 1990s. Both experimental and modelling studies have been conducted to address this important issue. Mauney et al. (1994) found that cotton water use efficiency would increase in a high CO_2 environment under different levels of irrigation and the increase in water use efficiency (WUE) was due to an increase in biomass production rather than a reduction of water use. Kimball et al. (1994) concluded that any effects of CO_2 enrichment to 550 ppm on evapotranpiration in cotton were too small to be detected. Based on research conducted in a Soil Plant Atmosphere Research facility, Reddy et al. (2005) could not detect changes in transpiration efficiency at the canopy level. The reason is that increased CO_2 concentration and temperature increased leaf area, which offset the effect of increased leaf level transpiration efficiency. In essence the bigger canopy was transpiring more. Reddy et al. (2005) investigated the interactive effects of eCO_2 and temperature on cotton production and found that doubling of CO_2 concentration did not ameliorate the adverse effect of high temperature on reproductive growth (boll abscission or boll size). Reddy et al. (2002) quantified the effects of future climate change on cotton production in the Mississippi Delta by using the cotton simulation model GOSSYM with the effects of eCO_2 considered. A later study by Haim et al. (2008) assessed the economic effects of future climate change on cotton production in Israel without considering eCO_2. This study found that cotton would experience considerable decreases in yield with significant economic losses (−240 and −173% under A2 and B2 greenhouse gas emission

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scenarios, respectively) in a changing climate compared with the current situation. The A2 storyline and scenario family describes a very heterogeneous world. The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. More details on these emission scenarios can be found in IPCC (2000).

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, with changes in rainfall being season- and location-specific (i.e. increase in rainfall was projected for summer season) (CSIRO and BoM, 2007). A recent study by Luo et al. (2014) quantified the impact of increase in temperature on cotton crop phenology (without considering pests and diseases) and the occurrence of cold shocks and heat stress for the period centred on 2030 in Australia. It was found that there would be fewer cold shocks and a longer fruiting period, which could be beneficial for cotton production. However, the same study also suggested that there would be more hot days impacting growth, and more rapid crop development towards crop maturity, which might limit the opportunities associated with increases in fruiting period without adjustments in management. Changes in climate and in atmospheric CO$_2$ concentration and their impacts on the probability of the occurrence of cold shocks and heat stress and on cotton phenology will affect cotton growth. For example, an increase in temperature will increase water loss due to soil and plant evaporation, and increase the frequency of exceeding critical temperature thresholds for crop growth and development (Reddy et al., 2005; Luo, 2011), which, in turn, will impact on cotton growth, boll production, fibre quality, and ultimately farm profitability. Even though eCO$_2$ may have some positive effects on cotton production, these effects may be constrained or impacted by high temperature, and access to soil water and soil nutrients (Reddy et al., 2005).

For the Australian cotton industry to be sustainable, there is a strategic need to quantify the combined impacts of changes in temperature, rainfall, water availability and eCO$_2$ on cotton production, and to identify and evaluate existing and potential adaptation options in dealing with projected negative impacts and/or capitalising on the potential growth opportunities of future climate change. Utilising the Australian cotton model OZCOT, this research aims to (1) capture the physiological effects of eCO$_2$ on cotton key growth processes, (2) quantify the potential impacts of future climate change on cotton production from the perspective of cotton lint yield, water use and WUE, and (3) evaluate adaptation options in responding to future climate change.

2. Materials and methods

The outputs of CSIRO Conformal Cubic Atmospheric Model (CCAM) driven by four general circulation models (GCMs) were used by a stochastic weather generator (LARS-WG) to derive local climate change information including both the mean and variability of climate. This was then reapplied to the LARS-WG to construct long time series of climate scenarios. These scenarios and eCO$_2$ were then coupled with CSIRO OZCOT to assess their effects on cotton lint yield, water use, and WUE under both irrigated and rain-fed conditions for the period centred on 2030. Multi-model ensemble mean changes in these production components were derived from their mean values under future and baseline climate scenarios.

2.1. Current farming practices and study locations

The Australian cotton production is characterised as a high yielding (>1500 kg/ha, Cottee et al., 2010), semi-intensive broadacre cotton system with irrigated cropping using high inputs of water, fertiliser, and pesticides (Braunack, 2013). Both irrigated and rain-fed cotton production systems are practised in Australia. The average industry yield for irrigated production was 2452 kg/ha in the 2012/13 season, over a cropping area of 405,000 ha (Dowling, 2013). Rain-fed production constitutes a large area of Australian production – up to 15% of the industry (Bange et al., 2005). The average industry yield for rain-fed cotton was 818 kg/ha in the 2012/13 season (Dowling, 2013). A key characteristic of the modern Australian cotton industry is the use of transgenic varieties. Most farms utilise Bollgard II® cultivars containing the Cry1Ac and Cry2Ab Bt (*Bacillus thuringiensis*) proteins enabling growers to manage insects (e.g. *Helicoverpa* sp.) more effectively, consequently reducing the amount of pesticides required (Wilson et al., 2013). Current cultivars also include Roundup Ready Flex® traits, which have contributed to easier management of weeds without over-application of herbicides.

The amount of irrigation applied is highly variable depending on seasonal climate conditions with less water being applied if adequate rainfall occurs during the season or more if rainfall does not occur. The amount of irrigation also depends on water availability from either on-farm storages and bores or releases from dams as part of the regional irrigation system. On average, high yielding crops utilise 6–7 ML/ha irrigation water as seasonal evapotranspiration (Roth et al., 2013) and is predominately applied as gravity surface-irrigation systems.

Planting time varies between seasons and locations. The ideal soil temperature for cotton establishment lies between 16–28 °C (Bange et al., 2009). Soil temperatures below 16 °C result in slow emergence and increase the seedlings' susceptibility to soil borne insects and pathogens. The seed is normally planted between 2.5 and 5 cm depth depending on seedbed conditions and whether it is dry or moist. Growers aim for a plant establishment of 8–12 plants/m^2. Nitrogen (N, as urea or anhydrous ammonia gas) is generally applied pre-planting with phosphorus and micro-nutrients being applied at planting. Average N fertiliser inputs for high yielding

Table 1
Study locations and historical climate.
Data source (http://www.bom.gov.au/jsp/ncc/climate_averages/rainfall/index.jsp).

Locations	Latitude (°S)	Longitude (°E)	Elevation (m)	Annual season temperature (°C)	Season[a] rainfall (mm)	Average seasonal eto (FAO56)	Average seasonal day degrees
Emerald	23.55	148.24	188	25.7	752	1289.9	3293
Dalby	27.18	151.26	344	22.5	526	1249.6	2572
St. George	28.04	148.58	201	24.4	398	1327.7	3010
Goondiwindi	28.55	150.31	217	23.3	467	1248.7	2774
Moree	29.49	149.85	213	22.9	462	1260.8	2697
Bourke	30.09	145.94	106	24.1	264	1375.7	2953
Narrabri	30.34	149.76	212	22.7	481	1239.8	2665
Warren	31.78	147.77	198	22.0	382	1233.1	2507
Hillston	33.49	145.52	122	21.3	246	1215.6	2381

[a] Cotton season: Oct.–May inclusive.