focus on **climate** research

An overview of recent research into effects of climate change & extreme weather events on Australian cotton systems

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Introduction

Changes in climate factors such as warmer air temperatures and extreme fluctuations in precipitation as a result of rising CO^2 concentration may significantly impact plant growth and crop productivity. Over the past several years a range of research initiatives have been conducted to better understand responses of the cotton system to this changing environment. This review explores projected climatic changes throughout Australian cotton regions, summarises studies that assess the impact on productivity, and investigations to help mitigate potential negative effects.

Climate Change in Australian Cotton Regions

There have been substantial increases in atmospheric CO^2 concentration since the beginning of the industrial age. Atmospheric CO^2 during the past 800,000 years ranged between 170 and 300 µmol mol^{-1} in response to natural transitions between glacial and inter-glacial periods.

However, atmospheric CO^2 has been rapidly increasing over the past 200 years due to world-wide industrial activity from a pre-industrial concentration of about 280 µmol mol^{-1} to 406 µmol mol^{-1} in 2017 (Tans and Keeling, 2018), with projections for more rapid increases in the future. It is projected that atmospheric CO^2 concentration will rise to 450 µmol mol^{-1} by 2030.

As a consequence of rising greenhouse gases in the atmosphere, including CO^2, global air temperatures have also been increasing throughout many regions. Global average air temperature has warmed by over 1°C since records began in 1850, and each of the last four decades have been warmer than the previous decade (CSIRO and Bureau of Meteorology, 2018). Australia's climate has increased 1°C since 1901 with an increase in the frequency of extreme heat events (CSIRO and Bureau of Meteorology, 2018).

Eight locations spanning the current Australian cotton industry have been assessed to explore the temperature trends over three periods: (a) 1957 to 2017 (60 years); (b) 1957 to 1996 (39 years); and (c) 1997 to 2017 (20 years).

All eight locations exhibited a trend for an increase in the accumulation of the number of day degrees (a measure of heat accumulation throughout a growing season, from September to April) during the period 1957 to 2017 (Figure 1).

From 1957 to 1996, there was an increase in the number of day degrees at Emerald, and during the period 1997 to 2017 there was an increase in the number of day degrees at Griffith and Moree. Although the slopes of each regression were mostly positive, suggesting a possible increasing trend in day degree accumulation, the variation in the number of day degrees between years was large over a relatively short timeframe.

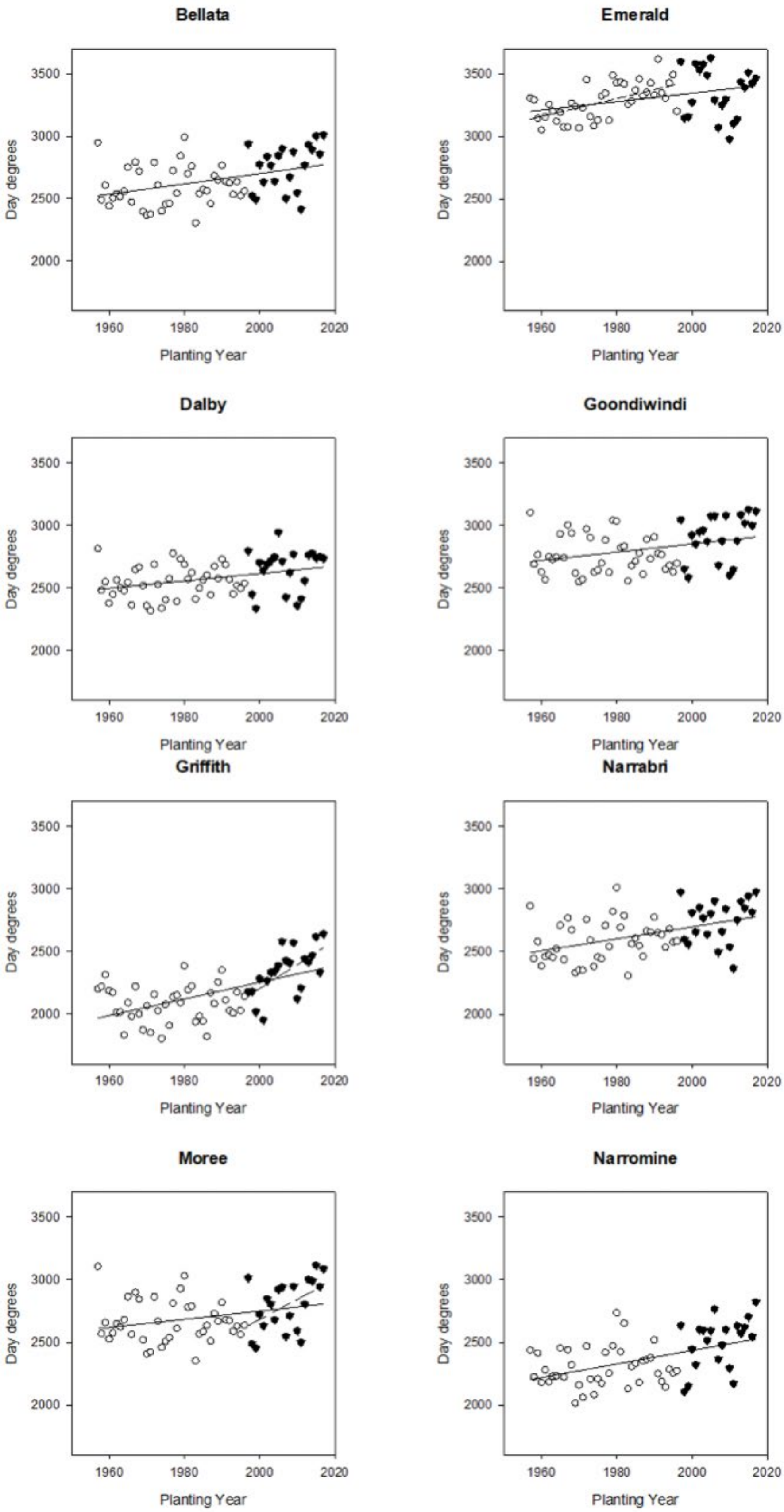

Figure 1: The number of day degrees (a measure of heat accumulation throughout the growing season from September to April) for eight cotton production locations in Australia for three periods: (a) 1957 to 2017 (all symbols); (b) 1957 to 1996 (white symbols); and (c) 1997 to 2017 (black symbols). Regression lines have been fitted for each period where the slope is significant at P<0.05.

However, the significant increasing trend in the number of day degrees from 1957 to 2017 for all eight locations indicates an increase in the number of hot days and warmer night-time air temperatures.

Associated with increasing day degrees, current climate projections indicate that Australia will exhibit more heatwaves (air temperatures greater than 35ºC). Recent examples were during the 2016-17 cotton season, where high temperature records were broken across the country. Moree, in the Gwydir Valley in North West NSW, recorded 54 consecutive days exceeding 35ºC. The previous record was 11 days above 35ºC. In addition to warmer day time temperatures, night time temperatures were also warmer. Mungindi, north of Moree, measured 49 consecutive nights of 20ºC or above. The previous record was 27 nights.

Climate projections indicate that there will be changes in rainfall distribution, including an increase in the intensity of drought and flooding. Drought conditions directly impact dryland crops during the season and reduce water availability for irrigated cotton systems. On the other hand, Australia's cotton is often grown on heavier soil textures (i.e. clay soils), so crops may experience yield losses due to waterlogging during heavy rainfall events.

Recent Australian Cotton Research into the Implications of Future Climate

Agricultural production is highly sensitive to climatic variability and extreme weather events. To gain a better understanding of how future climate change may affect Australian cotton production, recent research has utilised crop simulation technologies with climate forecasts, as well as undertaking field and controlled environment (glasshouse) research.

Crop Simulation Studies

Crop simulation studies were undertaken to assess the potential impacts on cotton lint yield, water use, and water use efficiency across nine cotton locations (Table 1).

All studies utilised the OZCOT cotton crop model that has been developed and tested for Australian environments (Hearn, 1994) and linked to climate predictions generated by global circulation models (GCMs). The locations included diverse irrigated and dryland scenarios across Emerald, Dalby, St George, Goondiwindi, Moree, Bourke, Narrabri, Warren, and Hillston.

Two separate initiatives have been used to assess impacts on cotton productivity. Research by Luo et al. (2014 to 2017) utilised a combined assessment of GCMs, while Williams et al. (2015) used a single GCM to predict future climate effects on cotton. In addition, the studies utilised different future climate scenarios regarding CO^2 emissions and slightly different timescales.

Luo et al. used four different general circulation models (GCMs): GFDL, CSIRO Mk3.5, MPI and MIROC with an 'A2' emission scenario. The Williams et al. studies used the CSIRO Mk3.5 GCM model with an 'A1F1' SRES emissions scenario. The A1F1 scenario projects a warm, dry scenario and is an example of a 'worst case' scenario based on future emissions occurring at historical rates with no mitigation strategies implemented. An A1F1 scenario suggests that Australian cotton regions are projected to receive less rainfall and consequently reduced inflow to rivers and water storages.

However, the A2 scenario describes a very heterogeneous world and is more conservative in terms of impacts on future climate change. The Luo et al. (2014) simulations suggested that mean air temperatures throughout the growing season would increase 1 - 1.2ºC, over the period 2020 to 2039. In contrast, the Williams et al. (2018) study assessed the impact on selected cotton regions for the present, and for the periods 2030 and 2050. Although both studies also investigated the impacts of future climate without the CO^2 effects, here we present only the combined interactive effects of future climate and CO^2 fertilisation.

The outcomes of both the Luo et al. and Williams et al. studies were consistent in that climatic conditions are most likely to contribute to a reduction in the time for biomass, and consequently yield, accumulation through warmer seasonal temperatures. OZCOT simulations by Luo et al. (2015) found that the combined effect of projected rainfall, CO^2 and warmer temperatures for the period 2020 to 2039 may increase cotton lint yield up to 26 per cent in both irrigated and dryland systems, and also increase water use efficiency.

For example, Luo et al. (2015) showed an approximate 4 per cent increase in cotton yield at Dalby across a range of water supply levels for the period centred on 2030.

The simulation study by Williams et al. (2015) found that yields at Dalby were projected to rise 5.9 per cent by 2030 but then decline by 3.6 per cent in 2050, noting that the outcome of the Williams et al. study is based on a longer time period than the Luo et al. study combined with a stronger climatic scenario.

The study by Luo et al. (2015) also suggested that higher temperature would increase water requirements for both irrigated and dryland systems in some areas. Although there are some physiological benefits of elevated CO^2 in reducing both leaf stomatal conductance (a measure of the degree of stomatal opening) and leaf-level water use, it is most likely that crop water use will rise because of increased cotton canopy development (leaf area) and increased vapour pressure deficit (VPD; lower humidity combined with higher temperatures). Although in some instances, water consumption may be lower if there is a substantial reduction in season length due to faster development of cotton grown in a warmer environment.

Luo et al. (2014) and (2016) also explored the effect of climate change on cotton crop development and cotton fibre quality. Results showed there will be less impact of cold temperatures on earlier growth and potentially a longer growing season that may help explain increases in predicted cotton yield (Luo et al., 2014). However, in later stages of crop growth, rising temperatures may negatively affect growth through more rapid crop development in the later growth stages (especially boll filling).

Without adjustments in management, this may limit the opportunities associated with a longer growing season and explain the predictions of greater negative impacts found in the Williams et al. studies where the scenario was more extreme.

In terms of fibre quality, Luo et al. (2016) showed that if normal planting is maintained, projected increases in temperature had a negative effect on the frequency of achieving optimal micronaire in the majority of locations, with the biggest impact occurring in hot areas: Emerald, St George and Bourke. However, warmer air temperatures during the fibre-thickening period led to an increase in the frequency of optimum micronaire compared with the baseline scenario in the cooler location, Hillston.

System type	Location	Change in lint yield	Change in water use	Change in crop WUE
Irrigated	Dalby	⇧ 6% (at 449 ppm) ⇩ 3.6% (at 555 ppm)	⇧ 2-4%	
	Bourke		⇧ 2-4%	
	Narrabri		⇧ 2-4%	
	Hillston		⇧ 2-4%	
	Overall	⇧ 0-26%	⇧ 0-4%	⇧ 0-24%
Dryland	Emerald	⇧ 15-26%	⇧ 2-8%	
	Dalby	⇧ *Only with solid planting config.	⇩ -5 to -2%	
	Moree	⇧ 15-26%	⇩ -5 to -2%	
	Narrabri	⇧ 15-26%	⇧ 2-8%	
	Overall	⇧ 15-26%		⇧ 2-22%

⇧ indicates increase, ⇩ indicates decrease

Table 1: Simulated cotton lint yield, water use and water use efficiency (WUE) across locations under future climate scenarios for the period centred on 2030 (unless otherwise indicated). Adapted from Luo et al. (2015) and Williams et al. (2015). Luo et al. used four general circulation models with an A2 emissions scenario for the period centred on 2030 and CO2 levels at 450 ppm, whereas Williams et al. used one general circulation model with an A1F1 emissions scenario for 30 year periods centred on 2030 and 2050 and under three different CO2 levels (350, 449 and 555 ppm).

Field and Glasshouse Studies

There has been detailed research into the effects of climate change in the past utilising a range of approaches (e.g. Soil-Plant-Atmosphere-Research units (controlled environment glasshouses) in Mississippi, Free Air CO^2 Enrichment field facilities in Arizona) that has provided an excellent foundation of understanding potential impacts. However, there has been no specific research into climate change impacts for modern Australian cotton systems, and little research attempted to assess the combined interactive effects (temperature x CO^2 x water) of climate change on cotton productivity; especially in the field.

Compared to previous research in the USA, where the average yield in Arizona when the studies were conducted in the early 1990s was 1200 kg lint ha^{-1} using inputs around 130 kg N ha^{-1}, modern Australian cotton systems are high-input and high-yielding cotton production systems (yields above 2500 kg ha^{-1} with inputs that can be high e.g. 250 kg N ha^{-1}) that may present unique challenges.

Leaf, Plant and Crop Level Effects

The integrated effects of warmer air temperatures and elevated atmospheric CO^2 concentration on cotton growth, physiology and soil microbiology have been studied in a number of glasshouse and field studies in recent years. Distinctly, Australian studies have used in-field facilities that have attempted to raise both air temperature and atmospheric CO^2; an especially challenging task in an Australian summer (Figure 2, Figure 3).

In field and glasshouse studies by Broughton et al., elevated atmospheric CO^2 increased vegetative biomass and photosynthetic rates of cotton compared with plants grown at current ambient CO^2 levels (Table 2). In glasshouse studies by Broughton et al., elevated CO^2 improved leaf and plant-level water use efficiency of cotton which was associated with improved photosynthesis and biomass production, rather than decreases in water use. However, these studies also showed that improved water use efficiencies were negated by warmer air temperatures, as more water was required to grow the plants.

Figure 2: Climate change facility at the Australian Cotton Research Institute (ACRI), Narrabri.

Figure 3: Using Canopy EvapoTranspiration and Assimilation (CETA) chambers in the field at Narrabri, NSW to generate warmer and higher CO2 environments for field-grown cotton

In field studies, Broughton et al. showed similar outcomes, but other crop level issues emerged. Increased vegetative biomass and reduced water use efficiency became evident as water consumption also increased.

Crops had excessive vegetative growth with large leaf areas significantly increasing transpiration. Further reductions of water use efficiency were then associated with high temperatures, as well as the excessive shading caused by the leaves, leading to the shedding of fruit throughout the season. In turn, this continued to exacerbate the vegetative growth and the loss of fruit because there was little fruit load to restrict vegetative growth (Figure 4).

Research has also been conducted to explore differences between cotton genotypes (Figure 5). Given there have been significant changes in Australian cotton cultivars, management and yields, it is important to ensure that beneficial traits for CO^2 and temperature have not been omitted, as these could contribute to maximising responses of cotton cultivars to future environments.

In a glasshouse comparison of an older and modern cotton genotype (DP16 and Sicot 71BRF, respectively), Broughton et al. (2017) found that the modern cultivar (Sicot 71BRF) had higher photosynthetic rates than the older cultivar (DP16), but also had lower leaf number and leaf area, such that Sicot 71BRF produced less biomass than DP16.

As future environments are anticipated to produce larger cotton plants with potentially greater requirements for water, plants with smaller, more compact vegetative growth habits and higher photosynthetic rates (e.g. Sicot 71BRF) may have an advantage over cultivars with substantial plant biomass and leaf area (e.g. DP16).

Although the study was limited in comparing two cultivars, it highlights variation in plant performance that could be utilised in the selection of breeding lines for future environments; however, implementation in capturing the needs for climate change in breeding programs remains a challenge.

Figure 4: Cotton grown inside the climate chambers were tall and highly vegetative, leading to large reductions in plant-level water use efficiency.

Figure 5: Collecting physiology measurements on cotton grown in the controlled environment glasshouse at Western Sydney University, Richmond, NSW.

Soil impacts

Studies have indicated that projected climate change may impact nutrient availability and soil microbial communities. This is important to consider given the key role soil microbes play in nutrient cycling and availability, and the importance of nitrogen use efficiency in cotton systems.

Most climate change effects on soil communities are linked to changes in plant responses, thereby generating plant-soil feedbacks. Low soil N may reflect greater plant N uptake and thus may not necessarily mean low nitrification rate.

	Variable	**Elevated CO_2**		**Warmer temperature**	
		Glasshouse	**Field**	**Glasshouse**	**Field**
Plant	Photosynthesis	⇧	⇧	⇧	⇧
	Vegetative growth	⇧	⇧	⇧	⇧
	Seed cotton yield	⇧	⇧	⇧	⇩
	Water use	⇧	⇧	⇧	⇔
	Plant-level water use efficiency	⇧	⇩	⇩	⇩
Soil	Soil pH	⇔	⇔	⇩**	⇔
	Soil nitrate concentrations	⇩	⇩	⇧***	⇔
Microbes	Nitrifier abundance	⇔ AOB ⇧ AOA	⇧ AOB ⇧ AOA	⇔ AOB ⇧ AOA	⇔ AOB ⇧ AOA
	Nitrifier community composition	↻ AOB* -	↻ AOB* ↻ AOA*	↻ AOB* -	⇔ AOB ↻ AOA*
	Potential nitrification rate	⇩	⇧	⇔	⇔
	Microbial abundance	⇩ Fungal-to-Bacterial ratio	-	⇔	-
	Microbial community composition	↻ Bacterial community*	-	↻ Bacterial community*	-
	Microbial activity (respiration)	⇧*	-	⇧*	-

⇧ indicates increase, ⇩ indicates decrease, ⇔ indicates no significant difference and ↻ indicates change
AOA indicates ammonia oxidising archaea, AOB indicates ammonia oxidising bacteria
* Dependent on growth stage of crop
** Dependent on soil type
*** Based on plant N uptake

Table 2: Summary of measured outcomes of climate change on plant and soil responses from glasshouse and field studies. Adapted from Osanai et al., Nguyen et al., and Broughton et al.

Additionally, limitations in plant growth may result in greater soil N levels than when plants are actively growing and utilising N from the soil. Recent studies by Nguyen (2017) determined that climate responses of soil physicochemical (physical and chemical) properties and nitrification rate (a two-step conversion of ammonium to nitrate involving the oxidation of ammonium to nitrite, followed by the oxidation of nitrite to nitrate) were also related to crop growth stage; only responding when the crop reached the early flowering stage.

The study found that the changes were related to the abundance of microbial nitrifiers (AOA= ammonia-oxidising archaea, AOB= ammonia-oxidising bacteria) in the soil. Specifically, warmer air temperatures did not significantly change potential nitrification rates, although the warmer temperatures did increase AOA abundance and thus change microbial community structure (Table 2).

However, the combined effects of warmer temperature and elevated CO^2 increased soil nitrification rate, and increased AOB and AOA abundance, but these alterations were dependent on the growth stage of the crop. Changes in the rate of nitrification processes and functional communities could potentially lead to alterations in soil nitrogen availability, which could affect cotton crop productivity and nitrogen use efficiency.

Impacts of extreme weather events

Using a multi-faceted approach, including model simulations, glasshouse and field-based studies, has increased our understanding and knowledge of the responses of the Australian cotton production system to projected environmental conditions.

Climatic projections include far greater variable weather conditions in the future, which is likely to have a more severe impact on cotton productivity. Projected climatic conditions are likely to increase inter-annual yield variability because of the high yield potential in seasons where there are no extreme climatic events, but large reductions in yield during seasons that are affected by extreme climatic events.

For example, Luo et al. (2014) demonstrated an increase in the number of days above 35°C across all locations in the simulation study (ranging from Emerald to Hillston).

There was also a reduction or no change in the number of cold shocks (≤ 11°C) throughout the majority of the growing season, with the exception of increased cold shocks in some NSW growing areas in January and February. Furthermore, Luo et al. (2015) reported increases of 2-16 per cent and 4-17 per cent in mean rainfall and rainfall variability, respectively, within cotton growing season for the period centred on 2030, which will have significant consequences on farming system.

For example, nitrate is highly mobile in soil, and thus susceptible to leaching in flooded conditions. Glasshouse studies have shown that flooding caused a rapid loss of N from the soil, contributing to a reduction in growth and yield of cotton, particularly at warmer temperatures (Osanai et al., 2017).

The outcomes from the recent glasshouse and field studies in assessing the effects of elevated atmospheric [CO^2], warmer air temperatures, waterlogging and drought on cotton physiology, growth, water use, and soil health are summarised in Table 2 and Table 3.

Legacy effect

The positive effect of elevated CO^2 on cotton growth and yield is generally consistent across studies, however, one-season experiments do not account for potential feedback or 'legacy effect' on the subsequent crops. Cotton plants under elevated CO^2 produce N-poor litter (i.e. non-harvestable biomass) which can reduce soil N availability for the subsequent crops through reduced decomposition rate. As a third of cotton's N uptake comes from mineralised N, reduction in decomposition can strongly limit the yield response to elevated CO^2 in the subsequent seasons.

This was demonstrated in a glasshouse experiment by Osanai et al., where elevated CO^2 strongly reduced yield in the second year, particularly at ambient temperature. Warmer temperature on the other hand had a consistent effect and seemed to negate the negative effect of elevated CO^2 on yield. Assessing the strength of this legacy effect in the field condition will be critical in developing fertiliser recommendations to mitigate the potential negative impact of elevated CO^2 on cotton yield in the future.

	Variable	Waterlogging		Drought	
		Glasshouse	Field	Glasshouse	Field
Plant	Photosynthesis	⇩	⇔	⇩	-
	Vegetative growth	⇩	⇔	⇩	-
	Seed cotton yield	⇔	⇔	⇩	-
	Water use	-	-	⇩	-
	Plant-level water use efficiency	⇩**	-	⇔	-
Soil	Soil pH	⇧	⇧	⇩ Residual N	⇩ Marginal
	Soil nitrate concentrations	⇩	⇩***	⇧ Residual N	⇧ Residual N
Microbes	Nitrifier abundance	⇩ AOB ⇔ AOA	⇩ AOB ⇩AOA	⇔ AOB ⇩ AOA**	- -
	Nitrifier community composition	To be analysed -	↻ AOB ↻ AOA	To be analysed -	-
	Potential nitrification rate	⇩	⇩	⇩**	-
	Microbial abundance	⇔ Bacteria*, ⇩Fungi*	-	⇔	-
	Microbial community composition	↻ Bacterial community*	-	↻ Bacterial community*	-
	Microbial activity (respiration)	⇧⇔*	-	⇔	-

⇧ indicates increase, ⇩ indicates decrease, ⇔ indicates no significant difference and ↻ indicates change

* Dependent on growth stage of crop

** Dependent on soil type

*** Dependent on the timing of waterlogging

Table 3: Summary of measured outcomes of extreme weather events on plant and soil responses from glasshouse and field studies. Adapted from Osanai et al., Nguyen et al. and Milroy and Bange 2013.

Key messages

Worldwide cotton production has broadly adapted to growing in temperate, subtropical and tropical environments, but growth and production systems in Australia may be challenged by future climate change. Key outcomes of recent modelling, glasshouse and field-based studies are:

- Climate change will have both positive and negative effects on cotton. Increased CO^2 may increase yield in well-watered crops, and higher temperatures will extend the length of the growing season. However, warmer temperatures also accelerate the rate of crop development and could potentially shorten the time to maturity, which may impact crop management decisions. Higher temperatures also have the potential to cause significant fruit loss, reduce water use efficiencies, lower yields and alter fibre quality.

- Environmental conditions that encourage excessive shading by the leaves may lead to fruit loss throughout the season. Consequently, fruit loss may exacerbate excessive vegetative growth and further loss of fruit, due to a lower fruit load to restrict vegetative growth.

- Extreme weather events such as droughts, heatwaves and flooding pose significant risks to improvements in cotton productivity. Inter-annual yield variability is likely to be greater, with benefits from increases in yield potential during favourable seasons, but also large reductions in yield during the seasons affected by extreme weather events.

- Research into integrated effects of climate change (temperature, humidity, CO^2 and water stress) on cotton growth, yield and quality will require further investment. This includes the development of cultivars tolerant to abiotic stress (especially for more frequent hot, water-challenged (deficit and waterlogged) conditions), and better understanding of whole system and management strategies to maximise production and minimise losses of cotton grown in variable environments.

- On-going research requires a multi-faceted approach that incorporates model simulations, glasshouse and field studies to better our understanding and knowledge of cotton plant-soil responses to projected environmental conditions for Australian cotton regions. In a systems context, climate change is a multi-factor complex issue that is likely to require more than one solution to address the multi-dimensional, integrated impacts on Australian cotton production systems.

Acknowledgements

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Further Reading

A review article highlighting the impact of climate change on cotton production in modern farming systems has been published by Bange et al. (2016).

Bange, M.P., J.T. Baker, P.J. Bauer, K.J. Broughton, G.A. Constable, Q. Luo, et al. 2016. Climate change and cotton production in modern farming systemsCABI.

Broughton, K.J., M.P. Bange, R.A. Duursma, P. Payton, R.A. Smith, D.K.Y. Tan, et al. 2017. The effect of elevated atmospheric [CO^2] and increased temperatures on an older and modern cotton cultivar. Functional Plant Biology 44: 1207-1218. doi:https://doi.org/10.1071/FP17165.
CSIRO and Bureau of Meteorology. 2018. State of the climate.

Hearn, A.B. 1994. OZCOT: A simulation model for cotton crop management. Agricultural Systems 44: 257-299.
Luo, Q., M. Bange and L. Clancy. 2014. Cotton crop phenology in a new temperature regime. Ecological Modelling 285: 22-29.

Luo, Q.Y., M. Bange and D. Johnston. 2016. Environment and cotton fibre quality. Climatic Change 138: 207-221. doi:10.1007/s10584-016-1715-0.

Luo, Q.Y., M. Bange, D. Johnston and M. Braunack. 2015. Cotton crop water use and water use efficiency in a changing climate. Agr Ecosyst Environ 202: 126-134.

Nguyen, L. 2017. Cotton farming and N cycling: adaptation to climate change. Doctor of Philosophy, Western Sydney University, Western Sydney University.
Osanai, Y., D.T. Tissue, M.P. Bange, M.V. Braunack, I.C. Anderson and B.K. Singh. 2017. Interactive effects of elevated CO^2, temperature and extreme weather events on soil nitrogen and cotton productivity indicate increased variability of cotton production under future climate regimes. Agr Ecosyst Environ 246: 343-353. doi:10.1016/j.agee.2017.06.004.

Tans, P. and R. Keeling. 2018. Trends in Atmospheric Carbon Dioxide. National Oceanic and Atmospheric Administration.

Williams, A., S. Mushtaq, L. Kouadio, B. Power, T. Marcussen, D. McRae, et al. 2018. An investigation of farm-scale adaptation options for cotton production in the face of future climate change and water allocation policies in southern Queensland, Australia. Agricultural Water Management 196: 124-132.

Williams, A., N. White, S. Mushtaq, G. Cockfield, B. Power and L. Kouadio. 2015. Quantifying the response of cotton production in eastern Australia to climate change. Climatic Change 129: 183-196. doi:10.1007/s10584-014-1305-y.