Chapter 22

High input irrigated crops

Rose Brodrick and Michael Bange

Introduction

Irrigated production in Australia constitutes a small proportion (4% of the land area) of broadacre cropping area in Australia but contributes 21% of the gross value of broadacre production to the Australian economy (ABS 2019). The three major irrigated broadacre crops grown in Australia are cotton, sugarcane and rice. Cotton is the largest of these crops grown under irrigation; both cotton and sugarcane are also grown under rainfed production (Table 1).

Table 1. Value, area and irrigation water applied in cotton, sugarcane and rice in Australia 2016-17 (source: Australian Bureau of Statistics 2019)

	Value of agricultural commodity produced $M	**Area under crop** ha '000	**Area watered** ha '000	**Volume applied** ML '000	**Application rate** ML/ha
Cotton	1681	519	328	2 566	7.8
Sugar cane	1621	453	212	974	4.6
Rice	252	82	82	940	11.4

Since 1987 there have been several agronomic changes and improvements in crop production that are not unique to irrigated production systems and are transferable across industries. Many of these are covered in more detail in other chapters. In many cases however, irrigated producers have been early adopters of precision agriculture, controlled traffic and automation. For all three crops, key production changes have included use of rotation crops for productivity gains, breeding of locally adapted cultivars with a dual focus on yield and quality, unique agronomic, policy or technological changes that have influenced production methods, and a shift in focus to integrated approaches to crop management (including an emphasis on protecting natural resources).

A very significant challenge in broadacre irrigated production has been the increasingly drier climate in cotton and rice growing regions and shrinking water resources (Jones 2010) caused by Australia's variable and changing climate (Humphreys *et al.* 2006, Bange *et al.* 2016). Indirectly, production is significantly affected by government regulation of water to mitigate these effects. In the case of sugarcane, arguably the impact of run-off into sensitive marine systems, and the associated impact of these pollutants on the Great Barrier Reef (GBR), has been the most significant challenge for that industry, and is yet to be overcome (Hamman and Deane 2018).

Regulations that require reduced environmental impact or resource use for these three crops have impacted on production methods and led to a focus on best management practices and improved water use efficiency. These challenges have been accompanied by reductions in land availability, rising costs of production, environmental concerns, and potentially a decline in trade as a result of competition from other commodities (*e.g.* such as man-made fibres for cotton, or increasing production from other overseas markets in the case of rice and sugar).

This chapter outlines briefly some unique changes in rice and sugar production and explores cotton as the main case study in greater detail to exemplify crop management, genetics, and agronomic improvements over the past 30 years. Modern agronomic management of rice is covered in detail by Bajwa and Chauhan (2017) so we do not attempt to repeat the details in their summary here. Irrigated cotton production in Australia is a high cost and capital-intensive industry which has necessitated innovation to remain viable. Due to challenges with insect pesticide resistance and concerns with the environmental impacts of pesticide use, in the 1990s the Australian cotton industry was the first to utilise genetically modified (GM) cultivars. The introduction of GM cultivars transformed the industry and enabled a strong focus on broad production improvements over the past 30 years. Using the Australian cotton industry as an example we endeavour to give a broad overview of practice change and strategies to address some current challenges facing irrigated broadacre production in Australia now and into the future.

Rice

Rice production and management in Australia is unique compared with other rice producing countries. Australian rice farmers produce high quality rice, attain the highest yields per unit area and grow the most water-use efficient rice in the world (Humphreys *et al.* 2006, Bajwa and Chauhan 2017). This is a significant achievement given the environmental challenges involved. Over the past 30 years, the rice production system in Australia has achieved substantial increases in yield through improved agronomy coupled with locally adapted cultivars; this makes the Australian rice industry an excellent example of agronomic innovation and adoption during this period (Bajwa and Chauhan 2017).

Key challenges faced by Australian rice growers include reduction in water availability, low temperature damage and continued environmental pressures (Humphreys *et al.* 2006). Reduced water availability has been due to both prolonged droughts and changes in legislation to reserve water for environmental flows.

A novel agronomic innovation that led to increased rice yields was flooding of the crop for the duration of the growing season, in order to provide protection from cold temperature stress, which can cause floret sterility during the reproductive period (Williams and Angus 1994). This practice has been adjusted as water availability has declined; under water-limited conditions, flooding is delayed in order to align better with the cold-sensitive early pollen microspore stage. Nitrogen management in particular has been adjusted to keep in step with changes in water management and yield improvements. In the past twenty years, average water productivity of the Australian rice crop has almost doubled (Humphreys *et al.* 2006), primarily due to yield improvement associated with the introduction of semi-dwarf cultivars and improved water management.

Rice production is now limited to suitable soil types of low permeability, in order to reduce drainage past the root zone. This produces better water use efficiency, keeps water tables at depth, and reduces incidence of soil salinity. Growers require approval from the local irrigation management corporation to grow rice on particular fields (Thompson *et al.* 2002) which are deemed suitable using electromagnetic induction soil surveys to assess the permeability of the soil (Beecher *et al.* 2002).

Rice production area in Australia has declined over the past 30 years; the major challenge facing the industry in the future is water availability and the competition from other crops with lower water consumption or higher value. There are limited soils and climates suitable for growing rice in Australia. For the industry to be sustainable, continued varietal improvement particularly for both heat and cold tolerance will be required, together with diversification of rotations and further improvements in water productivity (Thompson *et al.* 2002, Humphreys *et al.* 2006, Bajwa and Chauhan 2017).

Sugarcane

Sugarcane production over the past 30 years has shifted increasingly from a focus on production and practice changes that improve productivity or profitability to practices that reduce its environmental footprint. Prior to this, the combination of monoculture, intensive tillage and burning for harvesting had degraded the soil resource to the extent that the associated yield decline of the 1980s and 1990s threatened the viability of the industry (Garside and Bell 2011).

The continuing yield decline was reversed in recent times using a coordinated approach to address this decline (Bell and Garside 2014). The benefits of legume rotations were demonstrated in the 1990s with yield improvements of 15-25% due to improved soil fertility and structure (Garside and Bell 2011). Industry adoption of green cane harvesting, after about half a century of cane burning, delivered considerable agronomic benefits, including greater soil water retention, improved weed control, reduced erosion, improved soil structure and reduced tillage. As with many other crops, soil compaction due to heavy harvesters became an issue for the industry but was alleviated by controlled traffic farming (Braunack and McGarry 2006).

In the last thirty years, the sugar industry has faced numerous challenges including increased competition from other sugar producing countries, industry deregulation, rising costs of production, pests and diseases, increasing climate variability and cyclonic events, and prolonged periods of falling sugar prices. The industry has also been under increased social pressure regarding its environmental responsibilities (*i.e.* its social licence) due to the close proximity of particular cane growing regions to the GBR (Hamman and Deane 2018). Current strategies and practices are considered unlikely to provide sufficient protection to the GBR (Kroon *et al.* 2016).

Future sustainability of the sugar industry will rely on solutions to minimise sediments, nutrients and pesticides entering the GBR catchment; this has become the primary concern for policy-makers and industry alike (Thorburn and Wilkinson 2013, Hamman and Deane 2018). While the sugar industry faces many of the same challenges agronomically as other broad acre crops, it is an imperative that the industry reduces its environmental footprint to maintain its social licence to farm. Innovative approaches to monitor nitrogen use using remote sensing, and modelling to provide application recommendations are being explored (Thorburn *et al.* 2018, Bramley *et al.* 2019).

Cotton

In comparison with the rest of the world Australian broadacre irrigated cotton systems are characterised as high yielding, high quality and high input systems. For the past 25 years the Australian industry has been growing cultivars that contain transgenic traits, providing significant protection to the industry from insect pests and weeds which in the past had challenged industry viability. Overcoming these pest challenges has enabled the industry to refine its crop management substantially in other parts of the system, embracing new technologies; it is one of the most successful cotton industries worldwide (Constable and Bange 2015). The cotton industry has expanded and is now grown in areas much further south than 30 years ago (Figure 1). Current and future challenges in Australian irrigated cotton systems are presented and the current management principles and new research initiatives are discussed.

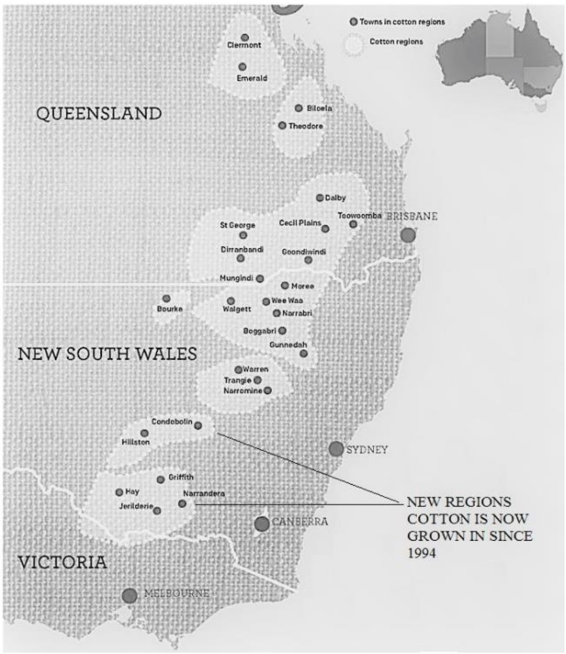

Figure 1. Map of eastern Australia showing cotton growing regions in 2019 (adapted from Cotton Australia 2019)

Historically the most significant challenge to cotton production was yield loss due to a range of insect and mite pests. To control these pests, Australian cropping systems relied on intervention with chemical pesticides, which were a significant component of the cost of production (Fitt and Wilson 2000). In addition, chemical use gave rise to pesticide resistance in key pests, and environmental concerns about pesticide movement off-farm (Fitt 2000, Wilson *et al.* 2004). Circa 1995 transgenic cotton, with *Bacillis thuringiensis* (Bt) genes, was made available to the world's cotton growers. The germplasm containing these genes offered significant potential to reduce pesticide use for the control of major Lepidopteran pests (particularly *Helicoverpa* spp.). However, as the system was changing, pests formerly suppressed by this GM control are emerging as new challenges (Wilson *et al.* 2013).

Agronomic changes were required along with the improved genetics for insect control, as retention of squares (flower buds) and young bolls were higher in these crops in some regions, resulting in a higher and earlier carbohydrate and nitrogen demand by the fruit. Yields can be reduced if management does not meet these internal assimilate demands and, as a consequence, agronomic practice needed to be more precise. Thus, management practices such as planting time (Bange *et al.* 2008), crop nutrition (Rochester and Bange 2016) and irrigation have been re-evaluated (Yeates *et al.* 2010).

Cotton pest management

Cotton growers also employ transgenic cotton that allows over-the-top application of herbicides for weed control, enabling a rapid response to weed infestations. However, this can predispose the system to herbicide resistance if not practised with integrated weed management which includes soil residual herbicides, farm hygiene and tillage. At greatest risk for developing weed resistance is the use of glyphosate in cotton systems (Werth *et al.* 2011). For both insect pest and weed control now and into the foreseeable future, there will be continued reliance on transgenic technologies to assist an integrated pest and weed management program that includes:

- Continued crop improvement to create insect, disease and herbicide tolerant cultivars through both conventional plant breeding and genetic modification; Morphological (*e.g.* leaf hairiness) and biochemical traits (*e.g.* gossypol) are being considered for selection for host plant resistance (Trapero *et al.* 2016).
- Implementation of effective integrated insect, weed and disease management practices that encompass all farm management techniques both 'in-season' and 'off-season' (Wilson *et al.* 2018).
- Effective crop monitoring and use of predictive models to improve timing of pest management interventions. For insect management in cotton there are numerous monitoring techniques to manage specific insects pests within a cropping cycle (Wilson *et al.* 2004), and many are coupled with decision support systems linked to climate (Hearn and Bange 2002).
- Effective industry and on-farm hygiene and bio-security; this has been especially important to curb the spread of Fusarium wilt (*Fusarium oxysporum*), a plant and soil borne disease that reduces cotton yield significantly (Kochman 1995).
- Landscape-scale management involving groups of growers cooperating to reduce communal threats (Hoque *et al.* 2000); this includes consideration of habitat type, and spatial and temporal distribution of habitats to suppress economically important pests (Schellhorn *et al.* 2014).
- Implementation of industry-wide strategies to prevent build-up of weed and insect resistance to pesticides; *e.g.* growers using transgenic cultivars to protect against insects are required to grow a susceptible refuge crop to dilute any potential resistant moth population (Carrière *et al.* 2019).

Water and irrigation management

There have been significant improvements in agronomic water use efficiency in the Australian cotton industry over time. Tennakoon and Milroy (2003) and Roth *et al.* (2013), in their reviews of cotton water use efficiencies, highlighted significant opportunities to improve water use efficiency at all levels (from whole farm to agronomic). Their analyses showed that irrigated cotton farms incurred significant losses through conveyance, storage and application of water, or improper scheduling.

Cotton production in many regions can be rain-fed, partially or fully irrigated. The main irrigation practice is furrow-flood irrigation and practices being developed to improve water use efficiency include:

- Implementing systems that monitor and assess whole farm water use efficiency to identify inefficient parts of the system; growers consistently adopt practices that improve water storage and furrow irrigation efficiencies, and reduce transmission and application losses.
- Use of alternative irrigation systems such as lateral moves, centre pivot, or drip irrigation systems; especially on soils of lighter soil texture. The agronomic crop water use efficiencies of these systems are comparable to furrow irrigation when used on heavier soils, however transmission losses are reduced. Bankless systems, which use gates instead of siphons are used in some regions to reduce the labour needs for irrigation practice. Automated gated systems that monitor water flow down furrows and shut off water at the optimum time can also reduce labour requirements (Uddin *et al.* 2018).
- Better scheduling of irrigation utilising technologies that continuously monitor weather (automatic weather stations), crop soil water use (capacitance probes, neutron moisture meters) and plant stress (canopy temperatures, stem diameter), but allow for differences in soil types, demands of the crop (crop stage) and climatic conditions (*e.g.* temperature and evaporative demand). Most commonly soil water is monitored, with capacitance probes. Some growers also use weather-based systems that provides estimates of current and predicted crop water use from potential evapotranspiration and crop coefficients (IrriSAT, Montgomery *et al.* 2015) Recent research is also demonstrating the value of continuous canopy temperature sensors utilising the Biologically Identified Optimal Temperature Interactive Console (BIOTIC) platform (Upchurch *et al.* 1996). These add extra insights to quantify the level of stress from the plant's perspective. Potential use of the BIOTIC in furrow-flood irrigation systems for cotton is supported by Conaty *et al.* (2012) showing that cotton canopy temperatures exceeding 28°C for 4.45 hours per day can lead to a significant reduction in yield.
- Changes in sowing time to shift periods of maximum water use into periods of lower temperatures or vapour pressure deficits (Braunack *et al.* 2012).
- Using reactive strategies to respond to weather forecasts at both daily and seasonal time steps. Decisions relating to irrigation management can be based on soil moisture storage, seasonal average rainfall, short- and long-term forecasts of weather and climate (rainfall and/or crop evaporative demand) as well as financial and commodity forecasts on a single field or whole farm basis (Power and Cacho 2014). *At the field level*, Brodrick *et al.* (2012) reported opportunities to vary timing of irrigation utilising short term (3 to 4 d) forecasts of evaporative demand. When the soil-water deficit for irrigation is reached and when the forecast for evaporative demand is low, they found irrigation could be delayed without affecting yield or fibre quality. In many instances, it also increased the time for the crop to capture rainfall, reducing the need to deliver irrigation water to the crop. *At the farm level*, water management is improved when water allocations are known well before planting, as this allows for planning cropping areas and level of inputs. This could be improved with improved seasonal forecasts (Ritchie *et al.* 2004).
- Using crop simulation Bange *et al.* (1999) showed that a relationship exists between forecasted wetter seasons and lower yield performance when compared with the average. Currently Nunn *et al.* (2019) are investigating the value of sub-season forecasts for decisions that affect early season crop management. Concurrently it will also be important to access information on business level impacts by downscaling weather and climate predictions to the farm level. Tools and extension networks will be needed to enable farmers to access these climate data, and interpretation provided through a sustainable means of delivery (Brown *et al.* 2019).
- Reducing the risk of crop failure by reducing the area of cotton grown to increase water delivery (ML per ha) from irrigation suppliers before the season begins. Determining the area to plant is a decision that considers crop yield, and therefore the water needed (accounting for climatic risk and system irrigation efficiencies) to break even (Hearn 1992). HydroLOGIC (Richards *et al.* 2008) which incorporates the Australian cotton crop simulation model OZCOT (Hearn

1994) can be used to help plan planting area by comparing yield estimates from simulations with different water allocations and climatic impacts (including rainfall variability). Recent advances in field irrigation management have included the development of a framework 'VARIwise' that develops and simulates site-specific irrigation control strategies for in-field management of water(McCarthy *et al.* 2010). VARIwise divides fields into spatial subunits based on databases for weather, soil, and plant parameters to account better for field variability. The OZCOT model is used to simulate the performance of the control strategies and identify the irrigation application maximises yield or water productivity.

- Improvements in practices to capture and retain soil moisture in crop fallows. Extending the fallow period can allow more stored moisture from rainfall. Reduced tillage and stubble retention are now standard practice for moisture conservation. Where there is flexibility in planting time using rainfall to establish crops, rather than pre-irrigation or 'watering-up' is used.
- Utilising supplemental irrigation strategies or modified row configurations (*e.g.* skip rows) to enhance crop access to soil moisture. These practices are not necessarily the most water use efficient but offer significant risk mitigation in years where rainfall is limited (Montgomery and O'Halloran 2008). In general, the strategy in limited water situations is to keep irrigating until irrigation water runs out and minimising stress where possible during flowering. Skip-row configurations can also offer significant insurance against losses in both yield and quality and can reduce input costs. Current recommendations are to move from a solid configuration to a skip configuration when yield potential of the available budgeted water falls below 2.2 bales/ha in a solid row configuration (Bange *et al.* 2005).
- Irrigation requirements can be reduced by shortening the time to crop maturity. However, this consideration needs to be balanced against a reduced lint yield due to shorter periods of reproductive growth and maturity (Bange and Milroy 2004). Roberts and Constable (2003) and Bange *et al.* (2006) have shown that after cultivar choice, the main factor driving differences in crop maturity is fruit retention. Transgenic cultivars, which can withstand early pest damage from *Lepidopteron* spp. maintain more fruit, can achieve similar yields to non-transgenic cultivars, and use less water by maturing earlier.
- Investigating the use of degradable polymer films as mulches to conserve water in both rain-fed and irrigated cotton systems, such as those described in Braunack *et al.* (2015). Thin plastic films have been used to increase soil temperature, conserve soil water and to improve crop establishment for cotton. Plastic film mulch is not ideal as itdoes not degrade and ends up as land-fill. However there are new formulations which degrade to water and carbon dioxide (oxodegradable films). It may also be possible to harvest and concentrate rain water from the film covered areas although consideration would need to be given to field layout for runoff and erosion potential due to slope.
- Reducing yield losses caused by risk of waterlogging through appropriate field design to ensure adequate drainage and runoff, by growing cotton on well-formed hills, and by avoiding irrigation before significant rainfall events using weather forecasts. Yield reductions may be avoided by the application of nitrogen and iron foliar fertilisers prior to waterlogging may (Hodgson and Macleod 1987). Application of the growth regulator amnoethoxyvinylglycine (AVG) prior to waterlogging may have beneficial effects by maintaining photosynthesis, improving node production and reducing fruit abscission (Najeeb *et al.* 2015).
- Choosing a cultivar with inherently longer fibre length can help avoid economic fibre discounts in situations where there is chance of stress around flowering and concern that fibre quality could be severely impaired.

Soil management, including crop rotations and cover crops

Tillage Tillage remains an important practice in irrigated cotton systems for stubble management, and for managing pest (weed and insect) resistance. In the last 30 years there has a move away from burning cotton stubble to incorporation of mulched stubble in the surface soil. Stubble is generally incorporated at the time when the soil is tilled to reduce the number of over-wintering *Helicoverpa spp*. pupae. This practice, 'pupae busting', is a mandatory requirement of utilising transgenic cultivars with insect pest resistance. Therefore, unlike other broadacre cropping systems there is generally no irrigated cotton system that relies on a ‘single pass’ tillage operation. A reduction in tillage operations has led to increased crop yields (Hulugalle *et al.* 2005) although it is generally accepted that cover crops or rotations with high residue crops have better potential to increase the productivity of cotton systems.

Rotation The use of wheat and maize in rotation with cotton were shown to raise cotton yields due to improvements in soil physical structure (Hulugalle *et al.* 2007) and reductions in disease but only influenced soil organic C concentrations of the surface soil (Hulugalle *et al.* 2013). Crop rotation sequences with legumes on a different soil type with less sodicity, had higher levels of C in both the top and sub-soil and were associated with higher cotton yields (Rochester and Bange 2016). Rochester (2011b) demonstrated that soil C could be maintained over time with different crop sequences with some minimal incorporation of crop residues associated with crops producing large amounts of biomass in both the cotton and rotation phases.

Soil fertility Cotton production relies on a high levels of nutrition (especially N) to maximise yield. Monitoring soil fertility and crop nutrient uptake are important because growers realise the importance of avoiding nutrient deficiency, and the expense and environmental concerns (including greenhouse gas emissions) associated with excess fertiliser use. Excess N fertiliser can also reduce water use efficiency or yield by encouraging excessive vegetative growth and delayed maturity. Decision support systems (Rochester *et al.* 2001) are used by growers to determine the appropriate rates for N fertiliser use and the need for other nutrients, based on crop stage (utilising climate information) and performance. Current estimates of N requirements of high yielding crops in Australia are in the range of 240-270 kg N/ha crop uptake (Rochester and Constable 2015). A survey of Australian cotton fields by Rochester (2011a) and Macdonald *et al.* (2018) highlighted that a significant proportion of growers had low N use efficiency (kg lint/kg N uptake) because of excessive N fertiliser application increasing the chances of N being lost from the system and contributing to greenhouse gases.

One approach for crop N nutrition is to supplement or even replace entirely the use of artificial N fertiliser with nitrogen fixed by legumes which also improve soil structure. Cotton crops can be grown with N able to supply high yielding provided entirely by legumes (Rochester and Bange 2016), with vetch (*Vicia villo*) and fababean especially crops.

Crop husbandry

Cultivar choice Cultivar choice is a strong component of realising both target yield and fibre quality levels on farm. At a whole farm level, a key strategy is to select cultivars that have different adaptive traits to spread risk to variable climate and accommodate changes in management. Consideration should be given to cultivars that minimise impacts of water stress, disease (*e.g.* fusarium wilt), or crop maturity when season length is ill-defined.

Yeates *et al*. (2010) found that more early vegetative growth was necessary to support high yielding irrigated cotton systems in transgenic cotton cultivars with high and early fruit loads. In a recent analysis, Constable and Bange (2015) reaffirmed the need to have continued vegetative growth during early boll set, to allow crops to mature later to achieve higher yields. They suggested using a management strategy that regulated vegetative and reproductive growth using water, fertiliser, and growth regulators.

Planting Time Research by Bange *et al*. (2008) in Australia showed that crops with higher fruit retention (such as those generated with transgenic cultivars) can maintain yield and improve fibre length and micronaire for delayed planting dates in warmer and longer seasons. In these studies, yield was maintained for plantings up to 20 d later than the normal planting date, as early growth was more rapid when crops were planted into warmer temperatures. The improved fibre quality (length and micronaire) was associated with the cooler conditions during the early boll filling stages of the crops. Planting crops into warmer conditions also had the benefit of avoiding low temperatures at emergence, which can reduce cotton seedling vigour and lead to poor establishment, poor early growth, and increase the risk of seedling diseases. Braunack *et al*. (2012) also showed that, in longer season cotton growing regions in Australia, water use efficiency could be improved with later planting.

Plant growth regulators (PGRs) Plant growth regulators are commonly used in cotton production systems to control and manipulate growth, which is mainly regulated by endogenous plant hormones. PGRs are an important management tool to ensure optimal and sustainable yields.

While maintaining vigorous vegetative growth before flowering is important to support reproductive growth, there are some situations where vegetative growth can be excessive and reduce light and air circulation in the canopy. This can then increase physiological shedding of fruit and sometimes reduce yield. The main plant growth regulator used to restrict vegetative growth in Australia during the season is Mepiquat Chloride (an anti-gibberellin, Williams *et al.* 2018). Later in the season Mepiquat Chloride is also credited for a range of responses including inducing cut-out, achieving earliness, reducing attractiveness to late season pests and improving crop uniformity.

Strategies to improving Australian cotton production and sustainability

Key approaches to increase yields and fibre quality, and improve resource use efficiencies, are:

- to develop, refine and apply new technologies (*e.g*. precision agriculture, cultivars with both yield and fibre quality improvements, novel plant growth regulators);
- improve agronomic practices (*e.g*. sowing time, plant population, crop nutrition); and
- implement management systems (*e.g*. integrated pest, disease and weed management) that enable cotton to grow healthier or be more tolerant of both abiotic and biotic stresses.

To achieve this, detailed integrative systems research (see Chapter 23) over a greater range of environments and stresses are needed to assess impacts and adaptation options for yield and quality improvements. In a recent review by Hatfield and Walthall (2015), an emphasis was placed on leveraging opportunities by adopting a Genetic x Environment x Management (G x E x M) interaction as a foundational approach to meet global agriculture needs and realising potential of cropping systems in current and future climates. There are few studies in cotton that have demonstrated the value of G x E x M to improve cotton productivity, although analyses by Liu *et al.* (2013), using their advanced line trials containing cultivars grown over a 30-year period from 1982 to 2009, demonstrated that yield gain in the Australian cotton industry resulted from improvement in cultivars (G; 50% improvement), in crop management (M; 26% improvement), and from the interaction between improved cultivars and improved management (G x M; 24% improvement). This approach, termed incremental transformation by Kirkegaard (2019) and 'Transformational Agronomy' by Hunt and co-authors (Chapter 23) has essentially underpinned cotton research in the past, but will certainly be needed to continue to meet the challenges for cotton production in the future. The challenge remains on how to exploit the G x E x M interaction in research and commercial production to deliver the benefits of improved yield and quality to cotton growers. Noting these challenges and opportunities, we consider below aspects of Australian cotton production relevant to an enduring profitable and sustainable cotton industry.

Climate change

There is no doubt that one of the most significant challenges facing irrigated industries is climate change. It is a multifaceted and complex challenge for industries and it will affect the sustainability of farms, ecosystems and the wider community. The impacts of climate change on modern cotton systems has been extensively reviewed by Bange *et al.* (2016). Fortunately, many potential adaptation responses available have immediate production efficiency benefits making them attractive options regardless of the rate and nature of future climate change.

Genetic improvement

For Australian cotton breeders, delivering high yielding cultivars to cotton growers is essential to maintain economic viability. Along with traditional approaches to breeding, future breeding efforts will need to rely on both improved genotyping and phenotyping approaches for trait selection (see Chapter 17). Opportunities to improve yield remain possible (Constable and Bange (2015). Options for longer season and more indeterminate growth habit are required with relatively slow crop setting, but with greater final fruit numbers. A challenge for molecular biology is to increase photosynthetic capacity and translate this into improved canopy radiation use efficiency (RUE) (Wu *et al.* 2016). Such research is still in its infancy and there are many obstacles to overcome, but there may be long-term benefits in increasing rates of photosynthesis. When resources are not limited, it was determined that nutrient uptake and distribution would limit potential yield. Therefore, research in crop management is also required to understand improved nutrient use efficiency through better nutrient uptake and better redistribution to fruit.

Specific tolerances for heat (Constable *et al.* 2001, Cottee *et al.* 2010) and water stress in rain-fed environments (Stiller *et al.* 2005) have been recorded despite no specific selection pressure on these stresses. Recently, genetic variability of transpiration rates to vapour pressure deficits (VPD) has been found in cotton genotypes (Devi and Reddy 2018). Selecting for genotypes that have limited transpiration rates at high VPD could conserve water in the soil.

Current research efforts are attempting to break the negative association between yield and fibre quality in cotton using early generation selection strategies that employ a yarn quality index to integrate the fibre properties of length, strength and fineness together with yield (Clement *et al.* 2015).

Genetic engineering may assist to improve quality or generating novel fibre traits (*e.g.* elongation and moisture absorption). There are also opportunities to improve the value of cotton as a food and fibre crop by improving the quality of cotton seed oil by removing toxic gossypol (Palle *et al.* 2013) and altering the fatty acid composition (Liu *et al.* 2002).

Soil management

It is now widely recognised that microbial processes play central role in the nutrient cycling and hence are key determinants of nutrient availability and nitrogen use efficiency in arable fields (see Chapter 15). However, understanding mechanisms and magnitude of nutrient cycling response in Australian cotton production is an emerging area of research.

Cover crops can also be grown to reduce long fallow periods in a cropping cycle specifically to protect the soil from erosion and reduce nutrient loss through erosion or leaching. Incorporating cover crops as part of cotton rotations are difficult in highly capitalised, mechanised systems (Rochester and Peoples 2005). A better understanding is needed of soil and cotton yield improvements; water requirements and cost of cover crops; and the impact on nutrition uptake by cotton crops

An emerging concern related to modern Australian cotton production systems is soil compaction, caused by machine cotton pickers that have on-board module-building capabilities. These pickers have the potential to increase compaction in the sub-soil limiting efficiencies in both water and nutrition (Braunack and Johnston 2014). Growers using these pickers will need to consider strategies to: ameliorate compaction using crop rotations that dry the soil profile; further implement controlled traffic systems; and seek to reduce moisture in the profile at picking. A review of compaction issues in cotton systems by Antille *et al.* (2016) noted the need for machinery manufactures to customise their systems to allow a fully controlled traffic system to be employed.

Crop management

Strategies to mitigate damage incurred when encountering episodes of extreme environmental stress (through tolerance or avoidance) will need to be developed, building adaptive capacity and resilience. While formulating these strategies, they must take into account all aspects of the production system from planting through to harvest (and potentially post-harvest) and consider all the possible tools available (precision technologies and new genetics, for example).

To help build resilient and productive systems a knowledge of yield potential or ‘yield gap’ in different cotton systems across regions will be important. This will identify the major limiting factors in systems and provide insights into overcoming them. Importantly these limitations will require reassessment with future climate change predictions so that changes to the systems are not short-lived or maladaptive in the future. In many cases, the reduction in the ‘yield gap’ between farm averages and yield potential will be achieved more likely by removing yield constraints of the poorest fields and systems (Constable and Bange 2015). For rain-fed wheat systems, Hochman *et al.* (2012) measured farmers yield and compared that with the regional yields predicted using simulation models of an adapted crop without limitations, but under water-limited conditions. They also assessed yield potential using crop competition results. For irrigated crop comparisons, it will be important that knowledge of the amount of water available for irrigation across farms is considered specifically because it can vary considerably, thereby strongly affecting yield and fibre quality.

One of the most significant challenges for cotton management into the future will be diminished access to water through reductions in sources of irrigation (surface or groundwater), less rainfall or increases in evapotranspiration through temperature increases. Much existing research has been undertaken in well-watered conditions, and much less research has considered the implications of cotton growth, yield and fibre quality with less water availability. Australian cotton systems will require closer examination of the response to various water deficits and drought recovery cycles. These effects will also need to be considered in light of other management options suggested in this chapter that relate to water use: the development of cotton systems that are earlier maturing, that use less water and allow more crops to be grown in rotation; and improved management options in limited water situations utilising changes in planting time, alternative irrigation systems, row configurations, irrigation scheduling strategies, all with the intent to maximise yield, water use efficiency and fibre quality.

Given the importance of high fibre quality to maintain Australian cotton‘s share in the international marketplace it is imperative that the industry retains its focus on fully realising the benefits of improving fibre quality. The task for cotton growers/advisers and the industry is to optimise fibre quality in all steps from strategic farm plans, cultivar choice, crop management, harvesting and ginning. Bange *et al.* (2018) have termed this ‘Integrated Fibre Management’ to emphasise the importance of a balanced approach to managing fibre quality, to be analogous with approaches such as Integrated Pest Management**)**.

Policy and industry considerations

Sustainability of the Australian cotton industry will need adaptation approaches that also reflect changing social, political, and economic drivers at scales that move from the field, to the farm, across varied agriculture industries, and with national and international influences. As an example, there is a need to invest in field-based research on production, but concurrently research is needed that assists in government policy setting. Without these types of considerations, the marginal return on investment into adaptation options can be severely diminished. Key considerations that capture some of these issues from an Australian cotton production perspective include:

- An assessment of the likely impacts of changes in worldwide cotton production. Understanding these impacts is necessary for ensuring the cotton supply chain to maintain market share security against synthetic textile production. Strengthening information-sharing networks on impacts and adaptations to change will be vital in this process.
- Identifying opportunities for the expansion of cotton production in existing and new agricultural production regions (*e.g*. southern and northern Australia). Region-specific impacts will be needed so that cotton growers have the capacity to assess likely impacts into their business.
- Identifying competition and synergies for use of resources (*e.g*. land, water, labour) with other agriculture enterprises.
- Integrating production research outcomes that are optimal in delivering sustainable cotton systems in light of triple bottom line (environmental, economic, and social) concerns.
- Development of multi-peril crop insurance schemes to assist growers deal with extreme climate events.

Conclusion

High-input irrigated crops face many of the same future challenges as other broad acre crops. A combined integrated approach to solve these production challenges across commodities will accelerate Australian agriculture's ability to adapt and sustain production in the future. For irrigated crops, future water availability and irrigation management capabilities play a major role in enabling producers to maintain economically viable operations in variable climates. However, water use for irrigation will continue to compete with industrial and municipal use due to dwindling ground and surface water supplies in many areas. Policy makers will need to decide how this limited resource will be best divided amongst the various stake holders: a major challenge in light of future climate change predictions. Current and future crop management practices will continue to evolve from those, which were developed assuming reasonable access to water, to those that need to operate under constrained water availability.

To meet these challenges there will be a greater need to incorporate other aspects of production efficiencies into the analysis of modern irrigated cropping systems (*e.g.* fuel/energy use or carbon emissions per unit of lint produced) in addition to existing production use efficiencies (*e.g.* water and N). 'Trade-offs' will be needed to minimise economic, social and environmental harm, while maximising new opportunities. One example that highlights this tension is the need for continued improvement in water use efficiency – this has led to demand for more sophisticated irrigation systems that are likely more energy intensive. Importantly to assist in making valid and fair comparisons within the irrigated production system and beyond (*e.g.* with other cropping systems or industries), it will be necessary to present these efficiencies on an economic basis (*e.g.* $ generated/ML, unit of GHG emitted, kg N applied). A better understanding of the integrated effects (higher atmospheric [$C0_2$], increased temperatures and atmospheric vapour pressure deficits) of future climate on the physiology, growth and management of crops, including future water use is required.

Ultimately, sustainable and low environmental impact irrigated cropping systems (whether it be sugar, rice or cotton) are required to maintain the 'licence to farm'. Research into the development of new technology and tools that integrate knowledge at many scales, whilst understanding the linkages of on-farm production with the off-farm impacts, will be needed to harness opportunities reliably for ongoing investment in these industries.

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