CSIRO PUBLISHING

Crop & Pasture Science, 2013, **64**, 1033–1048
http://dx.doi.org/10.1071/CP13315

Review

Water-use efficiency and productivity trends in Australian irrigated cotton: a review

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Abstract. The aim of this review is to report changes in irrigated cotton water use from research projects and on-farm practice-change programs in Australia, in relation to both plant-based and irrigation engineering disciplines.

At least 80% of the Australian cotton-growing area is irrigated using gravity surface-irrigation systems. This review found that, over 23 years, cotton crops utilise 6–7 ML/ha of irrigation water, depending on the amount of seasonal rain received. The seasonal evapotranspiration of surface-irrigated crops averaged 729 mm over this period. Over the past decade, water-use productivity by Australian cotton growers has improved by 40%. This has been achieved by both yield increases and more efficient water-management systems. The whole-farm irrigation efficiency index improved from 57% to 70%, and the crop water use index is >3 kg/mm.ha, high by international standards. Yield increases over the last decade can be attributed to plant-breeding advances, the adoption of genetically modified varieties, and improved crop management. Also, there has been increased use of irrigation scheduling tools and furrow-irrigation system optimisation evaluations. This has reduced in-field deep-drainage losses. The largest loss component of the farm water balance on cotton farms is evaporation from on-farm water storages.

Some farmers are changing to alternative systems such as centre pivots and lateral-move machines, and increasing numbers of these alternatives are expected. These systems can achieve considerable labour and water savings, but have significantly higher energy costs associated with water pumping and machine operation. The optimisation of interactions between water, soils, labour, carbon emissions and energy efficiency requires more research and on-farm evaluations. Standardisation of water-use efficiency measures and improved water measurement techniques for surface irrigation are important research outcomes to enable valid irrigation benchmarks to be established and compared. Water-use performance is highly variable between cotton farmers and farming fields and across regions. Therefore, site-specific measurement is important. The range in the presented datasets indicates potential for further improvement in water-use efficiency and productivity on Australian cotton farms.

Additional keywords: cotton, efficiency, irrigation, water, yield.

Received 6 September 2013, accepted 5 December 2013, published online 18 December 2013

Introduction

Water is critical to the cotton industry to maximise crop yields and fibre quality. In most Australian cotton-growing regions, crop water demand exceeds the rainfall supply. Although dryland crops are successful in some regions and some seasons, irrigation enables high-yielding cotton to be grown in a wider range of regions. Uncertainty about the availability of irrigation water is widely accepted as the most limiting factor in Australian cotton-production systems. Increasingly, water is becoming scarce due to the rising demand of alternatives uses such as the demand from other crops, mining, urban communities, and environmental flows, as well as climate change. Therefore, farmers must continue to strive to improve water-use efficiency and productivity. Increasing water scarcity led to the Cotton Catchment Communities Cooperative Research Centre (Cotton CRC) goal of producing more cotton per unit of water used. The Cotton CRC research focussed on promoting measurement of water-use efficiency, optimising the performance of surface-irrigation systems, evaluating alternative irrigation systems to the conventional furrow-irrigation systems, understanding soil-water dynamics and deep drainage, reducing water losses from on-farm storages, and developing a better understanding of soil–water–plant relationships.

During the last decade, many Government- and industry-funded agricultural research and extension initiatives have been specifically aimed at improving water-use efficiency on cotton farms. These initiatives include the Queensland Rural Water Use Efficiency Programs, NSW Waterwise on the Farm, Commonwealth Government Rural Water Use Efficiency Fund, Cotton Research and Development Corporation Irrigated Cotton and Grains projects, and programs from several regional natural resource management bodies such as Namoi Catchment Management Authority and Condamine Alliance.

A body research from specific water projects has been published in the scientific literature on various aspects of cotton agronomy, physiology and plant–water relations. An analysis of the Cotton Catchment Communities CRC (2012) Final Report shows that publication on irrigation research made up 7% of its total peer-reviewed scientific journal publications, while 31% of the publications in industry magazines were articles on irrigation extension. This publication metric provides some insight into the large scale of the extension projects aimed at changing irrigation practices on farms.

The aim of this paper is to report changes and trends in cotton water-use efficiency and productivity from both the scientific literature and the unpublished reports from these extension programs. This paper also aims to bring together both the plant-based and irrigation-engineering research and development for irrigated cotton in Australia.

Australian cotton production and management of irrigation water

Market research with cotton growers found that the key issues affecting their water-management decisions were availability, continued security, cost of water, economic returns per megalitre (ML), water quality and water scheduling (Callen *et al.* 2004). Other important issues that have arisen since that research include rising energy costs for pumping, labour shortages for irrigating, and uncertainty associated with the reforms of Government policy on irrigation allocations.

Cotton is mostly grown in the 400–800 mm summer rainfall zone, which means that cotton crops can receive significant amounts of their water needs from rain during the growing season. The cracking clay soils where cotton is mostly grown can store up to 150–178 mm of plant-available water in a 130-cm profile (Cull *et al.* 1981*a*; McKenzie 1998), especially following a wet winter prior to cotton planting. Likewise, the highly variable climate can lead to droughts and flooding rains, and both extremes have been experienced in the last decade.

For the last 10 years, dryland production has, on average, made up 17% of the total planted cotton area and contributes 8% of the total cotton crop production in Australia. The area of rain-grown or dryland cotton fluctuates considerably in response to rainfall, seasonal conditions, and prices of agricultural commodities. During the last decade, the dryland cropped area ranged from 7370 to 206 250 ha, with the average yields ranging from 1.87 to 5.76 bales/ha (1 bale = 227 kg).

For the last 10 years, on average, 83% of the Australian cotton crop was irrigated and produced 92% of the national crop, with an average yield of 9.59 bales/ha. Up to 400 000 ha of irrigated cotton is grown in Australia, depending on water availability. Australian irrigated lint yields per unit area are now the highest of any major cotton-producing country in the world, being ~2.5 times the world average. Yields have continued to increase from 1200 kg/ha in the 1970s, through 1400 kg/ha in the 1980s to 1600 kg/ha in the 1990s, and are now usually >2270 kg/ha (10 bales/ha). Most of this yield gain is attributed to plant breeding and exploiting genetic variation and genotype response to modern management (Liu *et al.* 2013). Those authors found that the yield gain in a 30-year evaluation of cotton-breeding trials was attributed to gains in cultivars, i.e. genetics (48%), management (28%) and cultivar × management (24%) interaction.

In addition to their influence on yield, water and irrigation can have a significant impact on cotton fibre quality (Hearn 1976; Hearn and Constable 1984*a*; Hearn 1994). Water stress during the first third of boll-filling reduces fibre length when fibres are elongating, whereas water stress during the last two-thirds of boll filling reduces fibre maturity and thickening (Bange *et al.* 2009). In response to a survey, growers recognised irrigation timing and variety choice as the most critical management tools for fibre quality (Roth 2011).

Farmers grow cotton because they believe it is the most profitable crop for them per unit area of land and water used. The gross margin of cotton in 2012 was AU$1192/ha (Boyce Chartered Accountants 2013). Returns for corn, wheat and sorghum were considerably less. The International Cotton Advisory Committee (2010) provides a report on irrigation costs for most countries in the world. Australian irrigation costs are amongst the highest in the world. Irrigation costs represent 3–11% of total costs for most countries and were reported as 8% in Australia, compared with the USA, for example, at 3%.

At least 80% of Australia's cotton-growing area is irrigated using gravity surface-irrigation systems. Hence, the focus of this review is on surface-irrigation systems. However, there is increasing use of the centre-pivot and lateral-move irrigation machine systems, up from 10% in 2008 to ~17% in 2013 (9% lateral move and 8% centre pivots). About 3% is irrigated with pressurised, subsurface drip-irrigation systems. Anecdotally, there has been little additional drip-irrigation capacity added in recent years but the area under centre pivots and lateral-move systems has increased considerably.

Plant physiology and agronomy research on irrigated cotton

Many studies have investigated cotton plant–water relations, agronomic variables, water use, and yield and fibre quality relationships. Comprehensive discussions on the physiology of cotton plant–water relations can be found in Hearn (1979), Jordon (1981), Hearn and Constable (1984*a*), Turner *et al.* (1986), and Hearn (1994).

Research in the 1970s examined irrigation-scheduling regimes using water-balance models and soil-moisture monitoring to develop an understanding of seasonal irrigation requirements, and also established crop factor relationships between evapotranspiration and leaf area index (Cull *et al.* 1981*a*, 1981*b*). During that time, those authors recorded actual farm water-use efficiencies of 30–50% in the Namoi Valley and concluded that there was scope to improve. These projects led to the introduction of neutron probes to measure soil moisture for irrigation scheduling.

Other studies in a similar time-frame looked at irrigation strategies (Hearn and Constable 1984*b*), while Constable and Hearn (1981) examined the effect of irrigating at various water deficits at different times in the growing season. The best irrigation strategy varied from year to year due to variable rainfall patterns. The plant growth stages sensitive to water and nitrogen stress and stress interactions throughout the season were identified, including their impact on plant growth, yield and quality. Turner *et al.* (1986) investigated physiological and morphological responses to water stress using a rainout shelter and different irrigation treatments. They concluded that soil-water deficits reduced the capacity of the crop to carry fruit as a result of lower leaf photosynthesis.

Management of limited water scenarios during drought was reviewed by Hearn (1995). In this review 5–6 ML/ha was considered the optimum use, depending on location and irrigation water allocation prior to planting. This finding was supported in a recent review by Quinn *et al.* (2013). Tennakoon and Hulugalle (2006) studied effects of rotations and tillage practices on water-use efficiency and found that crop rotation with wheat and minimum tillage improved water-use efficiency in some years on the Vertosol soils of north-western New South Wales. They also found average seasonal evapotranspiration was higher with minimum tillage than conventional tillage systems and that plant-available water in minimum-tilled cotton was increased by 18 mm over that of conventionally tilled cotton. Hulugalle and Scott (2008) reviewed research that has examined rotations with irrigated cotton crops, including outcomes related to soil-water management. Soil properties in irrigation furrows on Vertosol soils were investigated by Hulugalle *et al.* (2007).

Partial root-zone drying is an irrigation strategy that involves the alternate drying and wetting of subsections of the plant root-zone. The application of partial root-zone drying irrigation strategies was investigated during 2002–05, and no significant difference in crop growth or yield was found in commercial field conditions. More effective water-use efficiency benefits were found with regulated-deficit irrigation strategies at ~80% of evapotranspiration using centre-pivot or lateral-move irrigation systems, and the increased ability for capture of in-crop rainfall (White 2007; White and Raine 2009). Those authors argued that deficit and regulated-deficit irrigation strategies were already inadvertently applied within some parts of the Australian cotton industry, as many of the centre-pivot and lateral-move systems had inadequate capacity to meet peak irrigation water requirements.

Before 2006, cotton irrigation research in Australia was conducted using conventional varieties that had lower fruit retention, were subjected to frequent insect attack, and often incorporated a period of water stress until squaring. Paytas (2009) demonstrated, using rainout shelters and plastic inter-row covers, the importance of maintaining adequate soil moisture during early growth phases of high-fruit-retention Bt cotton (Bollgard II™) crops. Leaf area index, vegetative and reproductive biomass, and numbers of squares, flowers and fruits were found to increase in well-watered treatments. Modest water deficits pre-flowering were found to reduce fruit retention, yield and lint quality (Paytas *et al.* 2008).

The widespread adoption of transgenic varieties by Australian cotton growers meant that it was important to investigate how these varieties respond to water stress and irrigation strategies. Yeates *et al.* (2010) measured the effect of this increased insect protection on morphology, growth and response to water using Bollgard II™ and non-Bt cultivars with the same genetic background. Scheduling experiments showed that irrigation at smaller deficits than commonly used for cotton increased Bollgard II™ yield by 17% and water-use efficiency by 8%. In addition, for Bollgard II™ crops, the importance of avoiding stress in late flowering was demonstrated, as the yield loss per day of stress was double that of conventional varieties at the same growth stage. More rapid accumulation of boll dry weight due to higher fruit retention and changed morphology (smaller plant without main-stem tipping by insects) was shown to increase crop sensitivity to short-term reductions in photosynthesis. Yeates *et al.* (2010) also found that when insect damage occurred in conventional varieties, Bollgard II™ varieties matured earlier and used ~10% less water. Where there was no insect damage there was little difference in yield and water use between conventional and transgenic varieties due to little difference in morphology between the two varieties (similar development of leaf area and boll load).

Neilson (2006) completed experiments to establish the response of cotton plants to soil-water stress under different soil types, climatic conditions and fruiting loads. That research was built on by Brodrick *et al.* (2012), who are investigating irrigation strategies using dynamic deficits, i.e. refining irrigation scheduling by dynamically changing soil-water deficits during periods of high and low evaporative demand. Their study has highlighted the need for a definitive measure of plant stress.

There have been a few studies on plant-based sensors for irrigation scheduling in Australia. Pressure chambers, also known as pressure bombs, were used by farmers in the 1970s and 1980s, and water stress thresholds were established (Browne 1986). Ground and airborne canopy spectral reflectance remote-sensing techniques found that near infrared wavelengths could detect plant moisture stress, but found the thermal canopy temperatures were most successful for monitoring crop moisture status (Roth 1991, 2002). More recent studies examined the use of canopy temperatures from peak flowering to maturity and found reductions in lint yield at temperatures >28−29°C, and explored a stress-time concept around these temperatures (Conaty 2010; Conaty *et al*. 2012).

Hyper-spectral radiometer sensors were evaluated to predict leaf water potential, but it was concluded that a lower cost sensor was needed (Robson 2010). A machine-vision system was developed to measure internode length of cotton, and had the capability to map internode length across a field, from which spatial trends in plant water stress maybe inferred (McCarthy *et al.* 2010). In summary, these sensors are effective at monitoring the water status of a crop in research trials, but they have not proven practical to schedule irrigations in a commercial operation. This is largely due to a high frequency of cloud cover, changes to solar radiation levels, variability in ambient air temperatures, and technology costs.

Irrigation scheduling strategies and optimisation for cotton growth and development have been summarised by Brodrick *et al.* (2013) and Gibb *et al.* (2013). The Australian cotton industry is one of the most advanced agricultural industries in terms of its use of irrigation-scheduling tools. The cotton industry had the highest use of soil moisture monitoring probes of any agricultural industry in Australia (~40%), compared with irrigated pastures at <5% (Montagu *et al.* 2006; ABS 2006; CCA 2007). In 2011, a survey of cotton growers found that 57% of growers used soil moisture capacitance probes and 22% used neutron soil moisture probes for irrigation scheduling (Roth 2011). Greve *et al.* (2011) investigated a 3D resistivity tomography moisture probe as a possible new irrigation-scheduling technology.

Cotton is known to be poorly adapted to excess water and waterlogging conditions. Waterlogging of cotton crops by inappropriate irrigation and/or excess rain has been identified as a major source of yield reduction (Hodgson 1982; Hodgson and Chan 1982; Hearn and Constable 1984*b*; Bange *et al.* 2004; Conaty *et al.* 2008; Milroy *et al.* 2009). These studies have explored opportunities to reduce the impact of waterlogging, such as the use of AVG ethylene inhibitor, correction of nitrogen, iron and other nutrient ion concentrations, hydrogen peroxide, plant genetics, and irrigation systems and designs.

Hornbuckle and Soppe (2012) investigated the use of weather-based irrigation water management and crop benchmarking using satellite imagery and the normalised difference vegetation index (NDVI) index to better determine site-specific crop coefficients as a means to more accurately calculate crop water use for individual fields. This system, known as IrriSAT, was trialled for the first time in the Australian cotton industry in 2010. Although developed primarily as an irrigation-scheduling tool, it is finding more potential for growers to benchmark their water-management performance between fields and across regions. Initial results showed wide variation in water-use productivity between fields, growers and regions.

Water-use efficiency and productivity measures

Water-use efficiency is a concept that has caused much confusion for scientists, extension officers and farmers due to the ambiguity of definitions and spatial and temporal differences of comparisons. Much of this confusion is due to the range of terms available to describe water-use efficiency and the difficulty and uncertainties in measuring aspects of the farm water balance, especially in surface-irrigated fields. Adding to the complexity are different irrigation systems such as centre pivots, lateral-move machines and drip irrigation, as well as different agronomic considerations such as row spacing, pests, disease, soil types, water logging, and extreme temperatures.

An important part of improving water-use efficiency is the ability to measure different components of hydrology pathways in the farm. Most cotton growers measure their water use and calculate water-use efficiency. In response to surveys in 2005–06 (CCA 2007) asking growers whether they measured water-use efficiency, 60% answered that they did. In a survey conducted the following year, this response was 76% (WRI 2007). However, in these surveys growers stated that they found measurement of water-use efficiency a difficult task, which is why considerable emphasis was placed on measurement tools and training as part of the Cotton CRC activities.

Generally, farmers refer to the amount of cotton produced per unit of irrigation water used as bales (227 kg of lint) per ML of water. When comparing crop water-use values from cotton growers, it is critical to check whether the numbers include or exclude rainfall. Summer rainfall is an important source of water during the crop growing season.

Water-use efficiency is itself a label that encompasses an array of performance indicators used to describe water use within a cropping system. In order to achieve consistency of measurement of water-use efficiency, the cotton industry adopted standard measurements developed by Barrett, Purcell and Associates (1999), who explained that many of these terms are not defined as efficiencies but instead are indices. These are listed below, and a detailed discussion of water-use efficiency terms and calculations can also be found in Fairweather *et al.* (2003) and Montgomery *et al.* (2013).

- Gross production water use index (GPWUI): the gross amount of lint produced per unit volume of total water input. The total water input includes irrigation, rainfall, and total soil moisture used. The rainfall component can be either total rainfall or effective rainfall, and consequently must be defined. Effective rainfall is the more typical and useful term; however, there is still some uncertainty as to how effective rainfall is calculated. The index can be applied at either a field- or farm-scale, and in Australia is usually discussed in bales (227 kg) of cotton lint per ML of total water used. The GPWUI is the most useful indicator for long-term comparisons of industry performance and for comparisons between seasons, regions and farms, as it accounts for climatic rainfall variability between seasons and all sources of water.
- Irrigation water use index (IWUI): similar to the GPWUI, but relates cotton production only to the amount of irrigation water used. It relates the lint produced per ML of irrigation water applied to a field or supplied to a farm. It is commonly used to compare fields on one farm, since it only accounts for irrigation water and can therefore reflect differences in irrigation management. It is less useful for comparing different farms and regions, as there is no accounting for differences in rainfall, which can obviously affect the amount of irrigation water required.
- Crop water use index (CWUI): the amount of lint produced (kg) per mm of actual crop water use (evapotranspiration) from a field during the cotton growing season. This index indicates the ability of the crop to produce cotton lint for the given water use.
- Whole farm irrigation efficiency (WFIE): the amount of irrigation water available and used by crops on the farm (for evapotranspiration) as a percentage of total irrigation water inputs to the farm. It is a measure of system efficiency and water losses as a percentage.

Water-use productivity trends from national statistics

One way to assess the trend in cotton water use is to examine nationally collected statistics. The irrigated cotton production data for each region in Australia can be obtained from a range of sources, such as Cotton Australia, who supplied the data used in this paper. The amount of irrigation water used in each valley can be obtained from the Australian Bureau of Statistics Water Accounts. From these data it is therefore possible to calculate the IWUI at a national level.

The IWUI is a coarse measure of the water productivity achieved by the cotton industry during the past decade, which can vary from year to year depending on the amount of rainfall received. It should always be considered in context with other water-use efficiency indices that have been measured at the individual farm and field level.

Figure 1 shows the trend in Australian national cotton production between 2001 and 2012. During this decade, the cotton industry experienced extreme climatic variability in droughts and flooding rains. The 2001 crop was a record production crop at the time. The 'Millennium drought' from 2003 to 2010 reduced the availability of water for irrigation and resulted in significantly reduced production levels that reached a record low in 2008. Since 2008, production rose to record highs in 2011 and 2012 (4.5 million bales) as a result of drought-breaking rains. Although every year is different, in 2011–12, the Australian Bureau of Statistics recorded 828 businesses irrigating cotton on 397 221 ha, using 2 068 908 ML of irrigation water, at an average rate of 5.2 ML/ha (ABS 2012). Preliminary data for the 2012–13 season for irrigated cotton estimate 4.4 million bales, with an average yield of 10.8 bales/ha (The Australian Cottongrower 2013).

Figure 2 shows that the lint yield per hectare of cotton has been increasing, while at the same time the average total amount of irrigation water applied has decreased. Some of the variability in trends is related to climatic variability. Drought-affected years included 2003, 2004, 2007 and 2008; see, for example, the lower yields in 2003. By comparison, 2010, 2011 and 2012 were wet years and there was significant flood damage, in particular in 2010 and 2011, which reduced national average yield figures. As these were wet years, the amount of irrigation water needed by crops was less and this possibly contributed to the downward trend in water use in those years.

Figure 3 shows an upward trend in IWUI between 2001 and 2012. Despite the numerous climatic and water availability challenges during this time, IWUI has improved 97% from 1.10 bales/ML in 2001 to 2.17 bales/ML in 2012. The drought resulted in the smallest crop ever in 2008, and it was also a dry summer, yet the IWUI was high, which could be attributed to growers being focussed on their irrigation management and water-use efficiency. As mentioned previously, 2010, 2011 and 2012 were wet years, which led to high IWUI values in those years, as rainfall reduces irrigation water requirements.

As the IWUI is a coarse measure of water-use productivity that can vary from year to year in response to the amount of rain received, it should always be considered in the context of seasonal rainfall. There are better water-use efficiency indices for comparisons across seasons and regions, which will now be explored on measured datasets from commercial cotton farms.

Water-use efficiency and productivity trends from irrigation benchmarking studies

The water use efficiency and productivity of the Australian cotton industry has been measured as part of several studies in the past 20 years, and the results are summarised in Tables 1–3. Each of the studies used different methods of calculations and, in some cases, represented a small number of growers. These studies also included different farms and have been carried out on a range of soils types under various climatic conditions. The methodology used in each study can be found in their original reports (Cameron and Hearn 1997; Dalton *et al.* 2001; Tennakoon and Milroy 2003; QRWUE 2003; Williams and Montgomery 2008; Montgomery and Bray 2010; Wigginton 2011). An

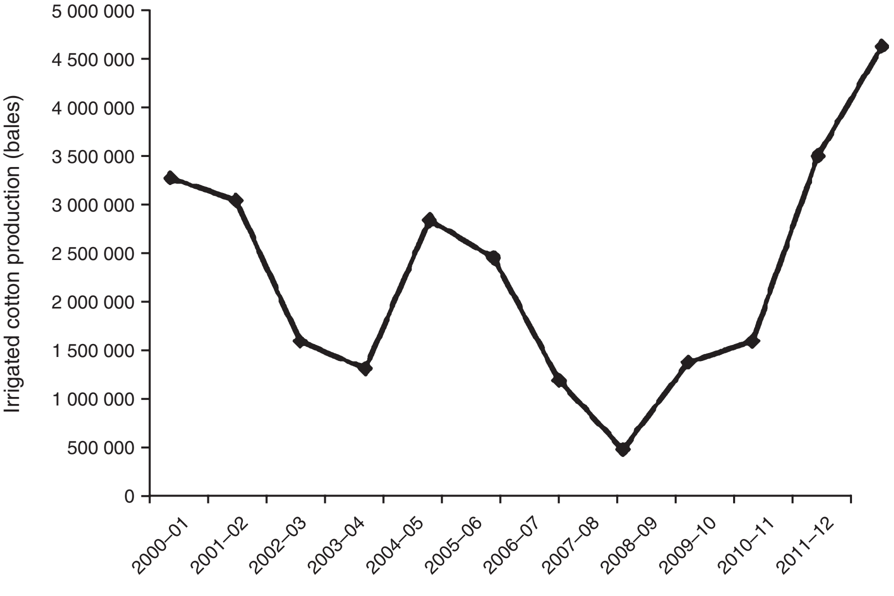

Fig. 1. Irrigated cotton production in Australia 2001–12 (1 bale = 227 kg). (Source: Cotton Australia.)

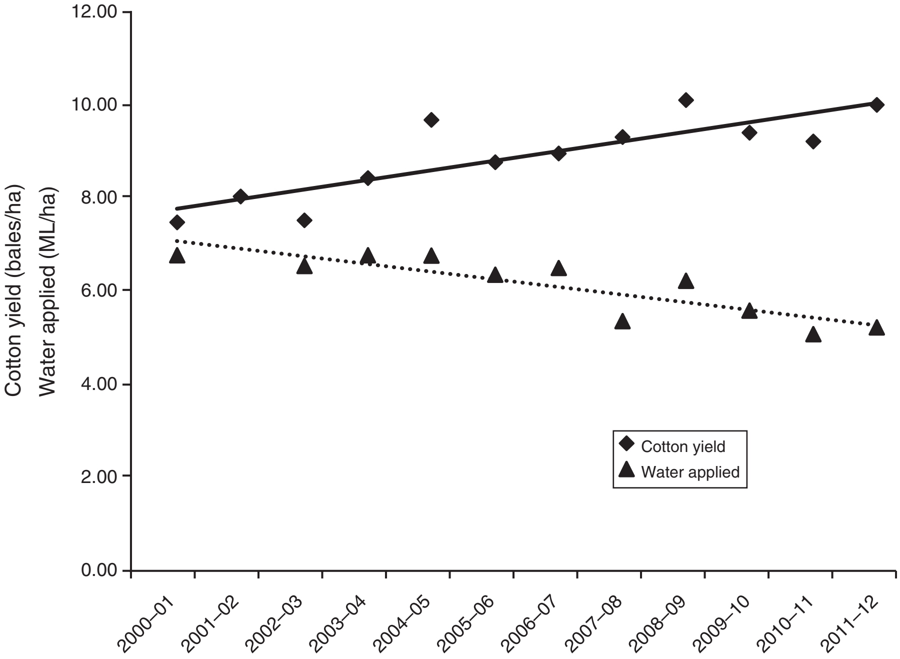

Fig. 2. Irrigated cotton yields and irrigation water applied in Australia, 2001–12 (1 bale = 227 kg).

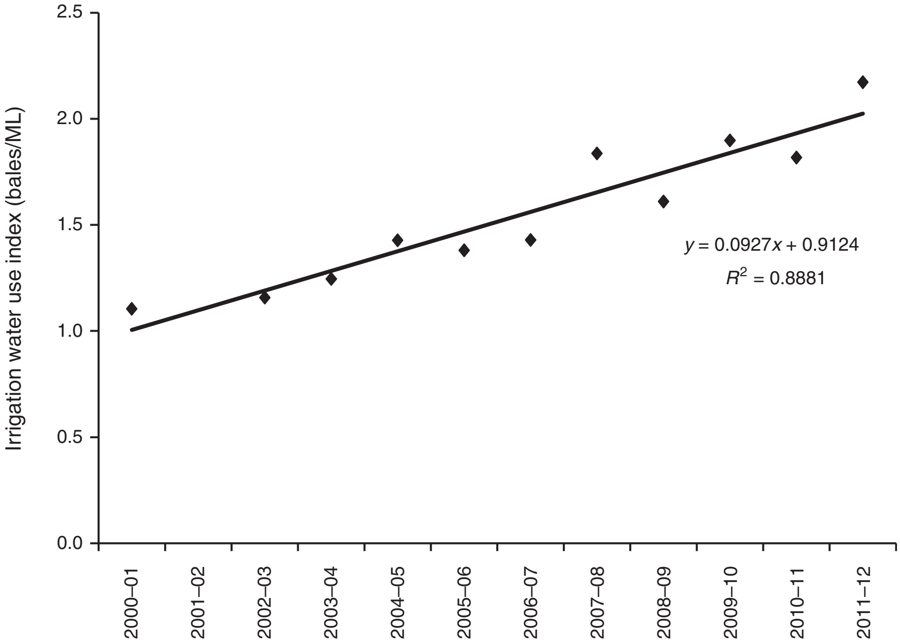

Fig. 3. Irrigation water-use index for cotton productivity 2001–12 (1 bale = 227 kg).

important aspect of most of these studies is they have each measured the whole-farm water balance on >10 commercial irrigation cotton farms.

The first major study of whole-farm water-use efficiencies of the cotton industry was completed by Cameron and Hearn (1997). They collected data from growers for the seasons 1988–95 for 11 farms in the Macquarie, Namoi, Gwydir and Macintyre regions. They pointed out that some rainfall events and subsequent water-storage data had not been well recorded, which may have inflated some of their water-index data.

During 1996–99, Tennakoon and Milroy (2003) collected data from 200 fields from 25 growers in the six major cotton-producing regions, which produced 80% of the national crop during those years. Their analysis included water pumped from rivers and bores, water stored on-farm, rainfall, and soil-water reserves used during the growing season. They calculated daily

Table 1. Summary of results in key studies of water use of the Australian cotton industry between 1988 and 2011
ET, Evapotranspiration. For lint yield, 1 bale = 227 kg

Year	No. of farms	Irrigation water applied (ML/ha)		ET (mm)	Lint yield (no. of bales/ha)	Source
		Average	Range			
1988–95	11	5.37	0.52–10.9		6.73	Cameron and Hearn 1997
1996–99	25	6.96		735	7.96	Tennakoon and Milroy 2003
1998–00	7	7.5				Dalton *et al.* 2001
2000–03	29	7.51	6.85–9.40	721	8.73	QRWUE 2003
2006–07	36	8.90	4.87–13.50	733	11.12	Williams and Montgomery 2008
2008–09	45	6.27	1.87–10.53	759	10.63	Montgomery and Bray 2010
2009–10	14	6.53	3.33–11.57	679	9.23	Wigginton 2011
2010–11	12	6.69	1.69–10.78	747	10.3	Wigginton 2011
Average		6.97		729	9.24	

Table 2. Values for key water use indices from research studies on commercial cotton farms between 1988 and 2011
IWUI, Irrigation water use index; GPWUI, gross production water use index; CWUI, crop water use index; 1 bale = 227 kg

Year	Average			Range			Source
	IWUI	GPWUI	CWUI	IWUI	GPWUI	CWUI	
	(no. of bales/ML)		(kg/mm.ha)	(no. of bales/ML		(kg/mm.ha)	
1988–95	1.48	0.82	2.9				Cameron and Hearn 1997
1996–99	1.32	0.79	2.52			2.0–3.2	Tennakoon and Milroy 2003
2000–03	1.16	0.93	2.79				QRWUE 2003
2006–07	1.30	1.13	3.47	0.9–1.92	0.82–1.71	2.66–4.31	Williams and Montgomery 2008
2008–09	1.99	1.14	3.20	0.8–5.75	0.64–1.58	2.29–4.36	Montgomery and Bray 2010
2009–10	1.47	0.93	3.11	0.96–1.89	0.78–1.14	2.20–4.04	Wigginton 2011
2010–11	1.84	0.94	3.14	0.97–3.17	0.64–1.33	1.73–3.56	Wigginton 2011

Table 3. Summary of whole farm irrigation efficiency (WFIE) values in the cotton industry between 1988 and 2009

Year	WFIE (%)		Source
	Average	Range	
1988–95	63	49–78	Cameron and Hearn 1997
1996–99	57	20–85	Tennakoon and Milroy 2003
1998–00		21–65	Dalton *et al.* 2001
2000–03	58	50–74	QRWUE 2003
2006–07	71	33–99	Williams and Montgomery 2008
2008–09	69	39–100	Montgomery and Bray 2010

soil-water balances for each crop to estimate evapotranspiration. The irrigation efficiency was calculated as a proportion of irrigation water input to the farm used in evapotranspiration.

Between 1998 and 2000, Dalton *et al.* (2001) used engineering survey tools to measure water use and losses on seven irrigation farms in the Macintyre region. During 2000–03, QRWUE (2003) monitored five major cotton-growing regions on 29 farms in Queensland. Their analysis included water pumped from rivers and bores, water stored on-farm, rainfall, and soil-water reserves used during the growing season.

During 2006–11, Williams and Montgomery (2008), Montgomery and Bray (2010) and Wigginton (2011) collected data from irrigators and used the WaterTrack ™ water-balance program to calculate water use indices. Their analysis included water pumped from rivers and bores, water stored on-farm, rainfall, and soil-water reserves used during the growing season. Montgomery and Bray (2010) and Williams and Montgomery (2008) included farms from New South Wales and Queensland, while in the study by Wigginton (2011) all farms were in south-western Queensland.

The average amount of irrigation water used for all of the studies in Table 1 was 6.97 ML/ha, with a range of 5.37–8.90 ML/ha. There was also a large range between the farms in any given year. The amount of irrigation water used depends on seasonal rainfall received and the efficiency of farm irrigation systems. Seasonal variability between seasonal average results is evident and expected. For example, 2009–10 and 2010–11 were wet seasons, whereas 2006–07 was a hot dry year. These results have led to the farmers' rule of thumb that, typically, 6–7 ML/ha of irrigation water is required to maximise cotton production.

The seasonal evapotranspiration values for irrigated cotton are in the range 679–759 mm and are reasonably consistent around the average of all the studies at 729 mm. Higher values would be expected in hotter years/regions such as 2010–11, when 10 of the 12 farms evaluated were at St George, and lower values in cooler years such as 2009–10, when 10 of the 14 farms evaluated were on the Darling Downs, which is also one of the cooler cotton-growing regions. These figures are similar to other research reports that suggest crops need to use 700–800 mm of evapotranspiration of water for high yields. Table 1 shows that the average cotton yield is rising, which is consistent with the trend in Fig. 2.

Table 2 presents values for key water-use indices from research studies on commercial cotton farms between 1988 and 2011. As expected there is some variation over time in the IWUI data. As previously discussed, it is strongly influenced by the amount of seasonal rain. That is, lower numbers in wet years and higher numbers in dry years. For example, the 2006–07 season was extremely dry with little in-crop rainfall, and irrigation water made up, on average, 88% of the total water supplied to the crop, whereas in 2008–09 the average irrigation water supplied was only 64% of the total gross available water (Montgomery and Bray 2010). The difference in the IWUI between these two seasons (1.30 in 2006–07 and 1.99 in 2008–09) illustrates the influence of rainfall on this index. It is a more useful index when comparing fields or farms within the same region and season.

The range in IWUI in any one season is also significant. The IWUI in 2008–09 ranged from 0.80 to 5.75 bales/ML. The farm with an IWUI of 5.75 bales/ML only grew a small area of irrigated cotton (36.5 ha) and applied only 1.8 ML/ha of irrigation water, with rainfall meeting the rest of the crop water requirements. This farm received 416 mm of effective rainfall during the growing season, which is equivalent to 4.16 ML/ha, and it obviously fell at the right time as this farm yielded well at 10.75 bales/ha. The minimum IWUI (0.8 bales/ML) occurred on a farm where they also grew a relatively small amount of cotton, 68 ha; however, yields were lower at 8.15 bales/ha and a large amount of irrigation water was applied. This farm applied 10 ML/ha of irrigation water and, on top of this, received 176 mm of effective rainfall. This crop was affected by waterlogging, resulting in reduced yields. This, along with a high application of irrigation water, resulted in a low IWUI.

Because it is easy to measure and calculate, the IWUI is the values usually quoted by growers when referring to the water-use efficiency of their crops. However, these data show that it must be used with some caution due to the influence of rainfall and that it is best used only when comparing nearby fields or farms within the same season.

The more meaningful index for comparing water use between farms or seasons is the GPWUI. The GPWUI includes irrigation, rainfall, and water stored in the soil and is the best measure for long-term seasonal comparisons. There is an improving trend in this index; the average GPWUI shows a 40% improvement over the decade from the studies of Tennakoon and Milroy (2003) (0.79 bales/ML) and Williams and Montgomery (2008) and Montgomery and Bray (2010) (1.13 and 1.14 bales/ML), all of whom sampled farms from most cotton growing regions in Australia.

Wigginton (2011) found slightly lower GPWUI values on the farms he sampled. This was attributed to some bias in the types of farms, as they were all within the Darling Downs and St George in Queensland. In both years several farms were affected by flooding and subsequently had lower cotton yields. As these farms were located in only two cotton regions, these figures provide benchmarks at a regional level only. The results cannot be compared with the industry-wide data collected by Tennakoon and Milroy (2003), Williams and Montgomery (2008) and Montgomery and Bray (2010) to gauge industry changes to water use over time. Farmers within St George and the Darling Downs can, however, compare their own performance to the regional benchmarks established by Wigginton (2011) and also compare their individual indices to the industry benchmarks established in 2006–07 and 2008–09 to gauge their own changes in water-use efficiency.

The influence of varying seasonal conditions and differences in crop management highlights the importance of continued collection of irrigation-benchmarking data. Ideally, irrigators should be benchmarking annually, while industry benchmarks should be established every 2–3 years to improve tracking of water-use performance overtime. The established industry benchmarks indicate that Australian cotton irrigators using conventional furrow surface-irrigation systems should be producing >1.1 bales/ML (>250 kg/ML) of total water used (total water includes irrigation water applied, in-season rainfall and soil moisture used).

The CWUI, a measure of the efficiency with which the cotton crop converts water supplied to lint yield or production per unit of crop evapotranspiration, averaged 2.95 kg/mm.ha between 1988 and 2011. There is also an increasing trend in the CWUI. Before 2003, the CWUI was <3 kg/mm.ha, whereas post-2003, it has mostly been above this level. However, as with the other performance indices, there is a large range in CWUI within any given year. The CWUI is rarely calculated by cotton growers due to the difficulty in measuring seasonal crop evapotranspiration, but is more commonly used in research trials. The CWUI is mostly dependent on agronomy inputs that affect yield rather than irrigation efficiencies.

The WFIE reflects the irrigation system efficiencies (Table 3); that is, it shows the amount of irrigation water that was used by the plant as a percentage of total irrigation water inputs to the farm. Therefore, inefficiencies in an irrigation system will result in a percentage of total water not being used by the crop. Surface-irrigation systems will never achieve a WFIE of 100%, as there are always losses due to evaporation and seepage across the fields, conveyance system (channels) and on-farm water storages. The aim is to reduce these losses to maximise the WFIE.

The WFIE values show a wide range in the data. However, the yearly averages indicate a significant improvement over time. During the late 1990s, the WFIE was ~57%, whereas in the latest industry wide-data, collected 10 years later, it has risen to ~70%. This indicates that there was less on-farm water loss and that more of the water used on-farm was used productively by the crop. Differences in seasonal conditions can also influence this performance indicator. For example, the highest WFIE was achieved in 2006–07, which was a very dry season. Soil profiles were dry and few irrigation storages were used. There was little, if any, in-crop rainfall across all regions, and surface-water allocations were either very low or non-existent. As a consequence, the area planted to cotton on any farm was significantly reduced. This meant that the available water was used carefully and management would have been precise with only small areas to water. Irrigators would have planted their best fields closest to on-farm storages or water extraction points to reduce conveyance losses.

The WFIE performance indicator provides an on-farm irrigation-efficiency benchmark, but does not indicate specifically where the water losses and inefficiencies are occurring. Further investigations are required to determine the potential water losses within farms.

International water-use efficiency information from commercial cotton farms in other countries is scant. Data collection challenges, accuracy, and variance in definition assumptions make it difficult to provide explicit international comparisons. Such comparisons are also problematic because of the climatic differences between countries, such as the significance of the amount of rain received, the different irrigation application systems or other underlying regional production problems such as extreme temperatures, soils, salinity, disease, or insect pests. However, reviews have attempted to compare crop water-use figures between countries around the world (Hearn 1994; Gillham *et al.* 1995; Grismer 2002; Payero and Harris 2007). These reviews suggest that Australia is among the higher performing countries in the world.

Cotton production globally uses 3% of the world's agricultural water, the largest three crop water users being rice (21%), wheat (12%) and maize (9%) (Hoekstra and Chapagain 2006). Zwart and Bastiaanssen (2004) reviewed 84 studies on irrigated wheat, rice, cotton and maize. They reviewed 16 publications on cotton from nine countries, including one study from Australia (Tennakoon and Milroy (2003) and found that crop water productivity had increased compared with a similar global review by FAO in 1979 (Doorenbos and Kassam 1979). The data had a large range, which they attributed to climate, management of irrigation water and soil fertility, as well as other variables.

Where are the water losses on-farm?

The previously discussed data lead to the question: where are the major water losses on irrigated cotton farms in Australia? Several studies have attempted to quantify the specific loss components associated with the whole-farm water balance.

Variation in whole-farm water irrigation efficiency was quantified for seven farms by Dalton *et al.* (2001) (Table 4). They found, on average, 43% of the total water extracted was used by the crop. The major water losses were storage evaporation 30%, field seepage 10%, channel distribution seepage 6%, storage-dam seepage 5%, channel distribution evaporation 4%, and field evaporation 2% (total 57%).

Table 4 shows that the more recent studies found smaller average losses (25% in 2006–07, 20% in 2008–09, 31% in 2009–10, 30% in 2010–11). Wigginton (2011) also reported that the largest loss of water was through the on-farm storage, which accounts for, on average, 19% of the total water, followed by in-field application loss, which accounted for 10% of the total available water. Channel and drain losses were minimal relative to other water-balance components. Again, all of the studies reported large variances in farm water-loss data, 5–45%, reinforcing the importance of individual site-specific measurements.

In a separate study, Wigginton (2011) reported measurement of 136 on-farm water storages across the cotton industry, ranging in size from 75 ML to 14 000 ML and depth from 1 to 9 m. Evaporation losses were the largest component of loss in most storages. Seepage losses averaged 2.3 mm/day and were <2 mm/day for 75% of these storages. These studies support earlier research (Sainty 1996; Dalton *et al.* 2001; Craig *et al.* 2007) that storage evaporation loss is a significant issue for the Australian cotton industry, as it has been shown to exceed 40% of the total available water.

Evaporation losses depend on the surface area of the water storage, ambient air temperature, relative humidity, wind speed and other factors. Craig *et al.* (2005) assessed the effectiveness of many methods of reducing evaporation, such as shade cloth, floating covers and chemical film monolayers, and summarised practical and technical limitations. An online tool has since been developed to help farmers calculate evaporation losses (Schmidt 2012). Mitigation measures for storage evaporation loss continue to be explored, but at present there are no commercially viable options for cotton growers, as evidenced by the current low uptake of postulated solutions.

Recent research on the development of new chemical monolayers has shown reduced evaporation in the laboratory (Prime *et al.* 2011; Schouten *et al.* 2012; Tran *et al.* 2013) and in field trials (Prime *et al.* 2012). Further modification of the chemical monolayer properties to improve surface-film properties for large water storages, as found on cotton farms, has led to development of a novel duo-layer surface-film system, which has significant advantages over all polymers previously investigated (Prime *et al.* 2013). Field trails of these new polymers are currently being evaluated.

The second-largest loss of water on irrigated cotton farms is deep-drainage and tail-water losses, both of which are more prevalent in furrow-irrigated fields. The types of improvements growers are making include objective irrigation scheduling, surface-irrigation evaluations, storage-efficiency calculations, installation of water meters, electromagnetic surveys and

Table 4. Water loss components and crop use of the total available water
Values are percentages

Water-balance loss area	1998–00[A]	2006–07[B]	2008–09[C]	2009–10[D]	2010–11[D]
Storage dam evaporation	30			20	18
Storage dam seepage	5				
Channel distribution evaporation	4			1	1
Channel distribution seepage	6				
Field evaporation	2				
Field seepage	10			9	10
Field tail water				1	1
Total losses	57	25	20	31	30
Crop use	43	75	80	69	70

[A] Dalton *et al.* 2001. [B] Williams and Montgomery 2008. [C] Montgomery and Bray 2010. [D] Wigginton 2011.

changing irrigation systems. Between 2006 and 2011, half of the cotton irrigators made changes to their siphon flow and or size (Roth 2011).

Application efficiency is a volumetric term indicating the percentage of water applied that remains in the root-zone that is available to the crop. The majority (>95%) of growers practice some form of tail-water recycling, and hence, runoff is not strictly a loss to the production system as it may be used for subsequent irrigations. For this reason, application efficiency is sometimes modified to account for the fact that a proportion (e.g. 75%) of the runoff is not lost.

Evaluation of in-field losses of surface-irrigation farm water

Techniques for modelling and evaluating surface irrigation have been reviewed by Dalton *et al.* (2001), Raine *et al.* (2006) and Gillies (2008). Measuring and modelling the infiltration characteristics of the soil under surface irrigation was hindered by the lack of reliable equipment and procedures to measure the many variables involved, and this held back the adoption of technology to optimise this simple form of irrigation (Purcell and Fairfull 2005). To address this problem, the Irrimate™ monitoring hardware and software tools were developed by the National Centre for Engineering in Agriculture (University of Southern Queensland, Toowoomba) and Aquatech Pty Ltd (Narrabri, NSW).

These tools and software gained popularity during the mid-2000s after commercialisation, and with further exposure by way of on-farm demonstrations of the Irrimate suite of tools by NSW Department of Primary Industries and Department of Agriculture, Fisheries and Forestry, Queensland. A description of these tools can be found in Purcell and Fairfull (2005) and Dalton *et al*. (2001). The system is based on the use of a hydraulic model (e.g. SIRMOD), which is calibrated to field conditions using in-field measures of inflow rates and water-advance times. Once calibrated, the model can be used to (*a*) evaluate the performance of the measured event and (*b*) optimise application rates and times.

Dalton *et al.* (2001) monitored 70 irrigation events over two seasons on 11 fields. Individual irrigation application efficiencies ranged from 37 to 100%. Average seasonal efficiencies ranged from 70 to 90%, assuming full tail-water recycling. Tail-water runoff ranged from 4 to 32% and deep drainage from 11 to 30%. Raine and Foley (2002) found application efficiencies of single irrigations ranging from 35 to 100% for 180 irrigations. Smith *et al.* (2005) examined 79 surface irrigation events and found efficiencies ranged from 17 to 100%, with an average of 48%. They calculated irrigation losses of 1.6-2.5 ML/ha. Raine *et al.* (2006) reported average savings of 0.15 ML/ha for each irrigation event when irrigators adjusted siphon flow rates and irrigation times.

In 2006–07, the Cotton CRC water extension team conducted 47 furrow-irrigation evaluations across nine farms in the Gwydir and Namoi Valleys using the Irrimate system (Montgomery and Wigginton 2007). Although about 35% of the irrigation events had an application efficiency that could be considered below standard (80%), importantly they also found that applications >90% could be achieved under furrow irrigation. Furthermore, application efficiency could be improved with simple changes such as reducing the time siphons are running and/or increasing the rate at which irrigation water is applied to the field. In their performance evaluation, the amount of water applied was reduced by 0.18 ML/ha for each irrigation event.

QDPIF (2009) evaluated 100 furrow irrigations in Queensland. They found a significant spread in the performance of furrow irrigation across Queensland, with an average application efficiency of 65%. Subsequent optimisation increased this to 81%, mostly by increasing flow rate and reducing cut-off time changes.

The Cotton CRC commissioned the National Centre for Engineering in Agriculture to develop an Irrimate Surface Irrigation Database (ISID). The completed database enables performance benchmarking and ongoing analysis of future data. Gillies (2012) compiled and analysed data from 631 surface-irrigation events measured by commercial consultants and researchers between 1998 and 2012. The average application rate for the typical 2-m alternate row irrigation is 4.4 L/s for 12.5 h, resulting in 1.3 ML/ha applied with an application efficiency of 64.6%. The losses are almost evenly split between runoff, 0.253 ML/ha, and deep drainage, 0.274 ML/ha per irrigation event. Correctly accounting for the tail-water recycling commonplace in the industry increases this efficiency to 76.1%, representing a water saving of 11.5%.

For growers, the major purpose of these field evaluations is identification of strategies to improve or optimise surface-irrigation performance through measures such as run times, flow rates and siphon sizes. Despite the considerable advances growers can make from these single furrow optimisations, there is considerable field variability of infiltration characteristics and further research is being undertaken to improve modelling (Gillies 2008).

The data within ISID were optimised to identify the potential irrigation performance with minimal changes to application time and or inflow rate (Gillies 2012). The results indicate that the average application efficiency can be increased to 84.7%, which represents potential water savings of 0.155 ML/ha per irrigation event (or 0.226 ML/ha, neglecting tail-water recycling), corresponding to a halving in drainage and runoff losses.

In-field deep drainage has been the focus of much recent research and this has been summarised by Silburn and Montgomery (2004), who found typical values were 100-200 mm/year, with a very large range (0–900 mm/year). Silburn *et al.* (2013; this issue) reviewed four decades of deep drainage research in the cotton industry. They reported that, more recently, deep drainage is being better managed, while some deep drainage is needed to avoid salt build-up in the profile. Gunawardena *et al.* (2011) reported deep-drainage information from seven farms in Queensland, finding that deep drainage varied along the length of the field and most deep drainage occurred during pre-irrigation or the first two or three in-crop irrigations. They also reported almost zero deep drainage under the lateral-move irrigation system. Deep drainage was measured under furrow-irrigated cotton at Narrabri by Ringrose-Voase and Nadelko (2013; this issue), who found that drainage accounted for up to 11% of the water applied. They observed that in cracking soils, drainage water may bypass the subsoil without fully wetting these layers. They also concluded that significant quantities of nitrogen were lost with this drainage.

Efficient management of furrow irrigation faces two major issues. First, field conditions vary both spatially and throughout the season, thereby altering the optimal application rate and time. Second, the high level of control required involves increased labour requirements. Adaptive real-time control of furrow irrigation combined with automated application systems offers the potential to overcome both of these problems. Prototypes of these systems are described by Koech *et al.* (2011) and McCarthy *et al.* (2012). The system is capable of monitoring, simulating and formulating the optimisation, and controlling the application while the event is still under way. Commercial development of this 'smart automation' for furrow irrigation is underway.

Correct management of soils to achieve good soil structure is fundamental to achieving water-efficient crops. A body of research, which is summarised in the SOILpak manual (McKenzie 1998), has been aimed at reducing compaction to increase the plant-available water-holding capacity of soils. Any program aimed at improving water-use efficiency and productivity should also focus on soil management.

Trends in alternative irrigation systems and water-use efficiency

The last decade has seen increased interest in alternative irrigation systems to surface-furrow irrigation. These include bankless-channel surface irrigation, drip irrigation, and both centre-pivot and lateral-move machine systems. The bankless irrigation system is being considered by some cotton growers as it provides significant labour savings as well as some energy savings. Field trials are currently being conducted by many growers to evaluate this system, and more information on their operation can be found in Grabham (2013).

Drip irrigation has been evaluated in the Australian cotton industry for 30 years. One of the first applications was in 1983, where a buried subsurface drip trial was established on a commercial farm near Narrabri (Warnock 1983), and there have since been many other examinations, summarised in Table 5. In general Table 5 indicates that drip irrigation saves 20–30% water, and yields are often 10–20% higher, but there are also many examples where yields have been less than with a comparable surface irrigation system.

The high capital cost and high energy costs associated with the pumping to create adequate pressure remain the main constraints to drip irrigation adoption in Australia. As water costs rise, in theory there may be wider adoption of drip irrigation, but this is unlikely given the rapidly rising energy costs associated with the pumping of water and the higher level of technical support required. Drip irrigation maybe the most appropriate tool in specific circumstances, such as in soil types that exhibit high deep-drainage rates. This is a conclusion also reached by van der Kooij *et al.* (2013), who reviewed 49 published studies on drip irrigation around the globe between 1974 and 2011.

Aeration of the irrigation water in subsurface drip irrigation systems in cotton has been investigated in a long-term trial from 2005 to 2012 on a Vertosol soil near Emerald, Queensland (Midmore and Bhattarai 2010; Pendergast *et al*. 2013, this issue). Positive effects (on average 10%) of the aerated water treatments were noted consistently on lint yield over a number of seasons. An increase in water-use efficiency was associated with the higher yield as well as improved soil biological properties. McHugh *et al*. (2008) showed that subsurface drip irrigation of cotton can reduce the off-site movement of sediments, nutrients and pesticides compared with surface irrigation.

The most important irrigation system change occurring on Australian cotton farms is that increasing areas of cotton are being grown under centre-pivot and lateral-move irrigation machine systems. Survey interviews were conducted with cotton growers in 2001 for the whole industry (Foley and Raine 2001) and in 2011 in the Queensland Murray–Darling Basin (Wigginton *et al.* 2011). Growers in both of these surveys cite labour savings and water savings as their main motivation for installing these systems. Other major advantages with these systems, compared with furrow irrigation, include reduced waterlogging, ability to apply fertiliser in the irrigation water, improved capture of rainfall, the ability to germinate crops with less water, and improved minimum tillage practices.

In terms of water use, growers in the 2001 study found greater improvements in the IWUI of these machines compared with surface irrigation than in the 2011 study. This may be because furrow-irrigation performance across the cotton industry has also improved over the last decade due to improved management practices (Foley *et al.* 2013). Wigginton *et al.* (2011) found that

Table 5. Trial results for drip irrigation compared with surface furrow irrigation in Australian cotton fields

	Year	Water saved by drip *v.* surface irrigation	Yield response drip *v.* surface irrigation	Yield response (%)	Source
Narrabri, NSW	1984–87	Yes	Decrease		Hodgson *et al.* 1990
Survey of 26 farms	2000	38%	Increase		Raine *et al.* 2000
Boggabilla, NSW	1999–00	35–40%	Increase	10	Cross 2003
Dalby, Qld	2001–03	29–31%	Increase	10	Harris 2007
Dalby, Qld	2002–07	27%	Decrease	13	Harris 2007
Macalister, Qld	2003–07	15%	Increase	20	Harris 2007
Narrabri, NSW	1996–99	20–30%	Increase	5	Anthony 2008
Warren, NSW	2001–03	40%	Increase	20	Anthony 2008
Moree, NSW	2011–12	38%	Decrease	7	GVIA 2012
Emerald, Qld	2005–12	Yes	Increase		Pendergast *et al*. 2013
NSW (5 farms)	2010–11	Yes	Increase		Montgomery 2011

Table 6. Summary of the irrigation water use index (IWUI) and gross production water use index (GPWUI) benchmarks for the centre-pivot and lateral-move irrigation systems for Australian cotton, 2010–11 and 2011–12

Year	IWUI	GPWUI	Sample size	Source
2009–10		1.28	1	GVIA 2012
2010–11	4.62	1.2	23	WaterBiz 2012; Wigginton *et al.* 2011
2010–11	4.25	1.37	40	Modified from Montgomery 2011
2011–12	4.01	1.43	29	WaterBiz 2012
2011–12		1.35	1	GVIA 2012
Average		1.33		

growers indicated water savings ~30% compared with traditional furrow-irrigation systems. These savings are usually from increased ability to capture rainfall and less in-field deep drainage below the root-zone. Table 6 shows higher IWUI and GWUI of these machines compared with surface-irrigation benchmarks in Table 2. The average GPWUI in Table 6 of 1.33 bales/ML would serve as a useful benchmark index of these systems.

In a survey of 150 irrigators in Queensland Baillie *et al*. (2010) found that farmers had generally focussed on the adoption of low capital, low technology on-farm water-use efficiency options. A similar finding was made by Roth (2011) from a survey of 177 growers in both New South Wales and Queensland. Current government co-investment schemes have increased the uptake of centre-pivot and lateral-move machines, but not drip irrigation. A greater conversion of furrow irrigation to other systems such as centre pivots and lateral moves is expected in the future. The major barriers to changing application methods include water-allocation uncertainty, cost of the system upgrade and escalating pumping-energy costs. A number of resources have been developed to help growers with the management of these systems, such as a DVD ‘Growers Guide to Centre Pivots and Lateral Moves’ (Pendergast 2012).

As mentioned earlier, the majority of the Cotton CRC effort was focussed on extension and delivery of management knowledge to growers and advisers. The needs of growers and crop agronomists in terms of irrigation knowledge were explored through a convergent interviewing process (Callen *et al.* 2004). Smith (2008) implemented the recommendations of that study, including focusing on building capacity of the advisory sector, improving grower-based peer learning knowledge sharing, and delivery of specifically designed training workshops. An extensive range of activities were undertaken such as field days, technology demonstrations, water-use efficiency benchmarking, cost–benefit analyses, workshops, case studies, media articles and e-information, by subsequent projects (Jackson 2008; Harris and Brotherton 2009; Montgomery 2011).

The latest management practices of water application continue to evolve and were compiled in the WATERpak—a guide for irrigation management in cotton and grain farming systems (Dugdale *et al.* 2008; Wigginton 2013).

Conclusion

The majority (at least 80%) of the Australian cotton-growing area is irrigated using gravity surface-irrigation systems. This review found that over 23 years, cotton crops utilise 6–7 ML/ha of irrigation water depending on the amount of seasonal rain received. The seasonal evapotranspiration of surface-irrigated crops averaged 729 mm over this period. Over the past decade, water-use productivity by Australian cotton growers has improved by 40%. This has been achieved with both yield increases and more efficient water-management systems. The whole-farm irrigation efficiency index improved from 57% to 70%, while the crop water use index is >3 kg/mm.ha, high by international standards.

Yield increases over the last decade can be attributed to advances in plant breeding, the adoption of genetically modified varieties, and improved crop management. In addition, there has been an increase in use of irrigation-scheduling tools and furrow-irrigation system optimisation evaluations. This has reduced in-field deep-drainage losses. The greatest initial gains in water-use efficiency can be achieved by improving the management of existing surface-irrigation systems through site-specific system optimisation. The largest losses of water on cotton farms are through evaporation from on-farm water storages. This loss aspect of the farm water balance needs addressing and is not unique to cotton farms.

The standardisation of water-use efficiency measures and improved water-measurement techniques for surface irrigation are important research outcomes to enable valid irrigation benchmarks to be established and compared. While the Cotton CRC teams have achieved important new research outcomes, its major effort was related to water extension projects, training of growers and advisers, capacity-building, technology demonstrations and delivery of information. The review indicates that Australian cotton irrigators using conventional furrow surface-irrigation systems should be producing >250 kg/ML (1.1 bales/ML total water use as irrigation, rainfall and reserved soil moisture) with the surface-irrigation systems and 295 kg/ML (1.3 bales/ML) with centre-pivot and lateral-move machine systems. Water-use performance is highly variable between cotton farmers, farming fields and across regions. The range in the presented datasets indicates that potential remains for further improvement in water-use efficiency and productivity on Australian cotton farms.

Growers are making changes to alternative irrigation systems such as centre-pivot and lateral-move systems, and it is expected that there will be an increasing numbers of these machines in the future. These systems achieve labour and water savings (~30%) but have significantly higher energy costs associated with water pumping and machine operation. Drip irrigation has been extensively trialled in a variety of locations, where it has resulted in water savings of 20–30%, but yield results have been shown to both increase and decrease compared with surface-irrigation systems. It is unlikely there will be significant adoption of drip irrigation due to high capital and energy costs in Australia in the foreseeable future.

Changing irrigation systems involves a major step-change decision in terms of farm capital investment. Farmers learn by doing, and trust farmers more than any other source. Therefore, an even greater emphasis on capacity-building of people, on-farm evaluations, and local learning sites should be implemented as a partnership between farmers, scientists and research investors to build confidence and local knowledge. Better information is needed on the optimisation of water, carbon, energy, and labour interactions of alternative systems to surface irrigation. While some systems are more water-efficient, they usually require more energy for pressurised pumping and operation. Specific agronomy packages for alternative irrigation systems are required.

Community concerns about environmental issues and scarcity of water in major cotton-growing areas in Australia have stimulated the industry to improve on-farm water-use efficiency and productivity. Governments and industry have made considerable investments to improve water-management outcomes. The facts presented in this paper confirm that the research and development investments and activities of farmers with regard to irrigation improvement projects have paid excellent dividends. For scientists, it shows the positive outcomes of previous research projects and opens up new avenues for further research.

Research and development priorities continue to evolve. These should include a continued focus on plant breeding, agronomy, and soil and irrigation management, in fully irrigated, partly irrigated and rain-fed environments. An important focus, whilst challenging, should be aimed at reducing the major losses related to evaporation from storages, and improving application efficiency and uniformity. Improved technologies for soil-moisture monitoring and more accurate crop coefficients for irrigation scheduling are required. Individual growers must be encouraged to measure aspects of the water balance on their farms and calculate efficiencies. Further improvements in surface irrigation through automation, real-time control and optimisation are possible. More reliable weather forecasting is also required for irrigation scheduling and water planning.

Availability of irrigation water will remain the most limiting factor to cotton production in Australia. The main steps forward to improve water-use productivity include: good agronomy, good soil management, improving water-measurement tools, improving the delivery of water to the field, maximising storage and distribution efficiency, reducing evaporation and drainage, maximising application efficiency, achieving uniform application, and the use of alternative irrigation systems such as centre pivots and lateral-move machines where applicable.

Acknowledgements

Funding for much of the research was provided by the Cotton Research and Development Corporation, the Cotton Catchment Communities Cooperative Research Centre, and the NSW & Queensland Governments' Water Use Efficiency in Agriculture Programs. We acknowledge all the researchers, advisers and growers who have contributed to project activities.

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