CSIRO PUBLISHING

Crop & Pasture Science, 2013, **64**, 834–844
http://dx.doi.org/10.1071/CP13172

Cotton farming systems in Australia: factors contributing to changed yield and fibre quality

M. V. Braunack

CSIRO Plant Industry and Cotton Catchment Communities CRC, Locked Bag 59, Narrabri, NSW 2390, Australia.
Email: michael.braunack@csiro.au

Abstract. This study was undertaken to identify factors in Australian cotton farming systems that influence yield and fibre quality of cotton and how these have changed with time after the wide adoption of Bollgard II® cultivars (containing the proteins Cry1Ac and Cry2Ab, providing easier control of *Helicoverpa* spp.) in the 2003–04 season. Data from Australian commercial cotton variety trials conducted from 2004 to 2011 were used to link management inputs, yield, and fibre quality.

Restricted (residual) maximum likelihood (REML) and regression analyses were used to determine which factors had a significant effect on yield and fibre quality. Results showed that lint yield was significantly influenced by cultivar and growing region, and the interaction between region and the amount of applied nitrogen and phosphorus (kg ha^{-1}), plant stand (plants ha^{-1}), in-crop rainfall (mm) and the number of irrigations, season length (days), and days to defoliation. Generally, the same factors also influenced fibre quality. Regression analysis captured 41, 71, 50, 30, and 36% of the variability in lint yield, fibre length, micronaire, fibre strength, and trash, respectively, for irrigated systems. For dryland systems the variability captured was 97, 87, 77 80, and 78%, respectively.

Changes in cotton farming systems from 2004 to 2011 have occurred with applied nitrogen fertiliser increasing under irrigation and decreasing under dryland systems. However, phosphorus fertiliser use has remained steady under irrigated and decreased under dryland systems, and the number of insect sprayings has decreased under both systems. Under irrigated systems, lint yield, fibre length, and trash levels increased while micronaire and fibre strength decreased. Under dryland systems, lint yield decreased while micronaire, fibre length, strength, and trash levels increased. All fibre quality parameters satisfied criteria that would not incur a penalty.

The results considering which factors are the most important and which are of lesser importance provide some insight to changes in management in both irrigated and dryland systems and the effect on lint yield and fibre quality and provide some basis for future investment in research and development and extension to the Australian cotton industry.

Additional keywords: Bollgard II®, cultivar, dryland, irrigation, nutrition.

Received 15 May 2013, accepted 23 September 2013, published online 29 October 2013

Introduction

As the world population grows, there is increasing demand for food and fibre to feed and clothe people. Also, consumers are concerned about the sustainable and ethical production of food and fibre as well as maintenance of natural resources (Galan *et al.* 2007). Therefore, agricultural industries need to demonstrate that practices have changed and have contributed to the sustainability of the industry and benefitted the environments that the industry occupies (Skinner *et al.* 1997; van der Werf and Petit 2002).

Irrigated cotton in Australia is an intensive, broadacre cropping system, and the industry is facing many challenges, including rising cost of production, competition for water resources, energy use, greenhouse gas emissions, maintaining soil quality, chemical use for pest control, and management of biodiversity, along with the need to maintain yield and fibre quality (Roth 2010). Overarching this is the pressure of climate change, world markets, and community attitude and government policy. Public concerns about the sustainability of cropping include impact on aquatic systems, groundwater and rivers, biodiversity, soil degradation, erosion and salinity, water use, chemical use, pests and diseases, transgenic technology, dust and odour emissions, greenhouse gas footprint, and energy use (Roth 2010). In the past, there were public concerns regarding water, fertiliser and chemical (pesticides) use, and the amount of tillage undertaken by the cotton industry. The industry responded by investing in research to address these issues and readily adopting the outcomes (Constable 2004). Many of these issues are still being addressed by the cotton industry through the development of industry best management practices.

There is a lack of industry-wide information to link farm-management practices and the effect on cotton lint yield and quality. Individual growers may have appropriate records over time; however, there are no reliable, cotton industry wide data available. The Australian sugar industry collects and uses data during the season to assess the effect of rainfall on commercial cane sugar and compare productivity between regions; however, no management information is included (Lawes and Lawn 2005).

Cotton farming systems from the 1960s to the 1990s were intensive and consisted of high inputs of water, fertiliser, and pesticides (Hearn and Fitt 1992). A benchmark survey of the cotton industry documenting some changes from 1996–97 to 2000–01 indicated that conventional tillage was the norm in irrigated systems, whereas zero tillage was restricted to dryland, and these practices had not changed substantially over this period (McIntyre *et al*. 2002). The most common rotation practiced was 4 : 1 cotton : rotation crop, with wheat the most frequent rotation. Also, nitrogen (N) application rate was increasing, especially on the third or fourth cotton crop, with legumes being introduced in the rotation for the N benefit. Growers were starting to monitor water use and were using integrated pest management (IPM) strategies in the early 1980s to control insect pests and to protect beneficial insects (Fitt *et al*. 2009).

Change in the Australian cotton industry over the last 20 years has been mostly in response to the introduction of the new technology of Bt (*Bacillus thuringiensis*) insecticidal INGARD® cultivars containing the Cry1Ac protein in 1996–97 and Bollgard II® cultivars containing the Cry1Ac and Cry2Ab proteins in 2003–04, which enabled growers to manage insects (*Helicoverpa* spp.) more effectively (Knox *et al*. 2006). A consequence of this was a reduction in the amount of active ingredient (a.i.) applied, from 6.6 kg a.i. ha^{-1} in 2001–02 to 1 kg a.i. ha^{-1} in 2005–06, and a change in chemistry of the pesticides applied (Pyke 2007). The release of cotton cultivars incorporating the Roundup Ready® and Roundup Ready Flex® traits in 2000 and 2008, respectively, has contributed to easier management of weeds in the short term and potential weed resistance issues in the longer term (Charles and Taylor 2003). In a systems context, weeds cannot be ignored as competition with cotton can substantially reduce yield (Walker *et al*. 2005). Weed pressure was not considered in this study and was assumed to be minimal.

Cotton systems continue to develop in response to economic and environmental pressures, and Hearn and Fitt (1992) reviewed the evolution of several cotton cropping systems from around the world. Several issues at that time are still relevant today, such as soil degradation, resistance to insecticides and herbicides, and disease incidence. More recently, Roth (2010) reviewed the Australian cotton industry from a sustainability perspective to evaluate whether simple indicators could be identified to quantify the effect of management changes. One challenge was the lack of suitable, industry-wide data to enable benchmarks to be developed.

This work was undertaken to distinguish factors in cotton farming systems that are important in generating high lint yield and quality cotton from those with lesser importance, and how these may have changed over time. The hypotheses tested are that some agronomic practices have greater influence in producing yield and quality fibre than others, and that these practices change over time. It is acknowledged that agronomic practices will change in response to prevailing seasonal conditions.

Materials and methods

Data

To identify the important factors in farming systems that contribute to high yield and quality, it is necessary to align agronomic inputs with the resulting yield and quality parameters. The Cotton Seed Distributors (CSD) Ltd (Wee Waa, NSW) and Deltapine® (Monsanto Co., St. Louis, MO, USA) variety trial results and a long-term rotation trial (Hulugalle *et al*. 2006, 2009) were the only sources of longer term data reporting agronomic inputs and cotton yield and quality. The data covered both irrigated and dryland systems with a selection of cultivars grown across a range of environments and thus represented an industry-wide picture. All Australian cotton-growing regions were represented in the data: in Queensland, the Central Highlands, Dawson/Callide, Darling Downs, and St George–Dirranbandi ; and in New South Wales, Macintyre, Gwydir, Lower and Upper Namoi, Macquarie, Bourke, Tandou, and southern New South Wales.

The field trials were of replicated block design with four replicates for each cultivar. Row spacing was 1 m for irrigated sites, and the majority of dryland planting was double-skip (two rows planted, two unplanted). Irrigated sites were machine-picked into a module for each cultivar, with lint being commercially ginned, whereas for dryland sites, a fixed number of rows were machine-picked and lint yield was determined by weighing the picker or boll buggy and quality determined from hand grab samples processed through a 20-saw gin.

A limitation was the incompleteness of data, in that management inputs were not always recorded at all sites, e.g. nutrient applications, plant stand (plants ha^{-1}), the number of irrigations, row spacing, and previous crop. Management inputs by growers were the same across all cultivars in the trial, which varied from two to six. Also, there may be some bias in the data, as growers willing to participate were chosen to undertake the field trials. Notwithstanding this, the data represent the best available to determine factors contributing to yield and quality and trends for the Australian cotton industry.

Analyses

The most popular commercial cultivars (Sicot 70BL, Sicot 70BRF, Sicot 71, Sicot 71B, Sicot 71BR, Sicot 71BRF, Sicot 71RR, Sicot 71RRF, Sicot 73, Sicot 75, and Sicot 74BRF) were grown in all regions over the period and are used as the standards in providing an industry perspective (across regions and irrigated and dryland systems) on changes in management, lint yield, and fibre quality.

The analysis of data was limited to the seasons from 2003–04 to 2010–11, which included an extended period of drought from 2006 to 2008. This also corresponds with the wide adoption of Bollgard II® (genetically modified to provide easier control for the cotton pests *Helicoverpa* spp.) and Roundup Ready® and Roundup Ready Flex® cultivars (making weed control easier in growing cotton). Anecdotal evidence indicated that higher lint yield was being achieved over this period with the newer cultivars, and it was thought that greater application rates of N were being applied across the industry. It is suggested that seven seasons of experience with Bollgard® cultivars would be sufficient to determine trends in agronomic management, as previous industry surveys spanned a lesser period (McIntyre *et al*. 2002).

Restricted (residual) maximum likelihood (REML) was used to test linear mixed models in conjunction with regression on independent variables to identify factors that had a significant effect on lint yield and fibre quality in irrigated and dryland cotton systems (Piepho *et al.* 1998). One of the factors was of categorical nature, namely, region, previous crop, and cultivar; and the other factors were quantitative, namely, N, phosphorus (P), and potassium (K) rate (kg ha^{-1}), plant stand (plants ha^{-1}), number of irrigations and in-crop rainfall, number of insect sprayings, days to defoliation, and season length (days between sowing and picking). Individual sites indexed by season and region were treated as random to take out region and season effects with all other variables as fixed in the model.

Only factors with significant effects on lint yield and fibre quality were selected and used in multiple regression analysis. The regression analysis was used to determine whether each variable and/or its interaction with others were required to capture the variability in the dataset. Once the model was determined for each dependent variable, the relative contribution of significant factors ($P < 0.05$) was calculated as a percentage of the total sums of squares from the accumulated analysis of variance produced from the regression analysis; it was not intended to use the regression for predictive purposes, merely to identify the contribution of the significant factors to lint yield and fibre quality. The analyses were done using GENSTAT13 (VSN International 2010). To minimise bias in the data due to unequal numbers of data points between factors, predicted values from the REML analysis of factors are presented and discussed rather than mean values for each factor.

Results

Although individual sites were indexed by region and season and treated as random effects to take out their influence, they had a major effect on the outcome. This may be expected as there are underlying factors, such as inherent soil fertility, profile depth (affecting water storage), history, etc., that growers respond to in managing climatic conditions when attempting to maximise productivity.

Lint yield

Factors significantly influencing lint yield were similar in both irrigated and dryland farming systems, with region, cultivar, plant stand, N, P, number of irrigations (irrigated systems) and in-crop rainfall (dryland system), season length (time between planting date and harvest date), and days to defoliation accounting for most variation (Table 1). Cotton growing region had the greatest influence on lint yield for both irrigated and dryland systems, while cultivar was only a factor in dryland systems. The irrigation and rainfall × region interactions also affected lint yield for irrigated and dryland systems, respectively, as did the N × region interaction, more so in dryland than irrigated systems, whereas the P × region interaction was greater in irrigated than dryland systems (Table 1). Season length and days to defoliation × region interactions were similar for both irrigated and dryland systems (Table 1). Overall the regression accounted for 41% and 97% of the variability in lint yield for irrigated and dryland systems, respectively (Table 1).

The highest lint yield (predicted) occurred at Bourke and the Gwydir, Upper Namoi, Macquarie, and Macintyre regions of New South Wales, with lower lint yield predicted for southern New South Wales and for the Central Highlands and Darling Downs regions of Queensland (Table 2). Lint yield has increased as new cultivars were provided to industry, with the exception of Sicot 70BL and Sicot 71RRF under dryland conditions, which had the lowest lint yield (Table 3).

There was a significant contribution to lint yield in dryland systems from the plant stand × region interaction, due to a high plant stand and low lint yield in the Central Highlands (data not shown).

Nitrogen application in irrigated systems was relatively consistent across all growing regions, with lower rates applied at Bourke and the Upper Namoi, and considerably lower rates of application in dryland systems (Table 4). This pattern was repeated for both P and K (Table 4). Average in-crop rainfall was similar across all regions, as was days to defoliation (Table 4).

Fibre quality

Factors significantly influencing cotton fibre quality were also similar for both irrigated and dryland systems, with cultivar selection and cotton region, along with the interactions between region and water (irrigation and rainfall respectively),

Table 1. Percentage contribution for significant factors ($P < 0.05$) and interactions to lint yield and fibre quality for irrigated and dryland cotton systems (2004–11)

N, Nitrogen; P, phosphorus. Number of records for irrigated and dryland 624 and 74, respectively

		Region	Cultivar	Plant stand × region	N × region	P × region	Irrigation × region	Rainfall × region	Season length × region	Days to defoliation × region	Variability accounted for (%)
Lint yield	Irrigated	26.2	n.s.	n.s.	3.2	3.8	5.3		4.4	4.1	41
	Dryland	47.2	10.0	19.2	10.2	0.5		5.8	2.7	3.4	97
Micronaire	Irrigated	19.0	18.8	3.6	n.s.	2.5	4.9		6.6	n.s.	50
	Dryland	10.1	22.3	n.s.	n.s.	10.4		22.3	11.7	7.7	77
Length	Irrigated	8.6	60.0	n.s.	1.5	n.s.	1.6		1.4	n.s.	71
	Dryland	7.7	40.6	n.s.	n.s.	n.s.		4.9	6.1	n.s.	87
Strength	Irrigated	15.1	11.2	4.6	n.s.	n.s.	2.8		n.s.	n.s.	30
	Dryland	15.6	21.0	n.s.	25.9	n.s.		8.2	6.0	10.1	80
Trash	Irrigated	10.1	10.2	n.s.	3.8	3.3	4.3		8.4	5.8	36
	Dryland	9.0	11.8	13.4	13.2	n.s.		5.2	n.s.	n.s.	78

Table 2. Cotton region and the effect on lint yield and fibre quality mean predicted values (2004–11)

Fibre quality parameters before discount: length >1.125 decimal inch, strength >29 g tex^{-1}, micronaire 3.8–4.5, and trash <5. s.e.d., Standard error of difference. To calculate predicted values, equations of the following forms were used: Lint yield = constant + region + region × plant stand + region × nitrogen + region × phosphorus + region × in-crop-irrigation + region × season length + region × days to defoliation + cultivar (for irrigated); Lint yield = constant + region + region × plant stand + region × nitrogen + region × phosphorus + region × rainfall + region × season length + region × days to defoliation + cultivar (for dryland)

Region	Lint yield (kg ha^{-1})		Length (decimal inch)		Strength (g tex^{-1})		Micronaire (no units)		Trash (no units)	
	Irrigated	Dryland	Irrigated	Dryland	Irrigated	Dryland	Irrigated	Dryland	Irrigated	Dryland
Bourke	2864		1.203		32.6		4.3		3	
Central Highlands	1880	700	1.169	1.307	29.6	29.1	4.2	4.0	3	3
Darling Downs	1856	617	1.173	1.193	31.1	32.8	4.0	4.3	3	4
Dawson/Callide	2459		1.143		27.3		4.9		2	
Gwydir	2544	1216	1.183	1.224	31.2	34.3	4.2	4.8	3	3
Lower Namoi	2053	1205	1.163	1.290	31.5	27.5	4.4	5.0	3	3
Macintyre	2436		1.177		30.4		4.4		2	
Macquarie	2310		1.172		31.3		4.1		2	
St George–Dirranbandi	2647		1.177		31.0		4.3		2	
Southern NSW	1996		1.168		31.5		4.3		3	
Tandou	2198		1.158		31.4		4.3		1	
Upper Namoi	2724		1.212		30.2		3.8		2	
s.e.d.	427	464	0.029	0.107	1.3	6.0	0.3	1.5	0.6	2

Table 3. Effect of cultivar on mean lint yield and fibre quality (predicted values, 2004–11)

Fibre quality parameters before discount: length >1.125 decimal inch, strength >29 g tex^{-1}, micronaire 3.8–4.5, and trash <5. s.e.d., Standard error of difference

Cultivar (year released)	Lint yield (kg ha^{-1})		Length (decimal inch)		Strength (g tex^{-1})		Micronaire (no units)		Trash (no units)	
	Irrigated	Dryland	Irrigated	Dryland	Irrigated	Dryland	Irrigated	Dryland	Irrigated	Dryland
Sicot 70BL (2010)	2111	268	1.174	1.237	29.9	39.4	4.2	4.8	3	4
Sicot 70BRF (2007)	2256	348	1.183	1.233	30.5	41.3	4.2	4.5	3	5
Sicot 71 (2002)	2294		1.127		30.7		4.3		2	
Sicot 71B (2006)	2210	354	1.181	1.250	30.1	39.8	4.3	4.7	2	5
Sicot 71BR (2004)	2288		1.143		30.7		4.5		2	
Sicot 71BRF (2008)	2305	387	1.193	1.242	30.5	40.3	4.2	4.6	3	4
Sicot 71 RR (2005)	2212		1.148		30.3		4.1		2	
Sicot 71 RRF (2009)	2295	268	1.145	1.237	30.8	39.6	4.1	4.8	2	4
Sicot 73 (2004)	2159		1.177		31.6		4.3		2	
Sicot 74 BRF (2010)	2368	380	1.206	1.253	31.1	41.1	4.4	4.8	3	5
Sicot 75 (2007)	2169	273	1.222	1.365	31.1	45.2	4.2	5.6	2	6
s.e.d.	75	162	0.006	0.037	0.3	5.0	0.1	0.5	0.1	0.7

Table 4. Nitrogen, phosphorus, and potassium rate applied by region, in-crop rainfall, and days to defoliation for each region under irrigated and dryland systems (2004–11)

Region	Nitrogen (kg N ha^{-1})		Phosphorus (kg P ha^{-1})		Potassium (kg K ha^{-1})		In-crop rain (mm)		Days to defoliation	
	Irrigated	Dryland	Irrigated	Dryland	Irrigated	Dryland	Irrigated	Dryland	Irrigated	Dryland
Bourke	153		11		2		346		170	
Central Highlands	215	15	28	4	40		377	373	154	141
Darling Downs	182	34	18	6	19	5	393	410	170	166
Dawson/Callide	216		10		14		414		152	
Gwydir	222	14	20	1	12		372	303	171	160
Lower Namoi	214		19		13		335	442	178	175
Macintyre	187	1	22		11		345	343	168	163
Macquarie	216		23		8		293		169	
St George–Dirranbandi	203		21		12		307		157	
Southern NSW	215		30		3		191		185	
Tandou	224		32		10		81		166	
Upper Namoi	152	69	12		3		347	416	174	174

N, P, and days to defoliation accounting for the majority of variation in fibre quality (Table 1). Regression accounted for 71, 50, 30, and 36% of the variability in fibre length, micronaire, fibre strength, and trash in fibre, respectively, in irrigated systems, and 87, 77, 80, and 78% in dryland systems (Table 1).

Mean fibre quality parameters (predicted) for all regions were mostly within the accepted range before any discount would be applied and were consistent between all regions. Exceptions were for lower fibre strength in irrigated systems in the Central Highlands and Dawson/Callide and in dryland systems in the Central Highlands and Lower Namoi, and for high micronaire in dryland systems in the Lower Namoi (Table 2).

Mean fibre quality parameters (predicted) for all cultivars were also within the accepted range before discounts would apply, with the exceptions of trash level in dryland systems and of Sicot 75 under dryland conditions, which produced high micronaire and trash values (Table 3). The predicted values of strength for Sicot 70BRF (mean ± standard error, $41 \pm 5\ \mathrm{g\,tex^{-1}}$) and Sicot 75 ($45 \pm 5\ \mathrm{g\,tex^{-1}}$) are unrealistic (possibly due to the low number of occurrences of these cultivars grown under dryland conditions); average measured values correspond to 31 and 31.3, respectively.

Changes in cotton farming systems 2004–11

There were fewer management data for dryland systems, so mainly irrigated systems are reported; however, where sufficient data were available, dryland systems are reported.

A wide range of N application rates was observed (Fig. 1*a*), with the trend for application rate to increase and the range of application rates to become smaller, with a smaller spread in outliers (Fig. 1*a*), during the period 2004–11. Phosphorus application rates varied, with the range in application rates also narrowing over time (Fig. 1*b*), whereas the range in K applied varied and use decreased over time (Fig. 1*c*). The rates of change of nutrient application rates over the period for N, P, and K were $+1.9\ \mathrm{kg\,N\,year^{-1}}$ ($P = 0.3$), $-1.5\ \mathrm{kg\,P\,year^{-1}}$ ($P = 0.01$), and $-4.0\ \mathrm{kg\,K\,year^{-1}}$ ($P = <0.01$), respectively. Plant population also varied over time, with a trend to lower populations in 2011 than in 2004 (Fig. 1*d*).The number of sprayings for insect management decreased (Fig. 1*e*), and the average number of in-crop irrigations decreased (Fig. 1*f*).

Previous crop did not account for a significant amount of the variability in lint yield (previous crop was significantly correlated with lint yield only in dryland systems, 0.46) or fibre quality; however, it was noted that, compared with back-to-back cotton, all crops or a fallow resulted in an increase in lint yield under irrigation, whereas only the legume, sorghum, and corn crops resulted in greater lint yield under dryland conditions (data not shown).

For irrigated systems, lint yield (Fig. 2*a*) and fibre length (Fig. 2*b*) increased, while fibre strength (Fig. 2*c*) and micronaire (Fig. 2*d*) varied, and trash levels (Fig. 2*e*) were reasonably consistent. For dryland systems, lint yield (Fig. 3*a*) decreased, while fibre length (Fig. 3*b*), fibre strength (Fig. 3*c*), and micronaire (Fig. 3*d*) increased, and trash levels (Fig. 3*e*) varied over the period 2004–11.

Discussion

This is the first attempt to critically identify factors that are of greater or lesser importance in contributing to lint yield and fibre quality across the Australian cotton industry. Liu *et al*. (2013) showed that lint yield improvements in the Australian cotton industry were due to availability of new cultivars and to cultivars responding to improved management (crop rotation, fertiliser and water management, and disease, pest, and weed management). They also acknowledged that there were no data available (up to 2009) to quantify management changes over the 30 years of their comparison, although it is known that growers attempt to increase season length for high yield by planting early, applying high N rates, and defoliating late.

It is acknowledged that the results may be biased to the extent that more innovative growers may be inclined to host variety trials. Notwithstanding this possibility, the data are still suitable for determining trends over time. The data utilised for this study included both dryland and irrigated crops and conventional (non-transgenic) and transgenic cultivars. It was speculated that the inputs identified as influencing yield and fibre quality would be similar under both systems, with the exception of water, where rainfall may have a positive effect in dryland and a negative effect in irrigated systems (due to the possibility of rain immediately post-irrigation causing water-logging), and that only the magnitude of the effect would be different. Also, the data cover all cotton-growing regions encompassing a range of environmental conditions, soil types (fertility levels, soil texture, and plant available water), and management strategies (timing of planting, fertiliser application, etc.), as opposed to management practices (amount of fertiliser, number of insect sprayings, etc.), which are not captured in this study. The significance of the effects of cotton region and cultivar and interactions of other factors with region in contributing to yield and fibre quality reflects the different management strategies and environments. Another potential outcome is the identification of trends that may be important over time to demonstrate industry performance with respect to technological change and custodianship in the environment.

Management inputs and productivity

Some of the trends (N applications, insect sprays) observed over the period 2004–11 have, to some extent, been in response to seasonal conditions, especially in dryland systems. Also, the interactions with cotton regions reflect the variation in soils and fertility status, climate, and management strategies of growers as indicated by differences in the level of contribution of factors to lint yield and fibre quality.

The plant stand (plants $\mathrm{ha^{-1}}$) × region interaction was a significant contributor in dryland systems, which may reflect differences in plant stand between regions affecting competition for resources or more vegetative growth. Plant stands were similar across all dryland regions except for the Central Highlands, which had greater populations and low lint yield. Constable (1977) also demonstrated that high plant populations had a detrimental effect on lint yield. Bange and Brodrick (2010) determined that there was a degree of plasticity in plant population, with an optimum of 80 000–120 000 plants $\mathrm{ha^{-1}}$. The uniformity of the final plant stand is an important factor in

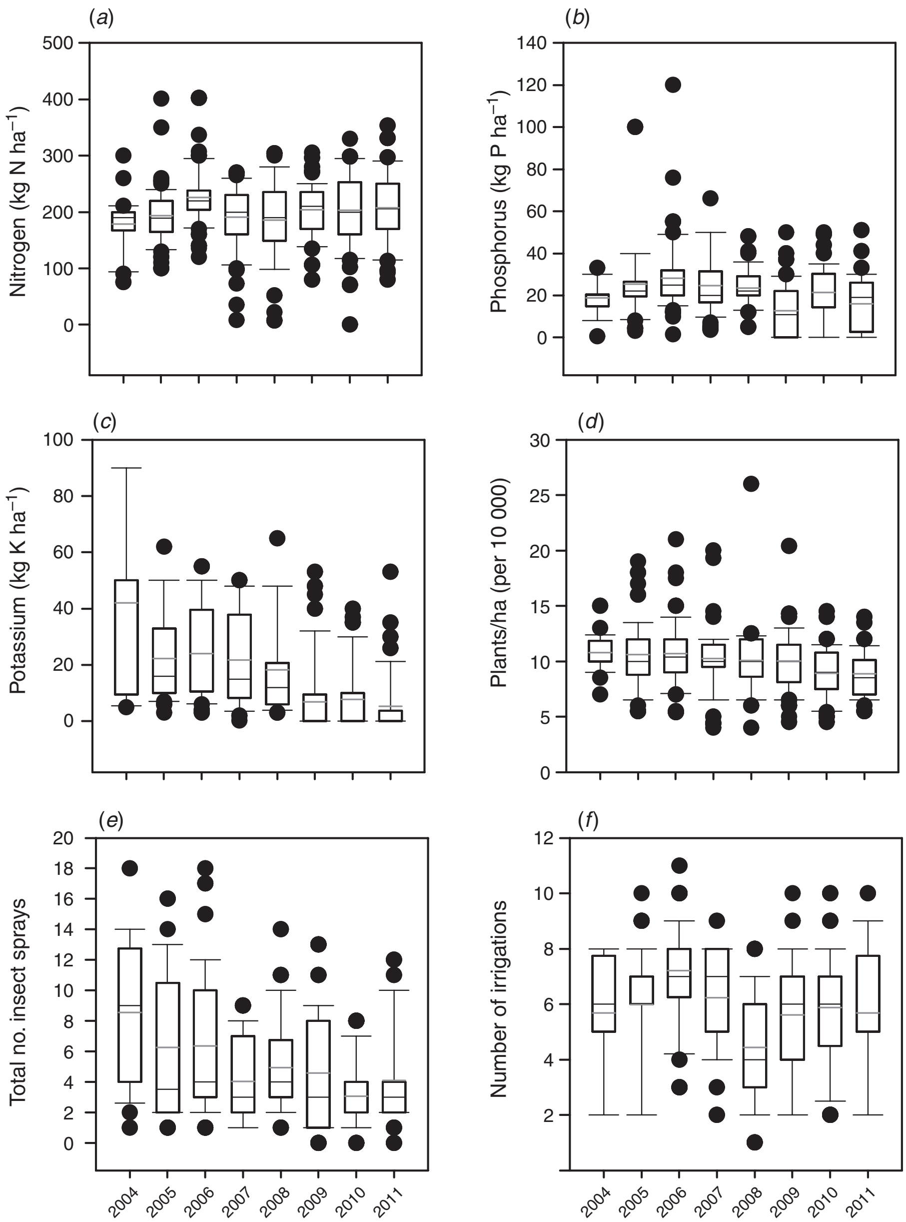

Fig. 1. Changes in management: (*a*) nitrogen application, (*b*) phosphorus application, (*c*) potassium application, (*d*) plant population, (*e*) number of insect sprays, and (*f*) number of irrigations under irrigated systems from 2004 to 2011. The top and bottom whiskers are the 90th and 10th percentile, the top and bottom of the box are the 75th and 25th percentile, with the grey and black lines being the mean and medium values, respectively; outliers are represented by dots above and below the whiskers.

managing the crop and determining yield (Wanjura 1980); however, this information was not recorded in the data used in this study. It may be useful to conduct an industry survey into uniformity of crop establishment to assess whether this is limiting productivity.

The interaction of N × region was identified as a significant factor contributing to lint yield in both irrigated and dryland systems, with greater importance in dryland than irrigated systems. This would reflect the differences in soil types and inherent fertility between regions. Research has demonstrated that application of 100–200 kg N ha^{-1} results in the greatest contribution to lint yield (Rochester *et al*. 2005). The amount applied would depend on residual fertility after a rotation crop and the amount required to replenish that removed in the harvested material. Lower and higher rates resulted in lower lint yield, indicating either under- or over-fertilisation (Rochester 2010). Further research could identify levels of application to optimise nutrient-use efficiency and potentially reduce the amount and cost of nutrient applied. Nitrogen rates were relatively consistent across all regions for irrigated systems and more varied across dryland systems. This possibly reflects seasonal conditions and profile water under dryland conditions.

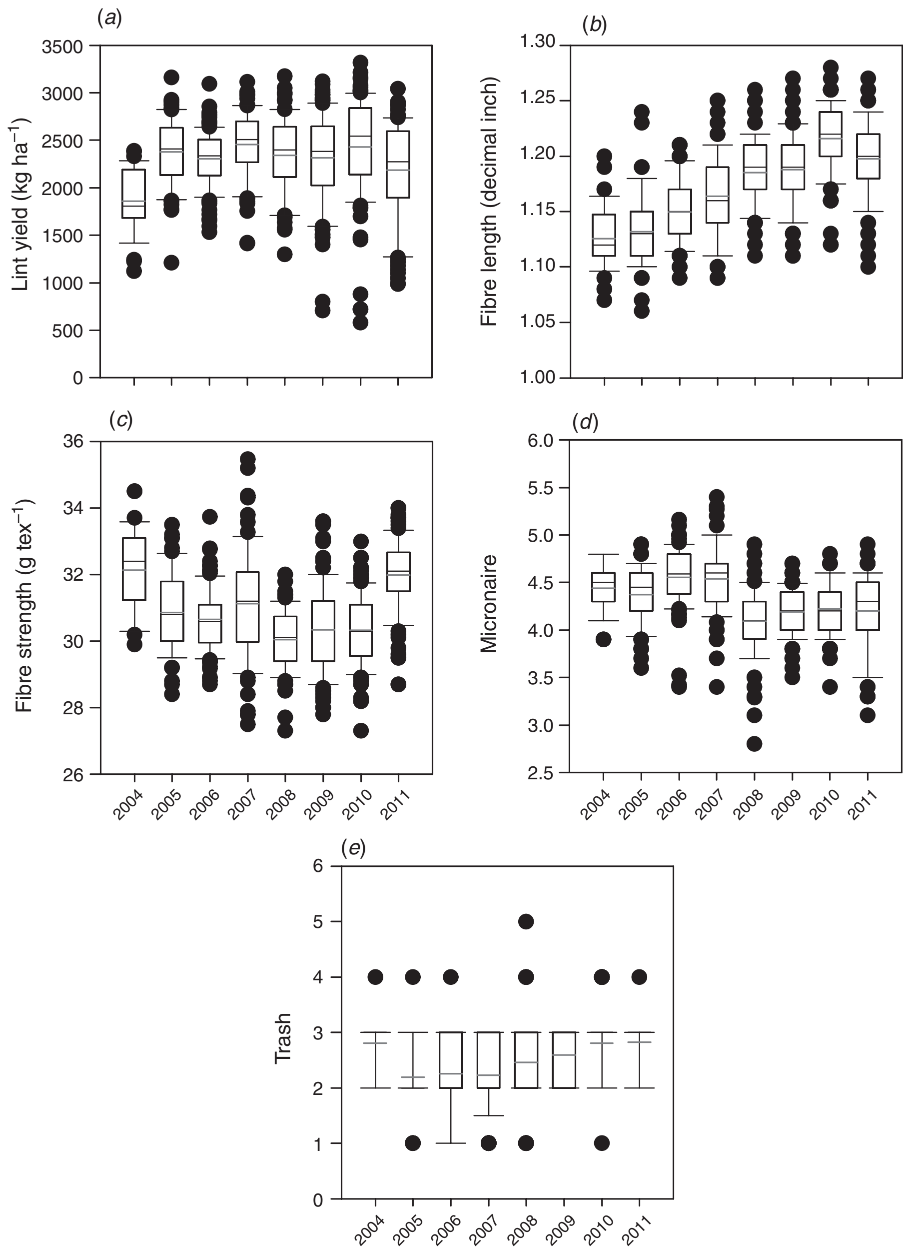

Fig. 2. Changes in lint yield and fibre quality: (*a*) lint yield, (*b*) length, (*c*) strength, (*d*) micronaire, and (*e*) trash score under irrigated systems from 2004 to 2011.

Under irrigation, the most distinctive region was the Central Highlands, where N application rates similar to other regions resulted in lower lint yield than in the other regions. This may be a response to environmental conditions (higher season maximum temperature) and highly variable rainfall. For different soil types and locations, Girma *et al*. (2007) and Saleem *et al*. (2010) showed that the highest lint yield was obtained at an N rate of 135 and 120 kg N ha^{-1}, respectively, which is within the range indicated above.

The interaction of P × region was also a significant factor in irrigated and dryland systems, being more important under irrigated than dryland systems. Research has indicated that 40 kg P ha^{-1} was required to produce a yield response in cotton on shallow cracking clay soils in central Queensland (Hibberd *et al*. 1990) and a clay loam soil in the USA (Girma *et al*. 2007). The data indicate that growers are applying about half this amount, which suggests accumulation of soil P may be occurring. The unknown in nutrition responses is whether the soil was responsive to the applied fertiliser or whether the application was required. It does appear that excessive amounts of some nutrients are being applied at some sites, as has also been observed by Rochester (2007).

The interactions of irrigation × region and rainfall × region were similar and significant for irrigated and dryland systems,

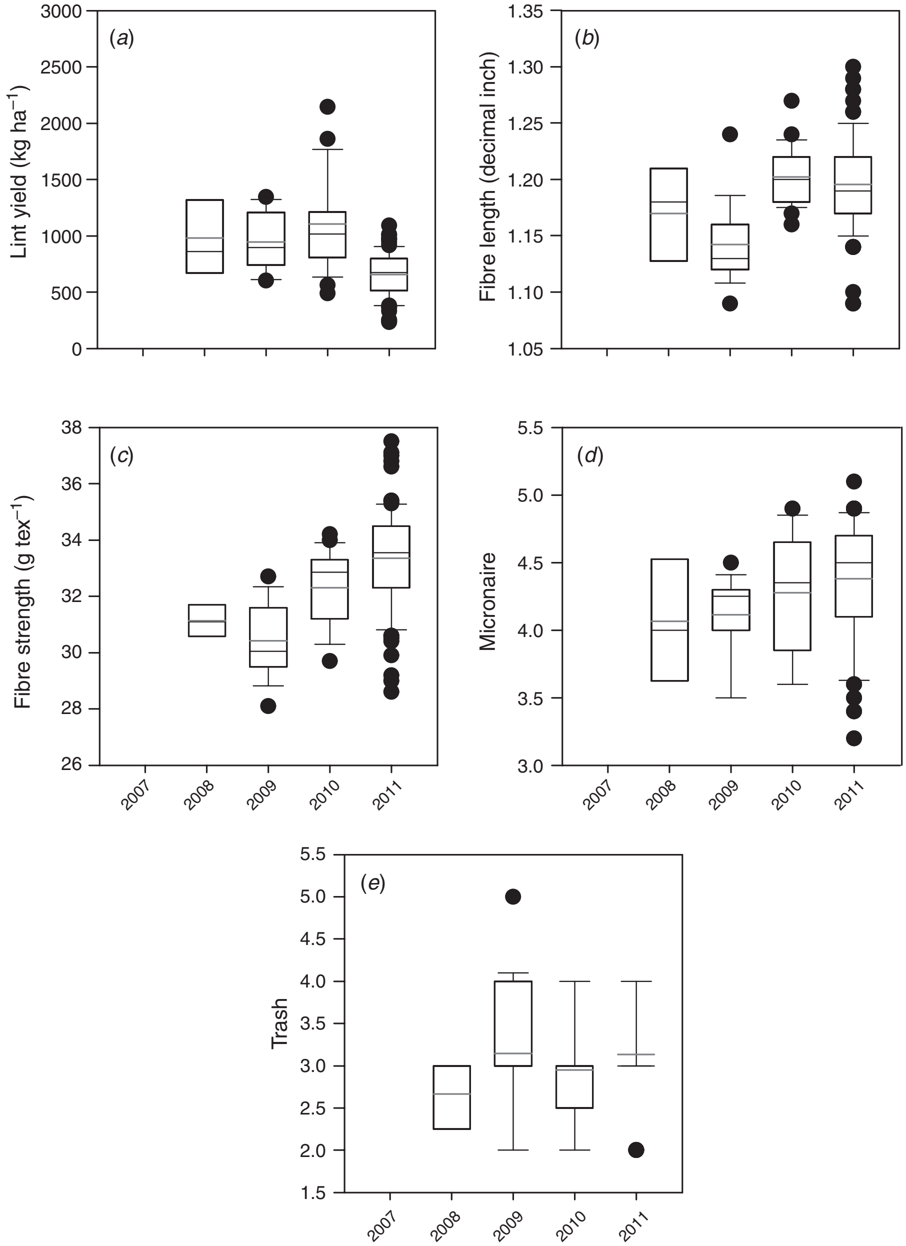

Fig. 3. Changes in lint yield and fibre quality: (*a*) lint yield, (*b*) length, (*c*) strength, (*d*) micronaire, and (*e*) trash score under dryland systems from 2004 to 2011.

reflecting the importance of water to both systems. The number of irrigations will depend on the amount of available water and on whether significant in-crop rainfall occurs. The timing of irrigation in relation to rain cannot be controlled, so if rain occurs after irrigation, there may be an effect on subsequent crop growth, lint yield, and quality of fibre (Bange *et al*. 2004). Generally, the number of irrigations varied, and this was in response to seasonal conditions and soils within a region. The data indicate that the average number of irrigations was six over the period 2004–11. Under dryland conditions, the general trend was for an increase in lint yield as rainfall increased across all regions.

In response to the adoption of Bollgard® cultivars and IPM strategies, the total number of insect sprayings has decreased without compromising lint yield, which agrees with the observations of Pyke (2007). This also contributes to reducing the cost of production. It is thought that this would also contribute to a more positive image of the cotton industry from a public perspective.

Although not a significant factor, lint yield tended to be greater after a rotation crop or fallow than after cotton in irrigated systems and was variable in dryland systems. Presumably this is due to improvements in soil conditions (physical, chemical, and biological), although few studies have been undertaken to quantify this (Hulugalle and Scott 2008). Also, the response under dryland conditions will depend on the amount of stored profile water and in-crop rainfall. Dryland lint yield following a legume was greater than after any other break-crop, presumably due to the N contribution by the legume (Daniel *et al*. 1999). However, in the USA, under a dryland system the effect of rotation crops (cover crops) varied, with the lint yield being greater after a vetch and rye mixture than after wheat in one season and no different after any rotation crop in the following season (Daniel *et al*. 1999), which highlights seasonal variability. It is speculated that the effect of a rotation crop on lint yield is due to improved soil conditions rather than the rotation *per se*. Hulugalle *et al*. (2004) indicated that wheat as a rotation crop under different tillage regimes improved soil chemistry, reduced black root rot, and increased air-filled porosity, resulting in greater lint yield; the response was most likely due to tillage rather than the rotation. Also, no assessment was made of other soil physical properties that influence root growth, such as soil strength and bulk density.

Fibre quality is the culmination of cultivar choice and crop management and, above all, seasonal conditions. The cultivars used in the analysis all produced fibre that met the base-grade criteria (Gordon *et al*. 2004), with the exception of Sicot 75 under dryland conditions, where micronaire and trash did not meet base grade. The general trend was that trash levels were higher under dryland systems than under irrigation. This could also be due to samples from dryland trials being subsamples taken during picking and processed using a 20-saw gin, which would not clean the lint as effectively as a commercial gin. Fibre length and strength are largely determined by the genetics of the cultivar, whereas micronaire is significantly influenced by seasonal conditions. Fibre quality is the result of many interacting factors, which makes it difficult to identify those that are of greater or lesser importance. It is assumed that growers choose the most appropriate cultivar for their particular growing conditions. The quality of cotton fibre affects the processing of the fibre and its attractiveness to spinners and garment manufacturers (Bange *et al.* 2009). It is presumed that when fibre quality falls to the level where a discount is incurred, this is due to circumstances beyond the grower's control, such as late rain damage, insect secretions, or dust (Bange *et al*. 2009).

Industry changes over time

Changes have occurred in the Australian cotton industry during the period 2004–11, in both irrigated and dryland systems. With few exceptions, the changes have been in the same direction in irrigated and dryland systems, with the magnitude of change being greater in irrigated systems. This reflects seasonal conditions and the difference in water availability between the two systems.

Nitrogen use had a small, non-significant increase under irrigation and a decrease under dryland systems, again reflecting seasonal conditions. Phosphorus use decreased in both systems, which may indicate build-up of soil P levels. Potassium use declined under irrigation and remained static for dryland systems. Potassium can have a direct effect on fibre length (through maintaining cell turgor) and micronaire (low K causes leaf senescence resulting in reduced fibre maturity; Bange *et al*. 2009). Growers may need to maintain a watching brief on soil K levels to ensure that they do not reach critically low levels, which may exacerbate fibre maturity.

The number of irrigations fluctuated, which was largely influenced by water availability during the period considered; an extended drought was experienced from 2006 to 2008. When considered in terms of crop water-use efficiency, both irrigated and dryland lint yield has increased over this period (Constable *et al*. 2011). Lint yield increased from 2004 to 2011 in irrigated systems, potentially indicating better resource-use efficiency (Montgomery *et al*. 2009) and wide adoption of better performing cultivars (G. Constable, pers. comm., 2012).

The number of insect sprayings also decreased due to the adoption of transgenic cultivars by the Australian cotton industry. This again reflects the industry's response to environmental issues and adoption of IPM strategies (Fitt *et al*. 2009).

The indication is that rotation crops are an accepted part of the farming system. These crops are utilised to provide soil cover and ameliorate structural degradation, to reduce soil-borne disease inoculums, provide weed control, increase soil N and soil carbon levels, and potentially generate income, which agrees with the findings of Cooper (1999). However, few studies have been undertaken to assess the interaction between soil physical, chemical, and biological conditions on subsequent performance of cotton.

Lint yield and fibre quality changes over time were similar in irrigated and dryland systems, with the magnitude of change being greater with irrigation; lint yield increased under irrigation and decreased under dryland systems. Overall lint yield increased from 2004 to 2011, by 35.8 kg ha^{-1} $year^{-1}$ ($P = 0.005$) for the Australian cotton industry, which is consistent with the observation of a 1.8% increase in lint yield per year since the 1970s (Constable *et al*. 2001) and a 1.17% increase (Liu *et al*. 2013) with the introduction of new cultivars. Strength decreased and length increased in irrigated systems, and both increased in dryland systems. The increase in fibre length in both systems can be attributed to the adoption of cvv. Sicot 71B, Sicot 71BRF, Sicot 73, and Sicot 74BRF with increased fibre length (Table 3). The trends for dryland systems were affected by the extended drought during the period considered. This may indicate that differences in management and climate have a greater influence than the underlying genetics of the cultivar.

The relative importance of components in a farming system differs with season and region and with the management style of the individual grower. Although N and P applications in the Central Highlands and Dawson/Callide were within the range suggested by Rochester *et al*. (2005), the resulting lint yield was lower than for other cotton regions where similar levels of nutrients were applied, and fibre quality parameters just fulfilled base-grade requirement. In contrast, the Gwydir region used similar levels of N and P, which resulted in greater lint yield and all fibre quality parameters meeting base grade. This suggests that differences in climate and natural resources may have a greater effect on the outcome than management decisions or inputs. The cultivars chosen as the standards all produced lint yield >2000 kg ha^{-1} under irrigation, and fibre quality was above base grade, which confirms data from the Australian Cotton Shippers Association (ACSA 2012). Under dryland conditions, Sicot 75 did not perform as well as the other cultivars, in that low lint yield and micronaire below base grade were produced; however, it should be remembered that these are predicted values (mean values from data: lint yield 1121 kg ha^{-1} and micronaire 4.0).

Kirkegaard and Hunt (2010) highlighted the importance of managing the system before the intended crop, in their case, wheat. They examined the effect of crop sequence (rotation), weed control, residue management, and the long coleoptile trait in wheat using a crop simulation model (Keating *et al*. 2003) in capturing the benefit of different management systems on yield and water-use efficiency. Such an integrated approach has not been undertaken for cotton production systems. Several long-term studies have examined the effect of rotations on soil quality and the profitability of cotton systems, without considering the wider aspect of previous management (Hulugalle and Scott 2008).

Conclusions

Factors with a positive effect on lint yield included region, cultivar, and the interactions between region and number of irrigations, rainfall, previous crop, N, P, days to defoliation, and season length for both irrigated and dryland systems. The factors affecting fibre quality were the same as those affecting lint yield.

For irrigated systems, the Central Highlands and Dawson/Callide regions produced the lowest lint yield despite applying rates of N and P similar to all other cotton regions. Under dryland conditions, Sicot 75 produced the lowest lint yield and below-grade micronaire; however, it also produced the strongest fibre. The results showing which inputs are the most important and those of lesser importance provide some insight to changes in management in both irrigated and dryland systems and the effect on lint yield and fibre quality. These results provide the basis for future research such as effects of crop uniformity on production, whether applied P is accruing at depth, why K use is declining, and the effect on fibre quality and levels of nutrients to optimise nutrient-use efficiency and potentially reduce the amount and cost of nutrient applied, and extension delivery to the Australian cotton industry. The database should be utilised for further studies on trends occurring in the Australian cotton industry.

Acknowledgements

Funding was provided by the Cotton Catchment Community CRC. Cotton Seed Distributors provided access to their electronic variety trial data (2004 to 2007). Dr Nilantha Hulugalle provided results from the long-term experiments at the Australian Cotton Research Institute. Dr Shiming Lui provided helpful insights for the REML and stepwise regression analyses. The reviewers are thanked for improvements to the manuscript.

References

ACSA (2012) 2012. Australian Cotton Shippers Association. Available at: www.austcottonshippers.com.au/reports2012.html

Bange M, Brodrick R (2010) Do the sowing rules change for Bollgard II cotton? *The Australian Cottongrower* **31**, 11–14.

Bange MP, Milroy SP, Thongbai P (2004) Growth and yield of cotton in response to waterlogging. *Field Crops Research* **88**, 129–142. doi:10.1016/j.fcr.2003.12.002

Bange MP, Constable GA, Gordon SG, Long RL, Naylor GRS, van der Sluijs MHJ (2009) 'Fibrepak. A guide to improving Australian cotton fibre quality.' (Cotton Catchment Communities CRC: Narrabri, NSW)

Charles GW, Taylor IN (2003) Herbicide resistance and species shift in cotton: the need for an integrated weed management (IWM) approach. In '3rd World Cotton Research Conference'. Cape Town, South Africa, 3 March 2003. (Ed. A Swanepoel) (South African Agricultural Research Council—Institute for Industrial Crops: Pretoria) (CD-ROM)

Constable GA (1977) Narrow row cotton in the Namoi Valley. 2. Plant population and row spacing. *Australian Journal of Experimental Agriculture and Animal Husbandry* **17**, 143–147. doi:10.1071/EA9770143

Constable GA (2004) Research's contribution to the evolution of the Australian cotton industry. In '4th International Crop Science Congress'. Brisbane, Australia. pp. 1–9.

Constable GA, Reid PE, Thompson NJ (2001) Approaches utilized in breeding and development of cotton cultivars in Australia. In 'Genetic improvement of cotton emerging technologies'. (Eds JN Jenkins, S Saha) (Science Publishers: Enfield, NH)

Constable G, Stiller W, Clancy L (2011) Dryland cotton water use efficiency—production statistics. *The Australian Cottongrower* **32**, 17–19.

Cooper JL (1999) A grower survey of rotations used in the New South Wales cotton industry. *Australian Journal of Experimental Agriculture* **39**, 743–755. doi:10.1071/EA98055

Daniel JB, Abaye AO, Alley MM, Adcock CW, Maitland JC (1999) Winter annual cover crops in a Virginia No-till cotton production system: II Cover crop and tillage effects on soil moisture, cotton yield, and cotton quality. *Journal of Cotton Science* **3**, 84–91.

Fitt G, Wilson L, Kelly D, Mensah R (2009) Advances with integrated pest management as a component of sustainable agriculture: The case of the Australian cotton industry. In 'Integrated pest management: Dissemination and impact'. Ch. 17. (Eds R Peshin, AK Dhawan) (Springer Science+Business Media B.V.: Berlin)

Galan MB, Peschard D, Boizard H (2007) ISO 14 001 at the farm level: Analysis of five methods for evaluating the environmental impact of agricultural practices. *Journal of Environmental Management* **93**, 131–145.

Girma K, Teal RK, Freeman KW, Boman RK, Raun WP (2007) Cotton lint yield and quality as affected by application of N, P, and K fertilizers. *Journal of Cotton Science* **11**, 12–19.

Gordon SG, van der Sluijs MHJ, Prins MW (2004) Quality issues for Australian cotton from a mill perspective. Technical Report. CSIRO/Australian Cotton Cooperative Research Centre, Narrabri, NSW. Available at: www.csiro.au/files/files/p4mz.pdf

Hearn AB, Fitt GP (1992) Cotton cropping systems. In 'Field crop ecosystems'. (Ed. CJ Pearson) pp. 85–142. (Elsevier: Amsterdam)

Hibberd DE, Laedwig JH, Hunter MN, Blight GW (1990) Responses in cotton yields to nitrogen and phosphorus fertilisers in the Emerald irrigation area, central Queensland. *Australian Journal of Experimental Agriculture* **30**, 661–667. doi:10.1071/EA9900661

Hulugalle NR, Scott F (2008) A review of the changes in soil quality and profitability accomplished by sowing rotation crops after cotton in Australian Vertosols from 1970 to 2006. *Australian Journal of Soil Research* **46**, 173–190. doi:10.1071/SR07077

Hulugalle NR, Nhel DB, Weaver TB (2004) Soil properties, cotton growth, yield and fibre quality in three cotton-based cropping systems. *Soil & Tillage Research* **75**, 131–141. doi:10.1016/j.still.2003.07.003

Hulugalle NR, Weaver TB, Scott F (2006) Maintaining profitability and soil quality in cotton farming systems. Final Report, CRC 45C. Cotton Research and Development Corporation, Narrabri, NSW.

Hulugalle NR, Weaver TB, Scott F (2009): Maintaining profitability and soil quality in cotton farming systems II. Final Report, CRC 45C. Cotton Research and Development Corporation, Narrabri, NSW.

VSN International (2010) 'GENSTAT version 13.' (VSN International: Hemel Hempstead, UK)

Keating BA, Carberry PS, Hammer GL, Probert ME, Robertson MJ, Holzworth D, Huth NI, Hargreaves JNG, Meinke H, Hocham Z, McLean G, Verberg K, Snow V, Dimes JP, Silburn M, Wang E, Brown S, Bristow KL, Asseng S, Chapman S, McCowan RL, Freebairn DM, Smith CJ (2003) An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy* **18**, 267–288. doi:10.1016/S1161-0301(02)00108-9

Kirkegaard JA, Hunt JR (2010) Increasing productivity by matching farming system management and genotype in water limited environments. *Journal of Experimental Botany* **61**, 4129–4143. doi:10.1093/jxb/erq245

Knox OGG, Constable GA, Pyke B, Gupta VVSR (2006) Environmental impact of conventional and Bt insecticidal cotton expressing one and two Cry genes in Australia. *Australian Journal of Agricultural Research* **57**, 501–509. doi:10.1071/AR05366

Lawes RA, Lawn RJ (2005) Applications of industry information in sugarcane production systems. *Field Crops Research* **92**, 353–363. doi:10.1016/j.fcr.2005.01.033

Liu SM, Constable GA, Reid PE, Stiller WN, Cullis BR (2013) The interaction between breeding and crop management in improved cotton yield. *Field Crops Research* **148**, 49–60. doi:10.1016/j.fcr.2013.04.006

McIntyre G, Pyke B, Hickman M, Shaw G, Gibb D, Dugdale H, Delaney K (2002) Cotton industry benchmarking study 2001—a review. In 'Proceedings 11th Australian Cotton Conference'. (Australian Cotton Growers Research Association: Orange, NSW) (CD-ROM)

Montgomery J, Jackson R, Quarisa I, Williams D (2009) Benchmarking water use efficiency in the cotton industry. In 'Proceedings Irrigation and Drainage Conference'. 18–21 October 2009, Swan Hill, Vic. (Irrigation Australia: Mascot, NSW)

Piepho HP, Denis JB, Eewijk FA (1998) Predicting cultivar differences using covariates. *Journal of Agricultural Biological & Environmental Statistics* **3**, 151–162. doi:10.2307/1400648

Pyke B (2007) The impact of high adoption of Bollgard II cotton on pest management in Australia. In 'Proceedings World Cotton Research Conference-4'. September 2007, Lubbock, Texas, USA. Revised edn. (International Cotton Advisory Committee: Washington, DC) (CD-ROM)

Rochester IJ (2007) Efficient use of nitrogen fertilisers. *The Australian Cottongrower* **27**, 48–50.

Rochester IJ (2010) Assessing internal crop nitrogen use efficiency in high-yielding irrigated cotton. *Nutrient Cycling in Agroecosystems* **90**, 147–156. doi:10.1007/s10705-010-9418-9

Rochester IJ, Constable GA, Dowling C (2005) Understanding Bollgard II nutrition. *The Australian Cottongrower* **26**, 14–16.

Roth G (2010) Economic, environmental and social sustainability indicators of the Australian cotton industry. PhD, University of New England, Armidale, NSW, Australia.

Saleem MF, Bilal MF, Awais M, Shahid MQ, Anjum SA (2010) Effect of nitrogen on seed cotton yield and fiber qualities of cotton (*Gossypium hirsutum* L.) cultivars. *Journal of Animal & Plant Science* **20**, 23–27.

Skinner JA, Lewis KA, Bardon KS, Tucker P, Catt JA, Chambers BJ (1997) An overview of the environmental impact of agriculture in the UK. *Journal of Environmental Management* **50**, 111–128. doi:10.1006/jema.1996.0103

van der Werf HMG, Petit J (2002) Evaluation of the environmental impact of agriculture at the farm level: a comparison and analysis of 12 indicator-based methods. *Agriculture, Ecosystems & Environment* **93**, 131–145. doi:10.1016/S0167-8809(01)00354-1

Walker SR, Taylor IN, Milne G, Osten VO, Hoque Z, Farquharson RJ (2005) A survey of management and economic impact of weeds in dryland cotton cropping systems of subtropical Australia. *Australian Journal of Experimental Agriculture* **45**, 79–91. doi:10.1071/EA03189

Wanjura D (1980) Cotton yield response to plant stand. *Transactions of the American Society of Agricultural Engineers* **23**, 60–64.