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**Evaluation of yield component changes in Australian
cotton cultivars**

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ABSTRACT	1
INTRODUCTION	3
MATERIALS AND METHODS.....	5
TREATMENTS	5
<i>Irrigated cotton experiment</i>	5
<i>Pima cotton irrigated trial</i>	6
CULTURAL PRACTICES.....	7
DATA COLLECTION.....	10
<i>Plant mapping</i>	10
<i>Yield components</i>	13
FIBRE QUALITY.....	16
DATA ANALYSIS	16
RESULTS.....	17
PLANT MAPPING	17
YIELD COMPONENTS	21
<i>Cultivar effects</i>	21
<i>Location (environmental) effects</i>	25
<i>Correlation and covariances of yield components</i>	25
<i>Relationship between yield components</i>	26
QUALITY	27
<i>Location (Environmental) Effects</i>	27
PIMA COTTON	30
DISCUSSION	31
PLANT MAPPING	31
YIELD COMPONENTS	32
LOCATION (ENVIRONMENTAL) EFFECTS	34
CORRELATION AND COVARIANCES OF YIELD COMPONENTS	34
RELATIONSHIP BETWEEN YIELD COMPONENTS	35
QUALITY	36
PIMA COTTON	37
CONCLUSIONS.....	38
ACKNOWLEDGEMENTS.....	40
REFERENCES	41
APPENDIX	43

Evaluation of yield component changes in Australian cotton cultivars

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Abstract

Cotton yield can be broken down into the components that make up the total lint yield. For cotton, these are bolls/m², seeds/boll and lint/seed. Whilst the cotton lint yields have been increasing, there has been little work done on whether yield components in Australian cultivars have changed over time. The aim of this experiment was to test the hypothesis that yield improvements in Australian cotton (*Gossypium hirsutum*) cultivars were primarily achieved through an increase in boll size (lint/boll). Six cultivars were used, two from the early 1970s (DP16 and Namcala), two from the mid 1990s (Sicala 40 and Sicot 189) and two current cultivars (Sicot 71 and Sicot 71B), the latter of which was a Bollgard II cultivar. These cultivars were grown in a replicated field experiment in three locations, selected to represent different cotton growing climates of NSW, Boggabilla (hot), ACRI (Australian Cotton Research Institute) at Narrabri (medium) and Carroll (cool). Throughout the fruiting period, plants were mapped at regular intervals to monitor fruit development. At maturity bolls were harvested and the various yield components and fibre quality traits were analysed. Yield components of two pima cotton (*Gossypium barbadense*) cultivars, SiPima and Pima S7 were also recorded. Throughout the growing season, all conventional cultivars set and retained similar numbers of fruit, while the Sicot 71B had significantly higher fruit retention rates. However, boll sizes (lint/boll) were smaller mainly due to reduced seeds/boll and hence, Sicot 71B did not yield any more lint than the other modern cultivars, including Sicot 71. Yield improvements over time were primarily due to an increase in boll

size (lint/boll), which is generally due to an increase in lint/seed. There was a negative linear relationship between boll retention and seeds/boll, and boll retention and fruiting sites/m². Lint/seed was a relatively stable component and was not negatively related to boll retention. Hence, to increase yields of future high yielding cotton cultivars, including Bollgard cultivars, it could be beneficial to select for high lint/seed in order to have larger boll sizes (lint/boll). Yields were quite similar in the three locations as there was compensation in yield components. This study will assist breeders to focus selection pressure on increasing lint/seed to continue the improvements in Australian cotton yields.

Keywords/phrases: cotton, yield components, yield, retention, fruit development, lint/seed

Introduction

Australia typically produces 3 million 227 kg bales of cotton lint each year, of which more than 95% is exported. Of all the countries that produce in excess of 200,000 bales of cotton per annum, Australia holds the record of the world's highest average yield at 1779 kg/ha. Second to Australia is Syria with 1364 kg/ha (Cotton Year Book 2004). Cotton farmers are paid according to the total amount of lint and seed that they produce, thus, producing as much cotton lint and seed as possible by having high yields is what farmers and breeders aim to do. Prices paid however, can be discounted if certain lint quality attributes are not met. Cotton breeding still focuses primarily on yield (Hearn and Constable 1984).

Yield is the result of a series of concomitant, difficult to define, responses. (Worley *et al.* 1976). The yield of any crop can be broken down into its components to determine how yield is attained. In an attempt to facilitate breeding for high yields it is logical to examine the various components individually. This way, the components having the greatest influence on yield, in both a positive and negative manner, can be identified (Kambal 1969; Sharma and Singh 1999). Thus, this gives direction for breeding programs aimed at improving overall yield (Board 1987).

The relationships among cotton lint yield and its components are complex. The components are influenced by genetic and environmental variation and by the interaction between these two (Worley *et al.* 1974). By knowing about yield components, the effects of various pressures, such as insect pressures, can be measured directly upon the yield forming structures and processes of the cotton plant.

The primary lint yield components that contribute to lint yield are bolls per unit area, seeds/boll and lint/seed (Kerr 1966; Manning 1956; Wilson *et al.* 1994; Worley *et al.* 1974) Lint, seed and seed cotton

biomass are closely related to the number of bolls per unit area (Wells and Meredith 1984). This is analogous to the relationship between kernel number and yield in grain crops.

The most commonly used and accepted yield component equation is the geometric model proposed by Kerr (1966) and is shown below. There are several equations that have been put forth relating yield to its components.

$$\text{Yield} = \text{bolls/unit area} \times \text{seeds/boll} \times \text{lint/seed} \text{ (Kerr 1966)}$$

More recently summarised by (Heitholt 1999) as $\text{Yield} = \text{number of bolls/unit area} \times \text{mass of lint/boll}$ which is very similar as seeds/boll and lint/seed are the key contributors to boll size. Different yield component equations are useful to help describe how yield is attained depending on the characteristics breeders wish to place emphasis on. Data availability also helps determine which equation is used.

Different yield components contribute varying degrees of importance to cotton lint yields. Increases in yield are generally associated with the number of bolls (Pettigrew 1994; Wells and Meredith 1984)). Other components, such as lint/seed, number of seeds/boll, and lint/boll are generally less likely to be correlated with yield than boll number (Meredith 1984). The number of bolls/m² is determined by the number of fruiting sites initiated and the number of bolls retained. Boll size was believed to be negatively correlated with genetic variation in yield (Meredith and Bridge 1971). Although higher yields due to favourable environmental conditions (within a genotype) can be associated with larger bolls (Mauney *et al.* 1978), boll size is often thought to be unrelated to yield (Heitholt *et al.* 1993).

More knowledge is required regarding how yield components have changed over time, and the environmental influences on Australian cultivars. Studies have shown which components have changed in American cultivars, but these were based on obsolete cultivars. By knowing what components have changed, the extent to which breeder's aims are being met can be quantified. The

important components can be targeted in specific environments to continue Australia's breeding efforts. The aim of this study is to test the hypothesis that the increase in boll size (lint/boll) is the primary contributor to yield advancements in modern Australian cotton cultivars. This study also tested the hypothesis that the increase in bolls/m² is the primary contributor to the increase in yield of Pima cotton cultivar Si-Pima compared to Pima S-7.

Materials and methods

Treatments

Irrigated cotton experiment

Six cotton (*Gossypium hirsutum*) cultivars were grown at three different locations in northern NSW over the 2004/2005 season. The three sites were chosen to give a range of environmental conditions across the cotton growing region of northern NSW. Boggabilla (near Goondiwindi) represents a hot cotton growing region, Australian Cotton Research Institute (ACRI), Myall Vale, 30 km west of Narrabri represents a moderate region and Carroll, the Breeza plains south of Gunnedah represents a cool cotton growing region for NSW. "Korolea" at Boggabilla (28° S, 150° E) and "Long Acres" at Carroll (30° S, 150° E) are commercial properties that allow research experiments to be conducted each year. ACRI (33° S, 151° E) is the principal research station for CSIRO's Plant Industry (Cotton Research Unit) and the Cotton Catchment Communities Research Centre in Australia.

The 6 cultivars were chosen to represent a progression in Australian cotton cultivars from the early 1970's to current cultivars (Table 1). DP 16 and Namcala were used in this project as reference cultivars for all others to be compared. The cultivar Sicot 71B is a genetically modified Bollgard II® cultivar that contains both *CryIAc* and *CryAb* genes of the *Bacillus thuringiensis* bacteria.

Table 1: Cotton cultivars used and their time of commercial release

Cultivar	When released
DP 16	Early 1970s
Namcala	
Sicala 40	Early 1990s
Sicot 189	
Sicot 71	Early 2000s
Sicot 71B	

The cultivars were planted in a randomised complete block design with four replicates (blocks) at each location. In each block, there were three 10 m rows of each cultivar next to each other. Looking from the tail drain, the row on the furthest right hand side of the three rows was used for measurements. The first plant measured was 1 m in from the end of the row and was marked. A one m row of plants were marked so that the same plants could be measured on each visit.

Pima cotton irrigated trial

Two Pima cotton (*Gossypium barbadense*) cultivars, Pima S-7 and Si-Pima, were grown under irrigated conditions both on the ACRI site and on the adjoining “Leitch’s” property. Pima S-7 is the reference cultivar and Si-Pima is a new cultivar bred by the CSIRO, yet to be released. Pima cotton is not grown extensively in Australia due to its low yields and susceptibility to bacterial blight but a premium is paid due to its long staple length. The only Pima variety grown in Australia for many years has been Pima S-7.

The experimental design for the Pima cotton experiment was also a randomised complete block design with 4 replicates at each site (“Leitch’s” and ACRI). As with the cotton experiments, there were three 10 m rows of each cultivar next to each other and 1 m of plants were marked for repeated measurement on the furthest right hand row looking from the taildrain.

Cultural practices

All of the sites used in this project were managed under “Best Management Practices” (as stipulated by Cotton CRC publications). Irrigation scheduling was decided by individual farm managers combining the software Hydrologic® and via field inspection as well by the calendar, so that irrigation generally occurs every 10-12 days, depending on temperatures and rainfall events.

All fields were monitored for insects by experienced personnel on a regular basis and a decision whether to spray with insecticide would be made. Decisions would be made by the farm manager with advice from the agronomist/consultant, and would follow the guidelines set out by the Cotton CRC’s Pest Management Guide. Sprays occurred via ground rig and by fixed wing aircraft following canopy closure. Weeds were also monitored closely but were not a significant problem due to proper management and planning during the period leading up to planting. Mechanical weed control was carried out by side furrow cultivation or by cotton chippers. None of the cultivars used were genetically modified Roundup Ready™ cultivars.

All plantings were carried out by experienced CSIRO employees with specialised planting equipment. The time of planting, immediately preceding crops, soil type and fertilisers used at planting are summarised in Table 2. “Korolea” at Boggabilla has been confirmed as a *Fusarium* infected property. *Fusarium oxysporum* forma specialis *vasinfectum* is a soil inhabiting fungus that invades cotton plants

via the roots and causes a blockage of the water conducting tissue causing wilting and eventual death of the cotton plant. However, there were no visible symptoms of Fusarium wilt present in the experimental site. ACRI, “Leitch’s” and “Long Acres” were not infected with the fungus at the time of the experiment. At the ACRI site, there were some Verticillium wilt (*Verticillium dahliae*) disease symptoms present as leaf mottling between leaf veins and around leaf margins on the Namcala and DP 16 cultivars. The disease was not severe enough to cause any defoliation. At “Long Acres”, there was an area in Block 3 where the plants were stunted due to damage from herbicide drift from an adjoining field. No measurements were taken from these herbicide-affected plants (Figure 1).

Table 2: Experimental site background information for each location

Site	Planting Date	Soil Type	Preceding Crop 2004	Preceding Crop 2003	N application at planting (kg/ha Urea)	P application at planting (kg/ha Single superphosphate)
“Korolea” Boggabilla	19.10.2004	Vertosol Grey Clay	Fallow	Wheat	182	24
“Myal Vale” ACRI, Narrabri	8.10.2004	Vertosol Brown Clay	Fallow	Wheat	180	0
“Long Acres” Carroll	20.9.2004	Vertosol Grey Clay	Fallow	Wheat	160	18
“Leitch’s” Narrabri	25.10.2004	Vertosol Brown Clay	Fallow	Wheat	180	0



Figure 1: An area at “Long Acres” affected by herbicide damage

On 8th December 2004, ACRI received 160mm of rainfall. The water however drained away quickly and did not pond on the experimental field site. On the same day, 79.8 mm were received at Boggabilla, and only 25 mm at Carroll, with 44 mm the following day. The water also drained away quickly at these sites and it was unlikely that the cotton suffered significantly from any waterlogging. No frosts occurred during the growing season (Appendix 1).

Data collection

Plant mapping

Each site was visited a minimum of four times during January and February, 2005 and plant mapping was carried out (Figure 2). A series of measurements and counts were performed on the 1 m row of plants that were permanently marked throughout the season on each cultivar in each block of each location. The measurements performed were:

- Plant height
 - Total node number
 - Total fruiting nodes
 - Total vegetative nodes
-
- First position retention
 - Total squares
 - Total flowers
 - Total bolls



Figure 2: Plant mapping

Total nodes include nodes that have been aborted. Commonly the first 5-7 nodes are aborted and a scar is left that can be seen and felt. The coleoptile scars are not counted as nodes. Fruiting nodes are the fruiting branches that have the ability to produce fruit directly on that branch, whilst vegetative nodes commonly occur low on the plant where a vegetative branch will grow but will not produce fruit directly on that branch. However, fruiting nodes can grow off a vegetative branch and produce fruit (Figure 3). Vegetative nodes also commonly occur when the plant has been ‘tipped out’. This is a term referring to when the plant has had the growing point removed by an insect or mechanical damage, thus losing the apical meristem and thus the plant loses apical dominance. The incidence of the plant being tipped out was also recorded. First position retention refers to fruits that have been retained on the first position of fruiting branches.

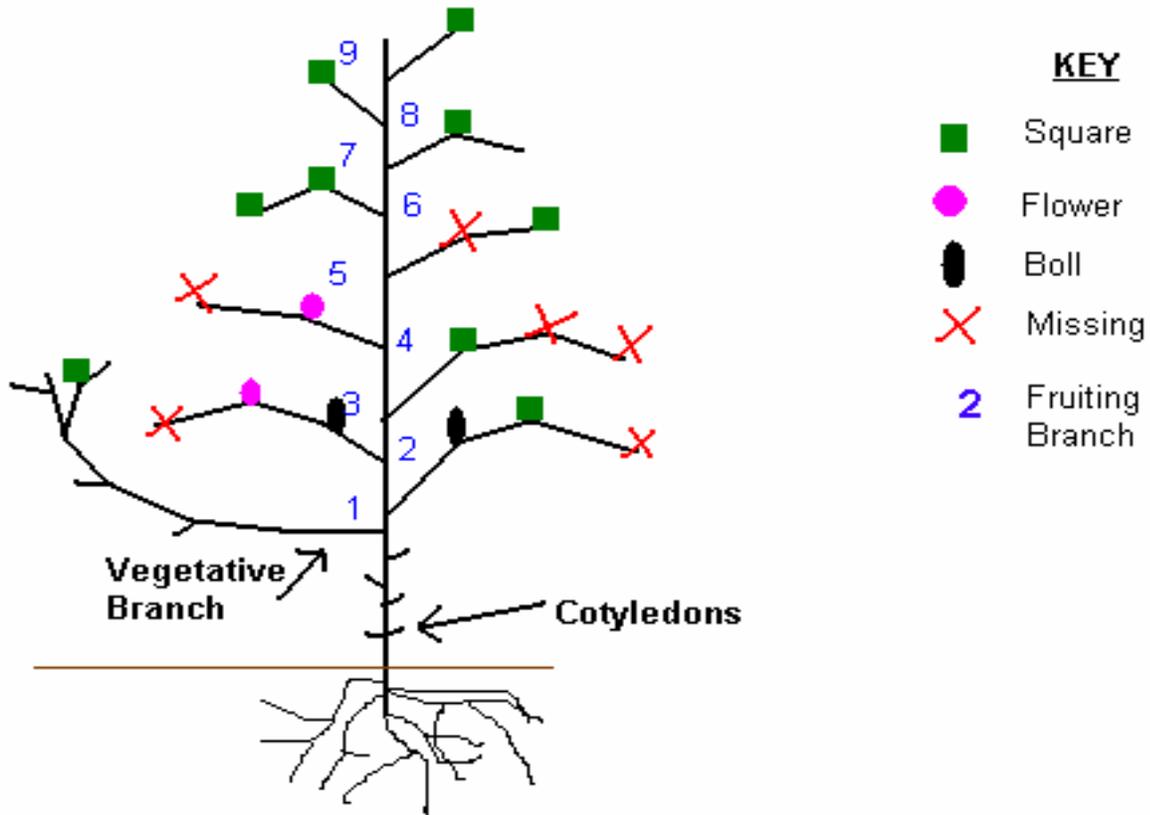


Figure 3: A schematic diagram of a cotton plant illustrating fruit abortion, fruiting branches, vegetative branches and fruiting forms.

Yield components

The various yield components measurements were carried out at maturity when the plants were ready to be harvested. All counts and measurements were carried out on the same 1 m row of plants that were measured for plant mapping. Since cotton was all planted on 1 m row spacing, all values in units/m were equivalent to units/m².

The measurements taken were:

- Boll number
- Green boll number
- Plant number (density)
- Fruiting sites
- Seed cotton weight (weight per boll of lint plus seed (g))

- Turnout
- Seed weight (g)
- Weight/100 seeds (g)
- Handpicked lint kg/ha

Seed cotton weight is the average weight of seed with cotton fibres still attached whilst gin turnout refers to the ratio of cotton lint to cottonseed that together make up the seed cotton. To obtain turnout, the cotton was ginned in a small hand gin. The gin is used for experimental small scale work and operates to remove any trash in the sample as well as separate the lint from the seed.

The multiplicative yield component equation used for this study was modified from Worley's equation (Worley *et al.* 1974) as follows:

$$\text{Yield} = \text{fruiting sites} \times \text{boll retention} \times \text{seeds/boll} \times \text{lint/seed} \text{ (Constable 2005, pers. comm.)}$$

The original yield component, bolls/m² was expanded to its components, fruiting sites x boll retention.

These measurements provide data that allows for further calculations of the yield components. The important yield components for yield determination are summarised in Table 3.

Table 3. Formulas used to calculate yield components.

Yield Component	Calculation formula
Retention %	$\frac{\text{Total open bolls}}{\text{Total fruiting sites}}$
Lint/boll	$\left(\frac{\text{Seed cotton weight (g)} \times (\text{Turnout} / 100)}{\text{Open bolls/m}} \right)$
Seeds/boll	$\left(\left(\frac{\text{Seed weight (g)}}{\text{Weight of 100 seeds (g)} / 100} \right) \right) \text{ Open bolls/m}$
Lint/seed	$\left(\frac{\text{Seed cotton weight (g)} - \text{Seed weight (g)}}{\left(\frac{\text{Seed Weight (g)}}{\text{Weight of 100 seeds (g)} / 100} \right)} \right)$

Fibre quality

Fibre quality measurements were made on a random sample of lint for each cultivar at each site. The measurements were made using a HVI (High Volume Instrument), similar to the fibre quality machines as used in industry. The three key fibre quality parameters measured were length (inches), strength (g/tex) and micronaire.

The HVI measures length by extending fibres to the full length and recording value, and then stretches the fibres further under force until they break to test for strength, both are very important parameters for spinning as long and strong fibres break less often and produce a better quality cloth. Micronaire is a measure of specific surface area (surface area per unit mass) and therefore indicates a combination of the sample fineness and maturity. It is measured from the pressure difference obtained when air is passed through an accurately weighed plug of cotton fibres.

Data analysis

Plant mapping

Plant mapping data was collected over a period of two months in January and February 2005. To calculate first position fruit retention, the proportion of fruiting forms (squares and flowers) at the first position of each fruiting branch that had been retained was recorded after all the plants had reached first flower, and the number of fruit retained divided by the total number of fruiting sites at the first position. Fruit number and first position retention were plotted against degree days from the sowing date using base temperature of 12 °C. The data was analysed using Genstat v8. Plant mapping data was analysed using a “repeated measurements” analysis of variance.

Yield components

The yield component data was recorded at physiological maturity, so all plants were at the same stage. Final yield and the various yield components were analysed by REML (Residual Maximum

Likelihood) analysis. Boll retention at maturity and first position retention were analysed using binomial logistic regression and analysis of deviance.

Relationship between yield components

A linear regression analysis was performed using Genstat to test for relationships between various yield components.

Stepwise regression analysis

Since the yield model is multiplicative (Yield = bolls/m² x seeds/boll x lint/seed), the data were transformed to logarithms so that the regression model is additive, $\ln(\text{Yield}) = \ln(\text{bolls/m}^2) + \ln(\text{seeds/boll}) + \ln(\text{lint/seed})$ (Worley *et al.* 1974). Stepwise regression and correlation analysis were performed to determine the covariances and correlations between the explanatory variates (O'Neill 2005, pers. comm.).

Cotton quality and Pima cotton

Data for both cotton quality and Pima cotton were subjected to analysis of variance.

Results

Plant mapping

During the summer growing season (January and February 2005), measurements on fruit (squares, flowers and bolls) development were taken on plants to determine genotype by environment effects.

Throughout the growing season, Sicot 71B set and retained more total fruit/m² than all other cultivars, except at Carroll (Fig. 4). At Carroll, Sicot 71B produced the highest total amount of fruit early in the season (Fig. 4c). However, cut-out or cessation of fruit production with shedding

occurred earlier than any other cultivar. Sicala 40 had the highest number of fruit/ m² at the final time of plant mapping at Carroll.

At all three sites, there was little difference in the total fruit number/m² between the conventional cultivars apart from Sicala 40 at Carroll. There was also no trend of modern conventional cultivars producing more fruit than reference cultivars (Namcala and DP16). During the fruiting season, the two warmer locations (Boggabilla and ACRI) continued to produce more fruit in all cultivars. However at Carroll, all cultivars had reached 'cut-out' before plant mapping had concluded. This was despite having accumulated only 1378 day degrees at the last date of plant mapping whilst Boggabilla and ACRI had accumulated 1545 and 1544 day degrees respectively.

At all locations, Sicot 71B had the highest probability of first position retention (Fig. 5b and 5c) except at the end of the fruiting season in Boggabilla (Fig 5a). There were no consistent differences in the probability of first position retention among the conventional cultivars. Although the conventional cultivars at Carroll cut-out early (Fig 4c), the plants compensated for this by retaining more first position fruit later on in the season as they continued to grow taller (Fig. 5c).

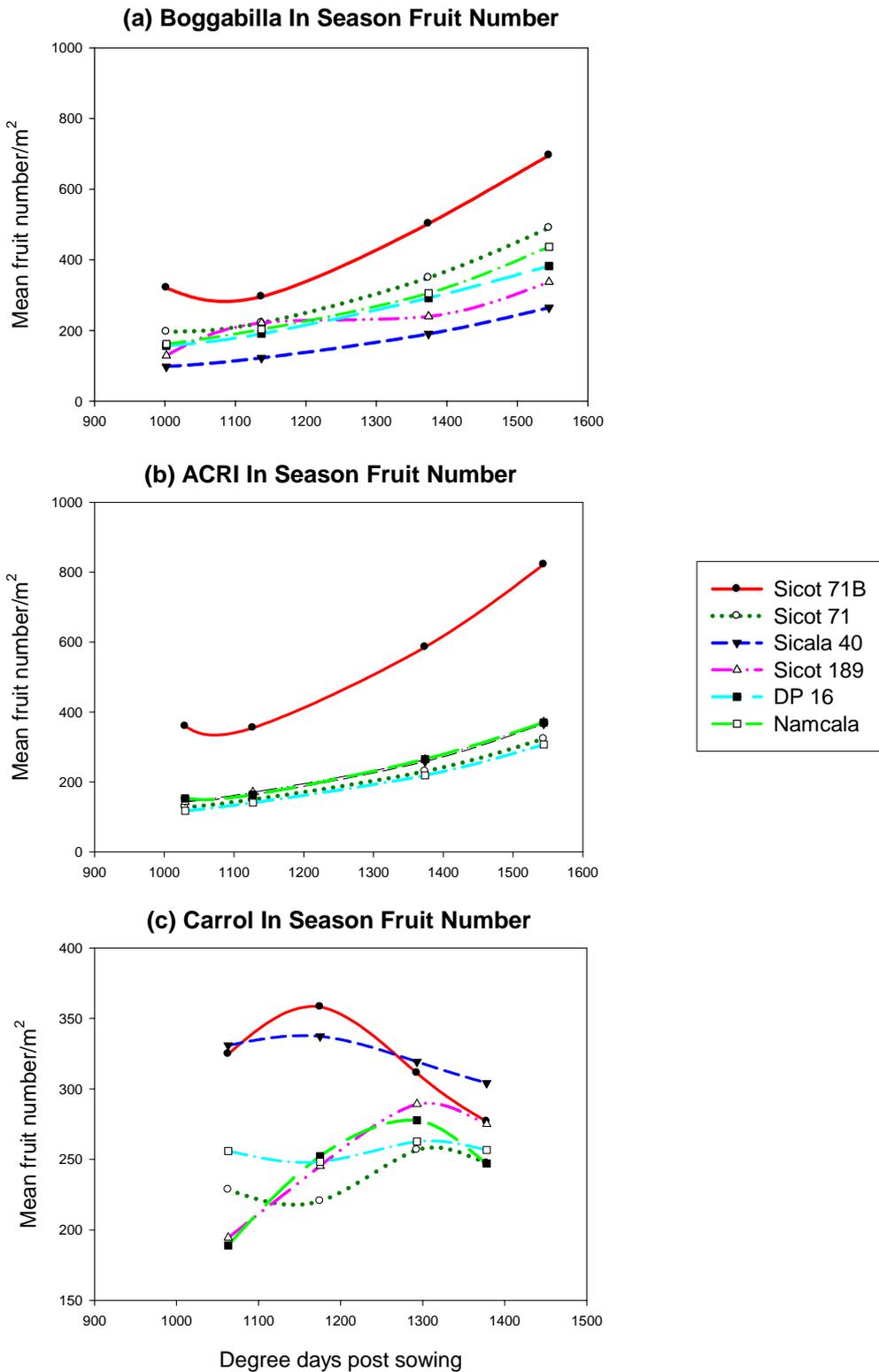


Fig. 4. Total mean fruit (squares, flowers and bolls) of 6 cotton cultivars (Namcala, DP16, Sicala 40, Sicot 189, Sicot 71 and Sicot 71B) through fruit development season at (a) Boggabilla (hot climate), (b) ACRI (medium climate and (c) Carroll (cool climate). The cultivar x location effect was significant at $P=0.05$ (l.s.d. 99.67).

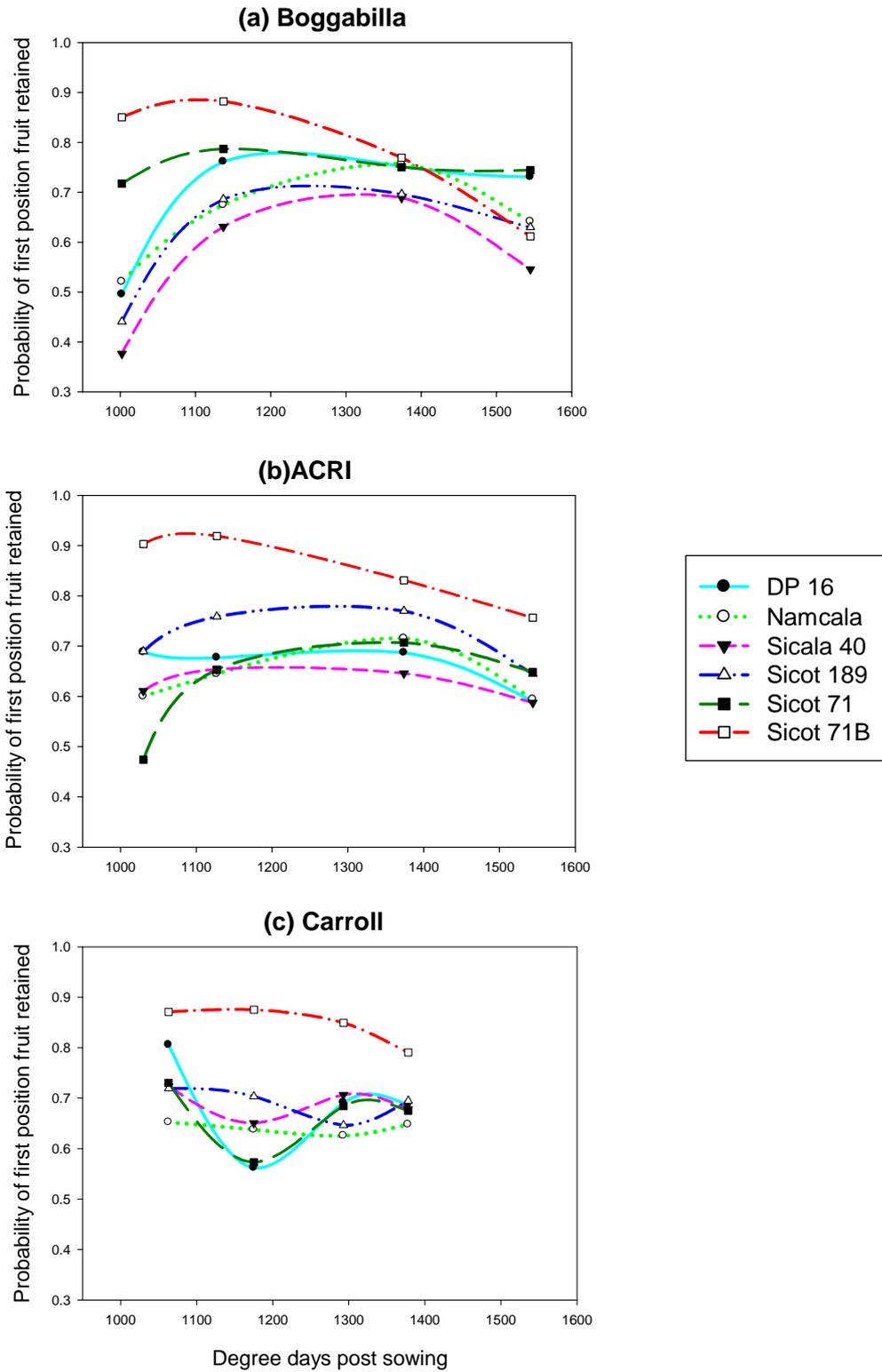


Fig. 5. Probability of first position fruit retention for 6 cotton cultivars (Namcala, DP16, Sicala 40, Sicot 189, Sicot 71 and Sicot 71B) through fruit (squares, flowers, bolls) development season at (a) Boggabilla (hot climate), (b) ACRI (medium climate and (c) Carroll (cool climate). Probabilities were analysed using binomial logistic regression.

Yield components

Cultivar effects

Upon maturity, the bolls were handpicked. Handpicked yields are generally higher than machine picked yields as less cotton is missed in the picking process. Australian cultivar lint yields have generally been increasing over time compared to the reference cultivars, DP 16 and Namcala (Fig. 6). There was a significant yield increase from the period of early 1970's to mid 1990's when both Sicot 189 and Sicala 40 were released. The most recent cultivars, Sicot 71 and 71B had similar yields to Sicala 40.

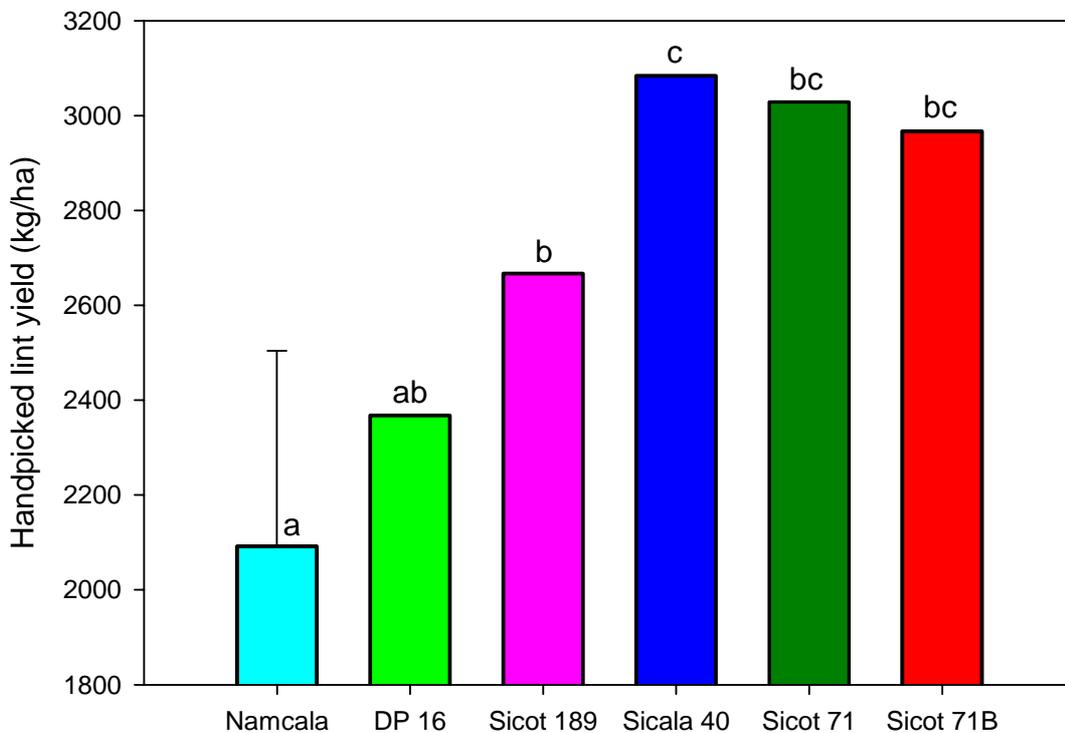


Fig. 6. Mean handpicked lint yields at maturity for 6 cotton cultivars (Namcala, DP16, Sicala 40, Sicot 189, Sicot 71 and Sicot 71B) averaged across three locations (Boggabilla, ACRI and Carroll). Means with the same letter are not significantly at $P = 0.05$. The l.s.d. values are at $P = 0.05$, using Fisher's protected l.s.d. tests for the cultivar main effect.

Since the release of Namcala and DP 16, the number of bolls/m² at harvest has slightly increased with one current conventional cultivar, Sicala 40 having a higher ($P < 0.05$) bolls/m² than both reference cultivars (Table 4). The Bollgard II cultivar, Sicot 71B has produced more ($P < 0.05$) bolls/m² than all conventional cultivars used including Sicot 71.

Similarly, the amount of lint/boll (equivalent to boll size) has also been increasing since the release of DP 16 and Namcala (Table 4). Both cultivars released in the 1990s, Sicala 40 and Sicot 189 had higher lint/boll ($P < 0.05$) than Namcala. The most recently released conventional cultivar, Sicot 71 had higher ($P < 0.05$) lint/boll than all other previously released cultivars. The Bollgard II cultivar, Sicot 71B had significantly less ($P < 0.05$) lint/boll than all of the other cultivars in this study possibly due to compensation resulting from its high boll load (bolls/m²).

Table 4. Mean open bolls/m² and lint/boll (g) at maturity for 6 cultivars (Namcala, DP16, Sicala 40, Sicot 189, Sicot 71 and Sicot 71B) averaged across three locations (Boggabilla, ACRI and Carroll). Means followed by the same letter within the column are not significantly at $P = 0.05$. The l.s.d. values are at $P = 0.05$, using Fisher's protected l.s.d. tests for the cultivar main effect.

Cultivar	Open Bolls/m ²	Lint/boll (g)
DP 16	89.2ab	2.71ab
Namcala	81.9a	2.69a
Sicala 40	104.2c	2.96b
Sicot 189	93.9abc	2.88b
Sicot 71	94.8abc	3.25c
Sicot 71B	119.9d	2.47a
l.s.d.	12.9	0.25

The boll load (bolls/m²) is related to the number of fruiting sites/m² and the probability of boll retention at these fruiting sites. There was no significant difference in the number of fruiting sites/m². The probability of bolls being retained at harvest has not changed over time for conventional cultivars (Fig. 7). The modern conventional cultivars have similar probabilities of retention to DP16. Namcala had a lower ($P < 0.05$) probability of retention than all conventional cultivars tested. Sicot 71B had a higher ($P < 0.05$) probability of retention than all conventional cultivars used in this study.

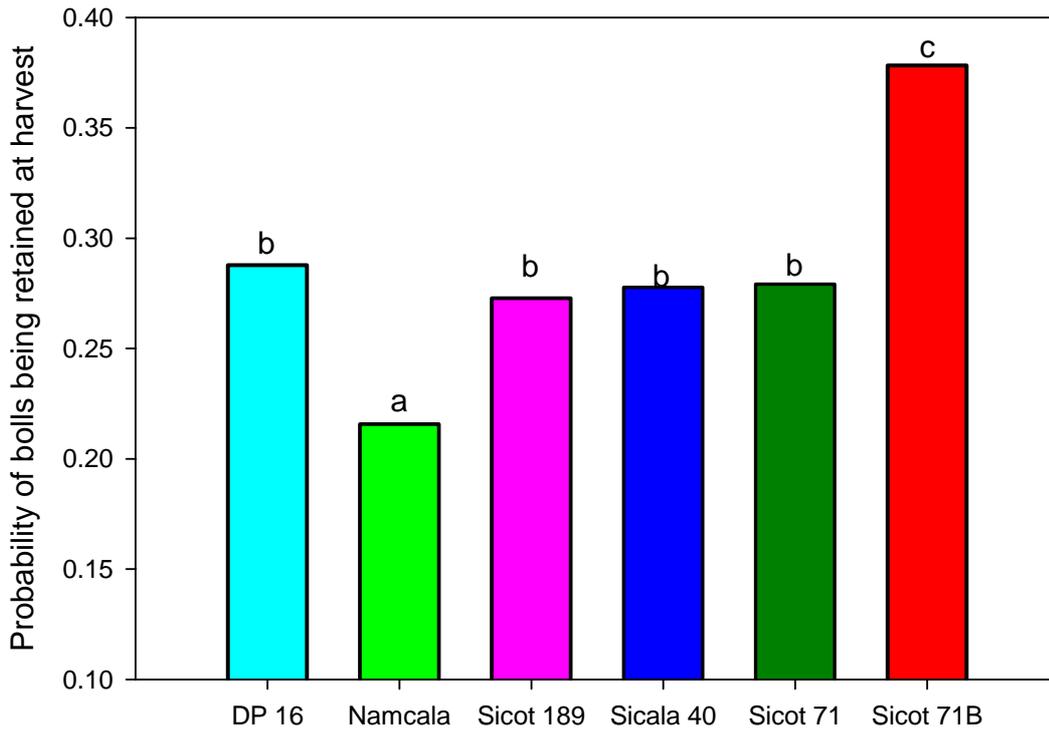


Fig. 7. Probability of bolls being retained at harvest for 6 cultivars (Namcala, DP16, Sicala 40, Sicot 189, Sicot 71 and Sicot 71B) averaged across three locations (Boggabilla, ACRI and Carroll). Probabilities denoted by the same letter are not significantly different at $P = 0.05$ using analysis of deviance in binomial logistic regression

Lint/boll or boll size, can be broken down into its components, seeds/boll and lint/seed. There was no consistent trend in seeds/boll over time. Sicot 71B had the lowest ($P < 0.05$) number of seeds/boll (Fig. 8a), possibly due to compensation from its high retention rate (Fig. 7).

The increase in boll size (lint/boll) was mainly due to the increase in lint/seed (Fig. 8b). The modern cultivars, Sicala 40 and Sicot 71 had an approximately 16% increase in lint/seed compared to the reference cultivars. Whilst the amount of lint/seed for Sicot 71B was higher ($P < 0.05$) than DP 16, Namcala and Sicot 189, it was lower ($P < 0.05$) than both Sicot 71 and Sicala 40.

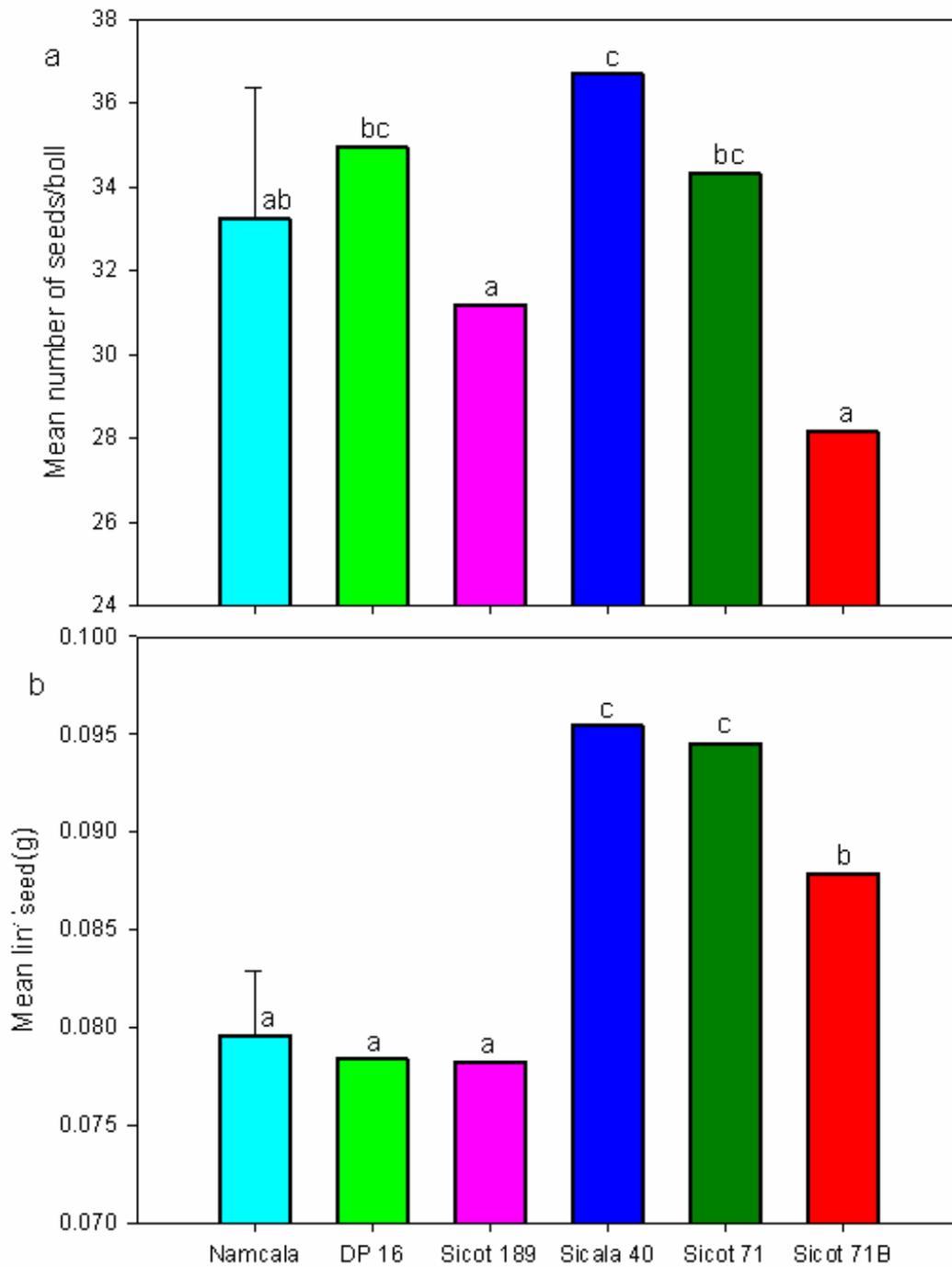


Fig. 8. Mean (a) number of seeds/boll and (b) lint/seed for 6 cultivars (Namcala, DP16, Sicala 40, Sicot 189, Sicot 71 and Sicot 71B) averaged across three locations (Boggabilla, ACRI and Carroll). Means with the same letter are not significantly at $P = 0.05$. The l.s.d. values are at $P = 0.05$, using Fisher's protected l.s.d. tests for the cultivar main effect.

Location (environmental) effects

Location had no impact upon overall lint yields ($P = 0.281$). Carroll (the cooler location) had a greater ($P < 0.05$) number of fruiting sites/m² and lint/boll but lower ($P < 0.05$) boll retention (Table 5). ACRI and Boggabilla (both warmer locations) had higher bolls/m² due to higher boll retention, but the boll sizes (lint/boll) were smaller possibly due to yield compensation.

Table 5. Mean fruiting sites/m², bolls/m², lint/boll (g), seeds/boll and lint/seed (g) at maturity for 3 locations (Boggabilla, ACRI and Carroll) averaged across six cultivars (Namcala, DP16, Sicala 40, Sicot 189, Sicot 71 and Sicot 71B). Means followed by the same letter within the column are not significantly at $P = 0.05$. The l.s.d. values are at $P = 0.05$, using Fisher's protected l.s.d. tests for the cultivar main effect. Probability of retention was analysed by binomial logistic regression and analysis of deviance.

Location	Sites/m ²	Retention	Bolls/m ²	Lint/boll (g)	Seeds/boll	Lint/seed (g)
Boggabilla	316a	0.34b	98ab	2.67a	29a	0.092b
ACRI	294a	0.36b	102.8b	2.61a	31.36b	0.083a
Carroll	414b	0.24a	91.2a	3.17b	38.89c	0.082a
l.s.d.	57.6	-	9.13	0.18	2.23	0.0023

Correlation and covariances of yield components

The correlation between $\ln(\text{yield})$ and $\ln(\text{bolls/m}^2)$ was 0.62 while the correlation between $\ln(\text{yield})$ and $\ln(\text{seeds/boll})$ was 0.54, and the correlation between $\ln(\text{yield})$ and $\ln(\text{lint/seed})$ was 0.54. Hence, the variate with the highest R^2 was $\ln(\text{bolls/m}^2)$, as it contributes most to $\ln(\text{yield})$ (Table 6b).

Table 6. (a) Covariances and (b) correlations between log-transformed yield components (bolls/sqm), seeds/boll and lint/seed (g) (O'Neil 2005 pers. comm.)

(a) Covariances	<i>ln(bolls/sqm)</i>	<i>ln(seeds/boll)</i>	<i>ln(lint/seed)</i>	<i>ln(yield)</i>
<i>ln(bolls/sqm)</i>	0.820			
<i>ln(seeds/boll)</i>	0.132	0.620		
<i>ln(lint/seed)</i>	-0.081	-0.098	1.022	
<i>ln(yield)</i>	0.870	0.654	0.843	2.367

(b) Correlations	<i>ln(bolls/sqm)</i>	<i>ln(seeds/boll)</i>	<i>ln(lint/seed)</i>	<i>ln(yield)</i>
<i>ln(bolls/sqm)</i>	1.0000			
<i>ln(seeds/boll)</i>	0.1851	1.0000		
<i>ln(lint/seed)</i>	-0.0889	-0.1233	1.0000	
<i>ln(yield)</i>	0.6248	0.5398	0.5417	1.0000

When the $\ln(\text{lint/seed})$ variable was constant, the partial correlation between $\ln(\text{bolls/m}^2)$ and $\ln(\text{seeds/boll})$ was 0.176 (Table 7). When $\ln(\text{seeds/boll})$ was constant, the partial correlation between $\ln(\text{bolls/m}^2)$ and $\ln(\text{lint/seed})$ was -0.068. When $\ln(\text{bolls/m}^2)$ was constant, the partial correlations between $\ln(\text{seeds/boll})$ and $\ln(\text{lint/seed})$ was -0.109.

Table 7. Partial correlation coefficients between each pair of variables, adjusting for all other variables in the matrix for log-transformed yield components, bolls/sqm, seeds/boll and lint/seed (g) (O'Neill 2005, pers. comm.).

Ln(bolls/sqm)				
Ln(seeds/boll)	0.176			
Ln(lint/seed)	-0.068	-0.109		
Ln(yield)	0.000	0.000	0.000	
	Ln(bolls/sqm)	Ln(seeds/boll)	Ln(lint/seed)	Ln(yield)

Relationship between yield components

There was a negative relationship between fruiting sites and the boll retention rate and between seeds/boll and boll retention rate. As the number of fruiting sites/m² increased, the probability of boll retention decreased ($R^2 = 0.66$, $P < 0.001$, Fig. 9). As retention rates increased, the number of seeds per boll decreased ($R^2 = 0.31$, $P < 0.001$, Fig. 10). See Appendix 2 for other regression.

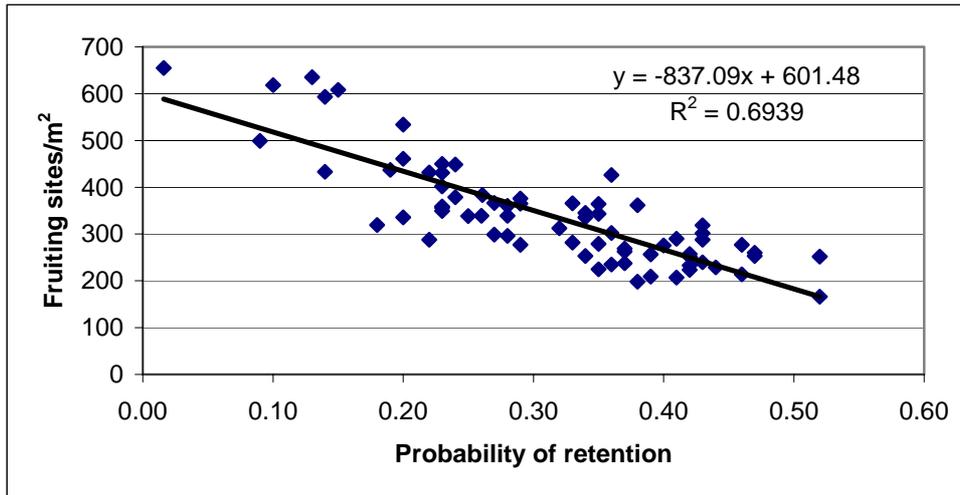


Figure 9. Effect of the probability of bolls retained on the number of fruiting sites/m² for 6 cultivars (Namcala, DP16, Sicala 40, Sicot 189, Sicot 71 and Sicot 71B) in three locations (Boggabilla, ACRI and Carroll).

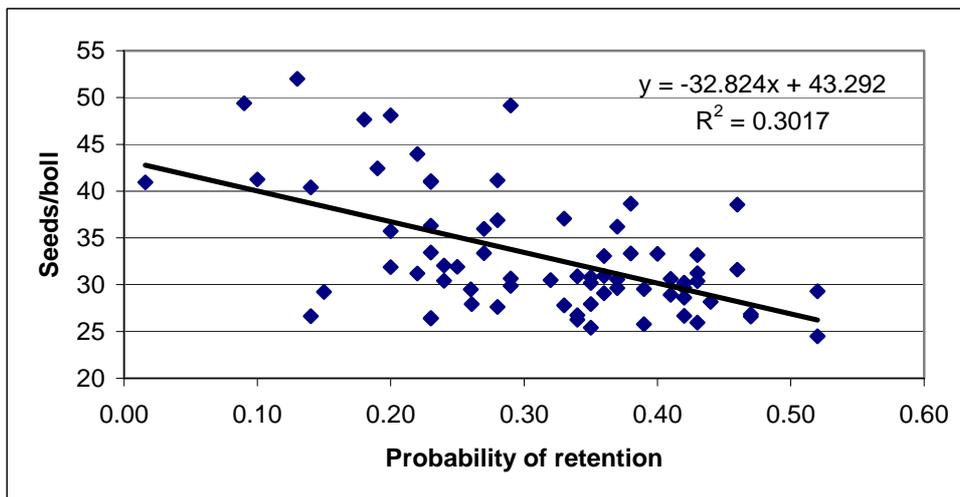


Figure 10. Effect of probability of retention on mean number of seeds/boll for 6 cultivars (Namcala, DP16, Sicala 40, Sicot 189, Sicot 71 and Sicot 71B) in three locations (Boggabilla, ACRI and Carroll).

Quality

Location (Environmental) Effects

The longest average fibres came from the cooler environment of Carroll, whilst the same environment had fibre with the lowest strength (Table 8). The strongest fibres were formed at the ACRI and Boggabilla site. The micronaire was the highest at ACRI.

Table 8. Mean fibre length (inches), strength (g/tex) and micronaire for 3 locations (Boggabilla, ACRI and Carroll) averaged across 6 cultivars (Namcala, DP16, Sicala 40, Sicot 189, Sicot 71 and Sicot 71B) Means followed by the same letter within the column are not significantly at P = 0.05. The l.s.d. values are at P = 0.05, using Fisher's protected l.s.d. tests for the location main effect.

Location	Length (inches)	Strength (g/tex)	Micronaire
Boggabilla	1.16b	30.16a	4.21a
ACRI	1.14a	30.81a	4.57b
Carroll	1.18c	29.82b	4.22a
l.s.d.	0.016	0.74	0.28

Staple lengths of Sicot 189 and Sicot 71B were higher than the DP16 and Namcala (Fig. 11a).

There was a slight trend showing a decrease in staple strength in the modern conventional cultivars compared to Namcala (11b), although all cultivars (except Sicot 71B) had a higher ($P < 0.05$) staple strength than DP16.

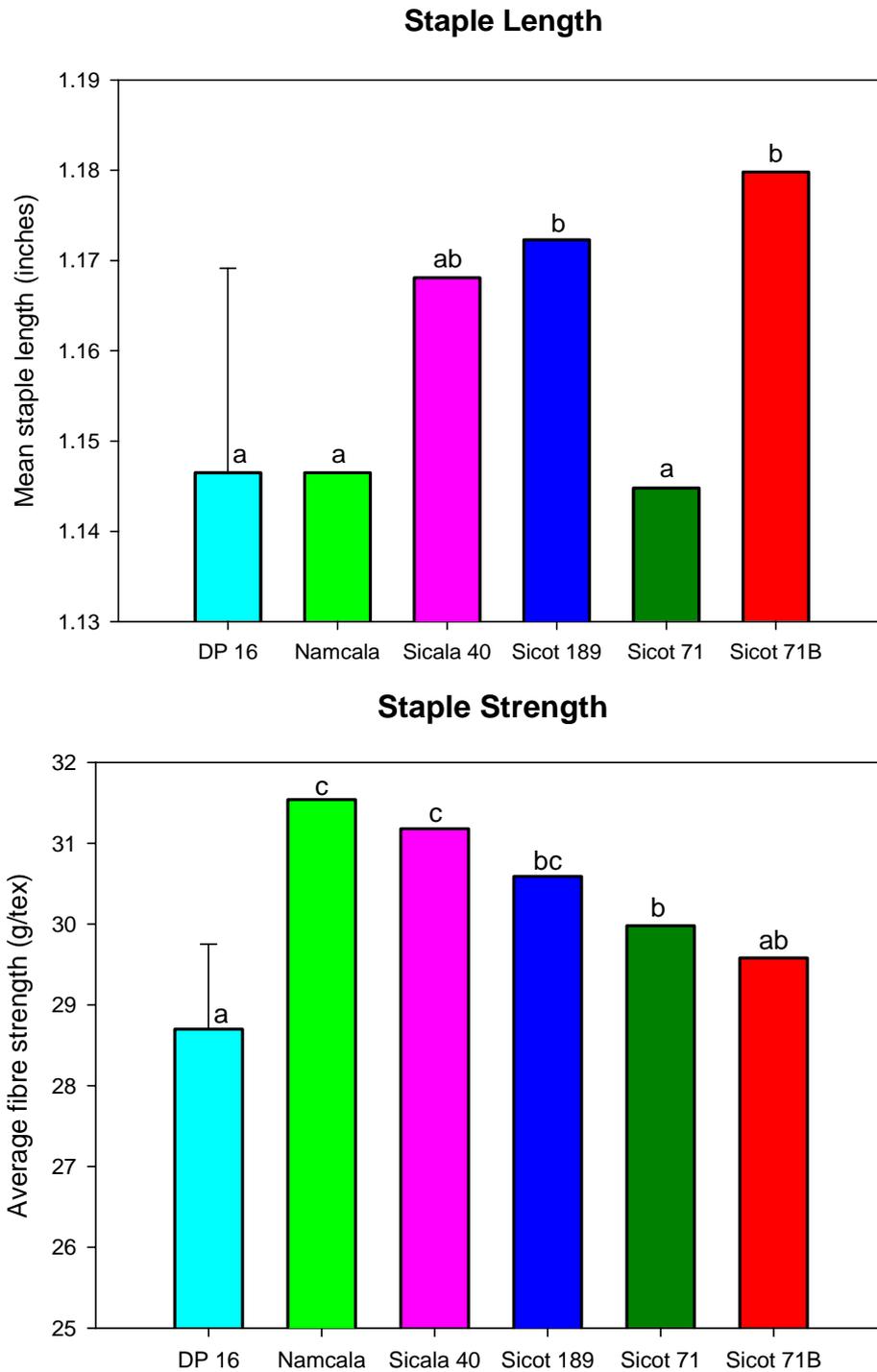


Fig. 11. Mean fibre staple (a) length and (b) strength for 6 cultivars (Namcala, DP16, Sicala 40, Sicot 189, Sicot 71 and Sicot 71B) averaged across three locations (Boggabilla, ACRI and Carroll). Means with the same letter are not significantly at $P = 0.05$. The l.s.d. values are at $P = 0.05$, using Fisher's protected l.s.d. tests for the cultivar main effect.

Pima Cotton (Gossypium barbadense)

The recently developed cultivar SiPima produced 2.4 times higher lint yields than Pima S-7 in ACRI (Fig. 12). Bolls/m² of SiPima was higher ($P < 0.05$) than S-7 and this higher boll load was mainly due to increased plant size and more fruiting sites as well as increased boll retention (Table 9). Lint/boll (boll size) of SiPima was not higher than S-7, but lint/seed was higher ($P < 0.05$).

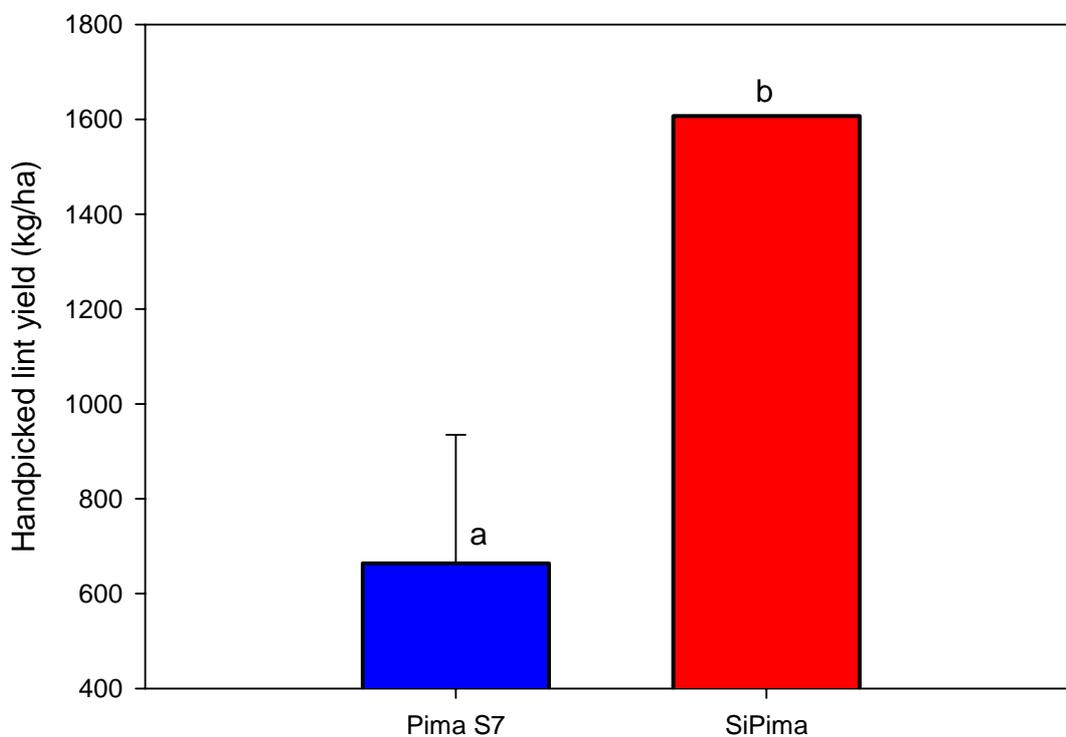


Fig. 12. Mean lint yields for Pima cotton cultivars (Pima S7 and Si Pima). Means with the same letter are not significantly at $P = 0.05$. The l.s.d. values are at $P = 0.05$, using Fisher's protected l.s.d. tests for the cultivar main effect.

Table 9. Means, P values and l.s.d.'s for yield components (bolls/m², boll retention, fruiting sites/sqm, lint/boll, lint/seed and seeds/boll) of SiPima and Pima S7 at ACRI

	Pima S7	SiPima	P Value	l.s.d.
Bolls/m ²	101	171	0.004**	62.62
Lint/boll (g)	0.68	0.94	0.094	n.s.
Probability of retention	0.37	0.57	0.001***	-
Fruiting sites/m ²	120.3	174.4	0.004**	32.66
Lint/seed (g)	0.071	0.074	0.019*	0.008
Seeds/boll	9.5	12.8	0.58	n.s.

Discussion

Plant mapping

Plant mapping is an effective method of defining fruiting patterns in response to insect pressure, crop management and genetic influences (Constable 1991). Across all locations, Sicot 71B, the Bollgard II cultivar, set and retained the largest number of fruit throughout the growing season (Fig. 1). Despite the experimental sites being managed to best management practices and being assessed regularly by agronomists and insect scouts, there still appeared to be an insect effect on the crop. Insect pests such as *Helicoverpa armigera* damage cotton by chewing off fruiting structures and tipping out growing shoots (Stewart and Sterling 1989). Whilst all plants were sprayed with insecticide when deemed necessary, insect damage occurred more in conventional cultivars compared to Sicot 71B. Sicot 71B produced toxins lethal to *Helicoverpa*, and retained significantly more fruit.

To breed Sicot 71B, the two desired *Bacillus thuringiensis* (Bt) genes were inserted into an obsolete cultivar, Coker 312, and backcrossed at least 4 to 5 times with Sicot 71. Whilst there is a small amount of background variation between the cultivars due to the backcrossing, it is still considered a powerful method of comparing the effect of the 2 Bt genes. Sicot 71B retained more fruit during the growing season due to better insect control. The higher fruit number in Sicot 71B compared to Sicot 71 during the growing season was mainly due to higher fruit retention rates.

Similarly, Sicot 71B had the highest probability of retaining fruit on the first position and there were few differences between the conventional cultivars. Caution is recommended when first position retention falls below 0.5 (CSD, 2004) as there might be significant insect, water or nutritional pressures that need rectification. During the growing season none of the cultivars fell below a 0.5 probability of first position retention except for Boggabilla early in the season. Shortage of photosynthate has often been considered the major cause of fruit abscission (Crozat *et*

al. 1999). There were no differences in fruit retention rates between obsolete and current conventional cultivars.

Peak fruit retention occurred between 1200-1300 degree days post sowing for both Boggabilla (hot) and ACRI (medium). Some of the conventional cultivars shed fruit early (between 1100 and 1200 degree days post sowing) in Carroll (cool climate). However, they soon compensated as the plants grew taller, and retained fruit at higher nodes on the plant. The Carroll location experienced 'cut out' earlier than the other sites as shedding continued to occur while fruit production ceased.

Yield components

Australian cotton breeders have been successful in improving cotton yields in cultivars released since the early 1970's (Figure 3). To ascertain how these yield increases have occurred, the various yield components were analysed individually. Yield components can be represented in the form of a multiplicative equation to determine final yield. The most commonly used is Yield = bolls/unit area \times seeds/boll \times lint/seed (Kerr 1966) and these are the primary lint yield components that contribute to lint yield (Manning 1956; Wilson *et al.* 1994; Worley *et al.* 1974).

There was no clear trend showing increased bolls/m² over time when comparing obsolete and current conventional cultivars except Sicala 40. The number of bolls/m² is determined by the number of fruiting sites present and the number of bolls retained. There has been little change in bolls/m² as boll retention rates and number of fruiting sites/m² at maturity were similar for all conventional cultivars, The higher bolls/m² in Sicala 40 was due to a slightly (though not significantly) higher number of fruiting sites.

There was a consistent trend of increasing boll size (lint per boll) over time for conventional cultivars. However, Sicot 71B had boll sizes similar to Namcala and DP16. Lint/boll can be

broken down into the components seeds/boll and lint/seed. There was little change in the seeds/boll between new and old reference cultivars except Sicala 40 and Sicot 71B. The low seeds/boll in Sicala 40 and Sicot 71B could possibly be due to compensation from their higher boll load (bolls/m²). The increase in boll size over time in Australian cultivars appears to be primarily due to the increase in lint/seed.

From 1983-1998, Australian cotton cultivars released by CSIRO have increased an average of 12.9 kg lint/ha/year, representing a 1.8% yield increase per year (Constable *et al.* 2001). American cultivars, however, displayed a steadily decreasing rate of improvement from the mid 1980s to 1992, when the rate of yield loss approached zero and then declined at a rate of approximately 20.3 kg/ha/year in 1998 (Lewis *et al.* 2000).

In America, the DP 16 produced approximately 0.72 g lint/seed, a value similar to the 0.078 g lint/seed in this experiment. Cultivars DeltaPine 50 and Suregrow 125 (cultivars from the mid to late 1990s) produced only 0.6 g lint/seed (Lewis *et al.* 2000). There has been a decrease in lint/seed and an increased seeds/boll produced in American cultivars of the mid 1990s whilst in Australia, seed numbers have remained relatively constant and lint/boll has been increasing, mainly due to an increase in lint/seed.

If a cultivar depends heavily on a high number of seeds/boll to obtain an acceptable yield, the plant must fix a higher amount of carbon to achieve this result. In terms of energy requirement, the cotton plant must fix nearly twice as much carbon to produce a kilogram of seed compared to a kilogram of lint (West and Todd 1956). This is because cotton seed contains approximately 20% triglyceride, or oil (Lewis *et al.* 2000). By selecting for high seed number for yield production, cotton yields can become more variable and less reliable (Lewis *et al.* 2000).

Australian and American cultivars have therefore been evolving in different directions, Australia keeping seed numbers fairly constant and increasing lint/seed, whilst American cultivars have been increasing seed/boll and reducing lint/seed. Environmental influences such as droughts, pests and diseases, are also likely to impact on yields in both countries. However, it appears that the contrasts in yield improvement could have been primarily due to the different selection emphasis on yield components.

Location (environmental) effects

The cooler location at Carroll had plants with a higher number of fruiting sites/m² than the other two warmer locations. This could be due to heat stress (Oosterhuis 1990) that might occur in the very hot climate of Boggabilla, and possibly ACRI. Boll retention was also lowest at Carroll possibly due compensation and competition for limited photosynthates. Despite having more fruiting sites and slightly larger bolls (lint/boll), plants at the Carroll site did not produce a higher yield than the other locations due the lower boll retention. In the warmer locations (Boggabilla and ACRI), plants with fewer fruiting sites compensated by retaining more fruit.

Correlation and covariances of yield components

Bolls/m² was thought the most important contributor to lint yield, followed by seeds/boll and lint/seed (Worley *et al.* 1974). Similar studies have not been conducted on Australian cultivars. However, boll number and improved disease resistance have been suggested to be the primary contributor to yield increases in Australia (Constable *et al.* 2001). In this study, it was estimated that bolls/m² had the highest R² but this does not mean that it contributes most to yield simply because it has the highest variance (Table 6b).

An American study found that boll size was often unrelated to yield (Heitholt *et al.* 1993). Other studies suggested that while lint/seed (component of boll size) made a relatively smaller

contribution to yield, and it is necessary to maintain or increase this component in order to secure the increased contributions of selection for an increase in seeds/boll (Worley *et al.* 1974).

Relationship between yield components

There was a negative linear relationship between the probability of boll retention and the number of fruiting sites (Figure 6). This was possibly due to competition for assimilates which is finite in supply and must be partitioned between the various sinks. Bolls are shed because there are not enough resources to carry all of the bolls through to maturity. Hence, it may be difficult to breed for increased yields through selecting for a higher number of fruiting sites, as increased fruit abortion may occur.

There is also a negative relationship between the probability of bolls retained at harvest and the number of seeds per boll (Figure 7). As retention rates increased, there is a linear decrease in the number of seeds/boll, possibly due again to competition for assimilates. Seeds are an expensive sink for carbon and energy because of their high oil content (Lewis *et al.* 2000). When there are more bolls retained, there were fewer seeds/boll due to compensation. The number of seeds/boll is set early in reproductive development (Oosterhuis 1990) and high retention rates during reproductive development may have reduced seeds/boll.

Lint per boll is therefore relatively stable as it is not correlated to boll retention. Sicot 71B, a cultivar widely grown in Australia, maintains its yield mainly by having high retention rates. The trade-off with high retention rates is that the number of seeds/boll falls, thus boll size is reduced. Hence, the yield of Sicot 71B is not higher than its conventional equivalent, Sicot 71. Breeding should therefore focus on increasing lint/boll, a relatively stable component that can be increased concomitantly with retention rates, especially in high boll retention Bollgard II cultivars.

Quality

Micronaire has not changed over time as it was similar for all modern and old reference cultivars. Certain fibre parameters are desired by spinners throughout the world (Table 10). The micronaire values obtained in this study (< 4.2-4.6) are considered ideal and a premium may be paid by some spinners for cotton in this range. Financial discounts generally do not apply until the micronaire exceeds 4.9 (Duggan 2005, pers. comm.).

Micronaire tends to be affected by environmental conditions. Under favourable conditions, the micronaire increases whilst under stressful conditions, it decreases (Duggan 2005, pers. comm.). Bollgard genes present in a cultivar were reported to decrease micronaire by 0.1-0.2 units (Verhalen *et al.* 2003), but the data from this experiment did not support this claim.

Table 10. Spinner’s cotton fibre property requirements (van der Sluijs *et al.* 2004)

Property	Preferred Value
Micronaire	3.8-4.2
Length	1.125 inches
Strength	>29 g/tex

Despite a slight downward trend in staple strength for modern cultivars over time compared to Namcala, the values for all cultivars (except DP 16) are still above the spinners requirements (ie. >29 g/tex). However, breeders should try to stop this downward trend from continuing to avoid falling below spinner’s specifications.

All 6 cultivars studied exceeded the minimum preference for staple length as stipulated by spinners (ie. > 1.125 inches) which is desirable as spinners prefer a long staple length (Duggan 2005). This helps to create a more uniform fabric with less chance of breakage in the spinning process. In this study, inclusion of Bollgard genes significantly increased staple length in Sicot 71B compared to

Sicot 71. In contrast, other workers have found that inclusion of Bollgard genes did not appear to affect staple length (Verhalen *et al.* 2003).

Pima cotton (Gossypium barbadense)

A premium is paid for Pima cotton due to its longer staple length than *G. hirsutum* and it is used for fine linen and underwear. Traditionally, limited Pima cotton has been grown in Australia because it is lower yielding than *G. hirsutum* and the premium paid for it is usually not enough to make it more profitable. With the development of the high yielding SiPima cultivar by the CSIRO breeding team, it is likely that more Pima cotton will be grown in Australia as the difference in profits between the two species is reduced. It will allow Australian farmers into new markets, giving greater flexibility and diversification.

Yield increases in SiPima have occurred primarily through an increase in the number of bolls/m². Boll retention rates for SiPima were higher than Pima S-7, as well as fruiting sites/m² (P<0.05). The plants produced more bolls by having more fruiting sites as well as retained more bolls. Despite a slightly higher lint/seed in SiPima, there was little difference in the number of seeds/boll, or boll size (lint/boll), so a greater number of bolls/m² has been the primary driver behind the yield increase.

A similar study was conducted on the now obsolete cultivars of Pima S3 and Pima S4 showing that most bolls contained approximately 17 seeds/boll whilst Pima S7 and SiPima in the present study only averaged 9.5 and 12.8 seeds/boll, respectively (Kittock and Pinkas 1975). The same report found that favourable environmental conditions increased the number of seeds/boll and the mean lint/boll was 0.54g (Kittock and Pinkas 1975), whilst lint/boll of Pima S-7 and SiPima were higher at 0.68 g and 0.94 g, respectively in this study. Although the plants in this experiment had fewer

seeds/boll (possibly due to unfavourable environmental conditions), there was a higher amount of lint/seed which maintained large boll sizes (lint/boll).

Conclusions

The data in this experiment have supported the hypothesis that yield increases over time in Australian cultivars have been due primarily to an increase in boll size, and this was generally achieved through an increase in lint/seed. This was done by analysing yield components of cotton cultivars representing a progression from obsolete cultivars in the 1970s to current cultivars, including a genetically modified Bollgard cultivar, Sicot 71B.

There was no clear trend for an increase in boll number/m² over time (except Sicala 40), mainly because retention rates were similar for all conventional cultivars studied. The Bollgard cultivar, Sicot 71B set and retained the highest amount of fruit throughout the growing season but did not yield any higher than other current conventional cultivars including Sicot 71 mainly because of smaller bolls sizes due to fewer seeds/boll. A linear relationship was found between boll retention and seeds/boll, and between boll retention and fruiting sites/m². Hence, for high yielding Bollgard cultivars with high boll retention rates, breeding efforts should select for larger boll sizes by increasing lint/seed.

Location had no overall impact on yield in this study. In Carroll, plants have more fruiting sites/m² and more lint/boll, but retained fewer bolls. Plants in Boggabilla and ACRI had higher boll retention rates but boll size (lint/boll) was smaller. Through compensation, plants are able to maintain similar yields across the different locations.

There were no clear trends in fibre length and micronaire between the current and obsolete cultivars. However, fibre strength is slowly decreasing, which is of some concern and breeding

efforts should be focused on maintaining or improving it. The new SiPima cultivar is higher yielding than Pima S7 due to increased retention rates and increased number of fruiting sites and therefore, higher boll number/m².

The information gained from this study will help cotton breeders to target specific yield components such as increasing lint/seed to breed for higher yielding crops with larger bolls (lint/boll).

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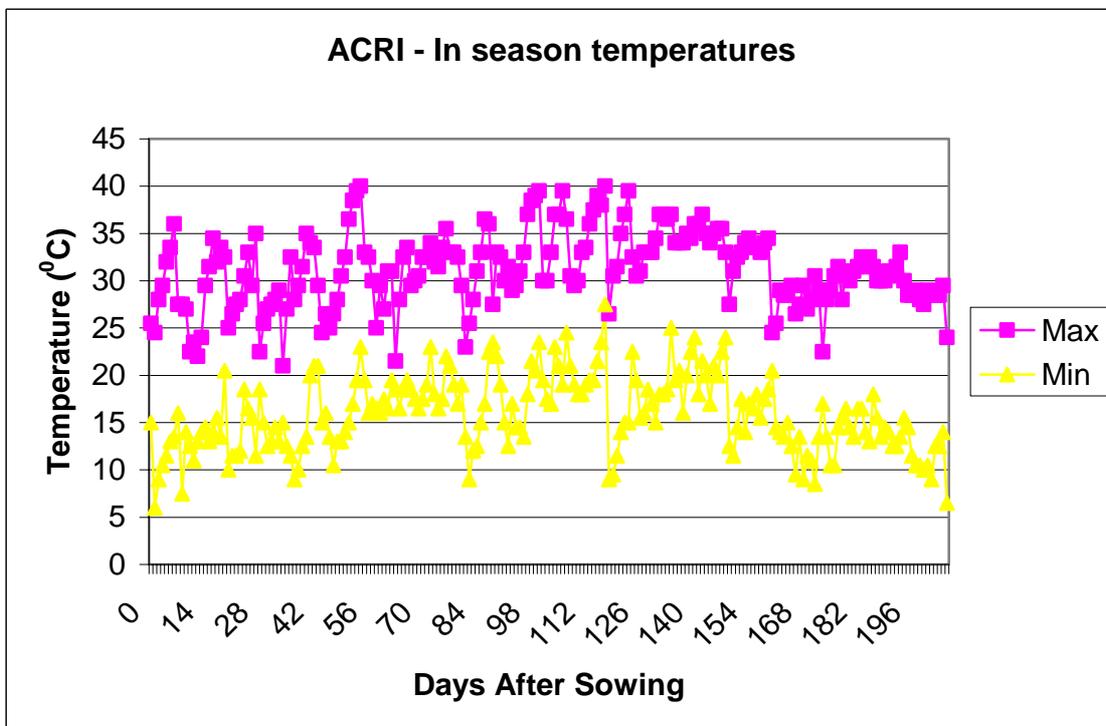
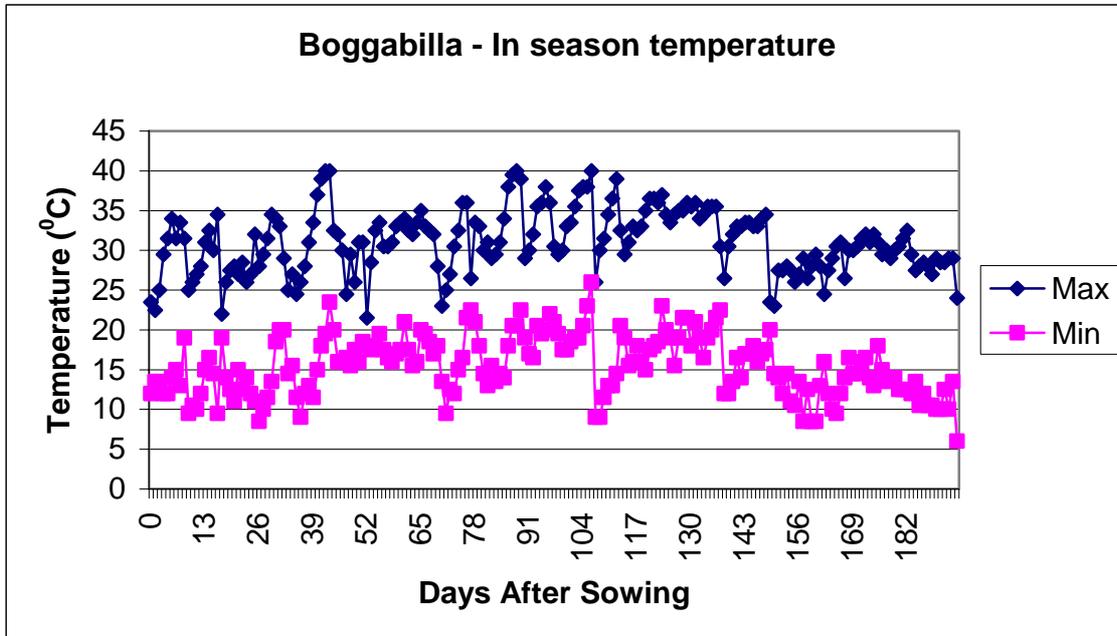
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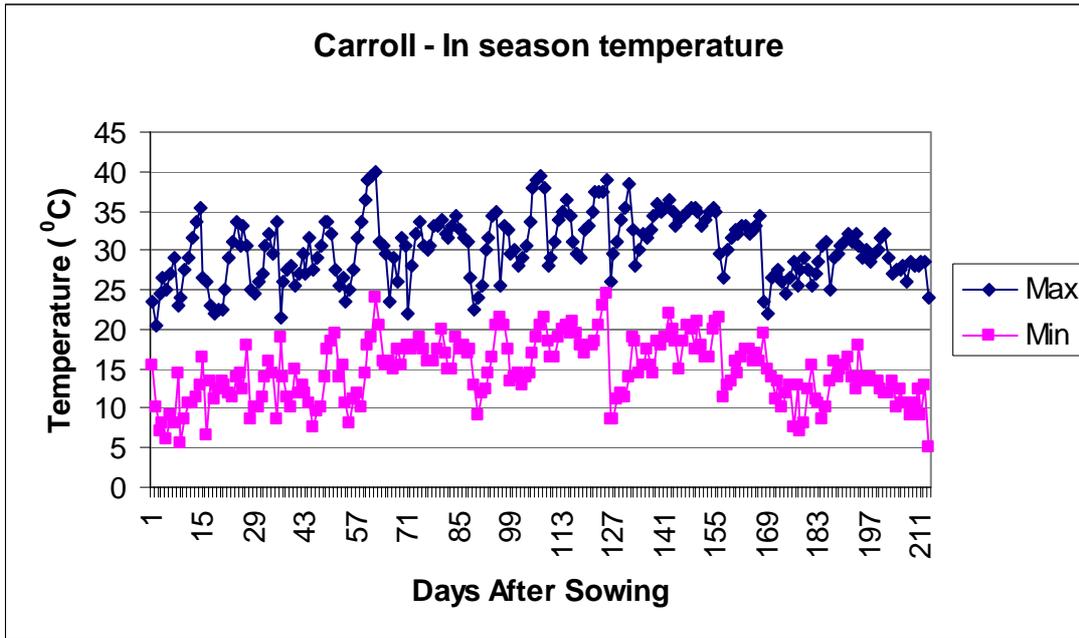
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Appendix

Appendix 1





Appendix 2

