Yield components of high-yielding Australian cotton cultivars

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Received 20 July 2013, Accepted 2 August 2013, Published on the web: 8 March 2014

Abstract

Cotton (Gossypium hirsutum) yield can be broken down into the components that make up total lint yield, namely bolls/m2 (fruiting sites and boll retention) and lint/boll (seeds/boll and lint/seed). Lint yields of Australian cultivars during the last 30 years increased by 1.8% per year and the aim of this study was to determine which yield components had contributed to that yield progress. Six cultivars were used, two released during the 1970s (DP 16 and Namcala), two from the mid 1990s (Sicala 40 and Sicot 189), and two from the early 2000s (Sicot 71 and Sicot 71B - the latter of which was a Bollgard II® cultivar). These cultivars were grown in a replicated field experiment at three locations, selected to represent different cotton growing environments in Australia; Boggabilla (warmer), the Australian Cotton Research Institute at Narrabri (medium) and Carroll (cooler). Plants were mapped at regular intervals to monitor fruit retention and development. At maturity bolls were harvested and the various yield components analysed. Across sites and cultivars, yield was most correlated with bolls/m2 (r=0.69***), then with lint/seed (r=0.44***) and also with boll retention (r=0.25*). There was a negative linear relationship between boll retention and fruiting sites/m2, and boll retention and seeds/boll. Lint/seed appeared to be a relatively stable trait and was not negatively related to boll retention. We conclude that yield increases have come from increased bolls/m2 and for selection for high lint percentage (lint yield divided by seed cotton yield) which has increased lint per seed. This study will assist breeders to focus selection pressure on improving Australian cotton yields.

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

Introduction

Australia typically produces 680 million kg of cotton lint per year, of which more than 95% is exported. Of all the countries that produce in excess of 45 million kg of cotton per year, Australia holds the record of the world’s highest average yield at 1779 kg/ha. Cotton farmers are paid according to the total amount of lint and seed that they produce. Thus, farmers and breeders aim to produce as much cotton lint and seed as possible, although the price paid can be discounted if certain lint quality attributes are not met. Crop yield is the result of a series of concomitant, difficult to define, responses. The yield of any crop can be broken down into its components to determine how yield is attained. 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). 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). The primary yield components that contribute to cotton lint yield are bolls per unit area, seeds/boll and lint/seed (Kerr 1966; Manning 1956; Wilson et al. 1994; Worley et al. 1974).
Yield = bolls/unit area x seeds/boll x lint/seed

Yield = bolls/unit area x lint/boll

Fruiting sites and fruit retention are components determining boll numbers. Sites and retention are components which can be monitored during early fruit development and possibly manipulated by management to maximise yield. The boll size yield components may be more genetically determined.

Equation (2) is similar to Kerr’s equation, since seeds/boll and lint/seed are the key contributors to boll size. More recently, other researchers have used modifications of these equations (Coyle and Smith 1997; Smith et al. 1976). Different yield component equations are useful to help describe how yield is attained depending on the characteristics breeders wish to emphasise. Data availability also determines which equation is used.

Different yield components contribute varying degrees of importance to lint yields. Increases in yield are generally associated with the number of bolls per unit ground area (Pettigrew 1994; Wells and Meredith 1984). The number of bolls/m² is determined by the number of fruiting sites produced and the number of bolls retained. Boll size (lint/boll) was believed to be negatively correlated with genetic variation in yield (Meredith and Bridge 1971). Changes in other components such as lint/seed, number of seeds/boll, and lint/boll are generally thought to be less important to yield gain (Meredith 1984). Although higher yields due to favourable environmental conditions within a cultivar can be associated with larger bolls (Mauey et al. 1978), boll size was often thought to be unrelated to yield (Heitholt et al. 1993).

More information is needed on how yield components have changed over time, and environmental influences on Australian cultivars. By knowing what yield components have changed, the extent to which breeder’s aims are being met can be quantified. The key yield components can be targeted in specific environments to continue Australia’s breeding efforts. The aim of this study was to determine which yield components had contributed to yield progress in modern Australian cotton cultivars.

Materials and methods

Treatments

Six cotton (Gossypium hirsutum) cultivars were grown in three locations chosen to give a range of environmental conditions across the cotton growing region of northern NSW over the 2004/2005 season. Boggabilla, near Goondiwindi represents a hotter 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 cooler region. “Korolea” at Boggabilla (28° S, 150°E) and “Long Acres” at Carroll (31° S, 150°E) are commercial properties that allow experiments to be conducted each year. ACRI (30° S, 151°E) is the principal cotton research station in Australia.

The six cultivars were chosen to represent a progression of cotton cultivars grown in Australian from the 1970s to current. DP 16 and Namcala were grown in the early 1970s and used as reference cultivars, Sicot 40 and Sicot 189 were released in the early 1990s and Sicot 71 and Sicot 71B in the early 2000s. Sicot 71B is a genetically modified Bollgard II® cultivar that contains both Cry1Ac and CryAb genes of the Bacillus thuringensis (Bt) bacteria from Monsanto. The cultivars were planted in a randomised block design with four replicates at each location. In each replicate, there were three 13 m rows of each cultivar.

Cultural practices

All sites used in this study were managed to attain non-limiting nutrient and water conditions. Weeds and insects were monitored and controlled as required. The time of sowing, rotation and soil type used are summarized in Table 2.

Data collection

Plant height, total node number, fruiting and vegetative nodes, fruit retention, total squares, flowers and bolls were measured over a 1 m row of tagged plants of each plot throughout the season. To calculate fruit retention, the proportion of fruiting forms (squares and flowers) on each fruiting branch that had been retained was recorded, and the number of fruit retained divided by the total number of fruiting sites at branch. The yield component measurements were carried out at harvest maturity. Boll number, plant density, fruiting sites, seed cotton weight, gin turnout, seed weight and handpicked lint were measured on the same 1 m row of plants that were used for plant mapping. Seed cotton weight is the weight of seed with cotton fibres still attached and gin turnout is the ratio of cotton lint to seed cotton. To obtain turnout, the cotton was ginned in a small gin. The multiplicative yield component equation used for this study was adapted from Heitholt’s equation, yield = bolls/m² x lint/boll equation (Heitholt 1999) and further expanded to:

Yield = fruiting sites/m² x boll retention x seeds/boll x lint/seed. The original yield component, bolls/m² was further expanded to its components, fruiting sites/m² x boll retention to provide information on yield potential, and lint/boll was expanded to seeds/boll x lint/seed.

Data analysis

Fruit number and first position retention were plotted against degree days using base temperature of 12°C from the sowing date. Final yield and the various yield components were analysed by Residual Maximum Likelihood (REML) analysis in Genstat v13. Boll retention at maturity and fruit retention were analysed using binomial logistic regression and analysis of deviance.

Results

Yield components

At all locations, Sicot 71B had the highest retention (Fig. 2b and 2c) except at the end of the fruiting season in Boggabilla (Fig 2a). There were no consistent differences in retention among the conventional cultivars compared with the reference cultivars. There was no
cotton cultivar by location interaction in any of the yield components measured. Hence, only the significantly \( P<0.05 \) different cultivar or location main effects are presented. The reference cultivars, DP 16 and Namcala had lowest yields (Table 2). The most recent cultivars, Sicot 71 (303 g/m\(^2\)) and 71B (297 g/m\(^2\)) had similar yields to Sicala 40 (308 g/m\(^2\)). Sicala 40 (104 bolls) produced higher \( (P<0.05) \) bolls/m\(^2\) than both reference cultivars (82 and 89 bolls) (Table 2). Sicot 71B (120 bolls) produced more \( (P<0.05) \) bolls/m\(^2\) than all conventional cultivars used, including Sicot 71 (95 bolls). There was no difference \( (P>0.05) \) in the number of fruiting sites/m\(^2\) and boll retention at harvest for modern conventional cultivars were similar to DP 16 (0.29) (Table 2). Namcala (0.22) had lower \( (P<0.05) \) and Sicot 71B (0.38) had higher \( (P<0.05) \) boll retention than all conventional cultivars tested.

### Table 1. Experimental site background information for the three locations (Boggabilla, Myall Vale and Carroll)

<table>
<thead>
<tr>
<th>Location</th>
<th>Sowing Date</th>
<th>Soil Type</th>
<th>Preceding Crop 2004</th>
<th>Preceding Crop 2003</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Korolea”</td>
<td>19.10.2004</td>
<td>Vertosol Grey Clay</td>
<td>Fallow</td>
<td>Wheat</td>
</tr>
<tr>
<td>“ACRI”</td>
<td>8.10.2004</td>
<td>Vertosol Brown Clay</td>
<td>Fallow</td>
<td>Wheat</td>
</tr>
<tr>
<td>“Long Acres”</td>
<td>20.9.2004</td>
<td>Vertosol Grey Clay</td>
<td>Fallow</td>
<td>Wheat</td>
</tr>
<tr>
<td>Myall Vale</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>“Korolea”</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>“ACRI”</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>“Long Acres”</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

There was a negative relationship between fruiting sites and boll retention rate, and between seeds/boll and boll retention rate. As the number of fruiting sites/m\(^2\) increased, boll retention decreased \( (r = 0.83, \ P<0.01, \ Fig \ 4a) \). As boll retention rates increased, the number of seeds/boll decreased \( (r = 0.55, \ P<0.01, \ Fig \ 4b) \). Interestingly, lint/boll increased with an increase in seeds/boll \( (r = 0.84, \ P<0.01, \ Fig \ 5) \). Across sites and cultivars, lint yield \( (g/m^2) \) was most correlated with bolls/m\(^2\) \( (r=0.69, \ P<0.001) \), then with lint/seed \( (r=0.44, \ P<0.001) \) and also with boll retention \( (r=0.25, \ P<0.05) \) (Fig 6).

### Discussion

**Plant mapping and yield components**

Plant mapping is an effective method of studying fruiting patterns (Constable 1991). Generally, Sicot 71B produced the highest fruit/m\(^2\) and had the highest fruit retention. Although the standard cotton insect pest management strategies were implemented throughout the growing season, there still appeared to be an insect effect on non-Bt cultivars. Sicot 71B retained more fruit than Sicot 71 and other conventional cultivars because of better protection from *Helicoverpa* by Bt proteins. There were no consistent differences in the number of fruit/m\(^2\) or fruit retention among the modern conventional cultivars compared with the reference cultivars. Shortage of photosynthates has often been considered the major cause of fruit abscission (Crozat et al. 1999). Peak fruit retention occurred between 1200-1300 °Cd after sowing for both Boggabilla and Myall Vale. Some of the conventional cultivars shed fruit early between 1100 and 1200 °Cd after sowing in both Boggabilla and Myall Vale. At the end of the season when the demand for photosynthate increases and exceeds the supply (Gerik et al. 1998)


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**Table 2. Mean lint yield \( (g/m^2) \), bolls/m\(^2\), fruiting sites/m\(^2\) and probability of boll retention at maturity for six cultivars (Namcala, DP16, Sicala 40, Sicot 71, Sicot 71C and 71B) averaged across three locations (Boggabilla, Myall Vale and Carroll).**

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Yield ( (g/m^2) )</th>
<th>Bolls/m(^2)</th>
<th>Sites/m(^2)</th>
<th>Boll retention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Namcala</td>
<td>209.2a</td>
<td>82a</td>
<td>380</td>
<td>0.22a</td>
</tr>
<tr>
<td>DP 16</td>
<td>236.8ab</td>
<td>89ab</td>
<td>310</td>
<td>0.29b</td>
</tr>
<tr>
<td>Sicot 189</td>
<td>266.7b</td>
<td>94abc</td>
<td>344</td>
<td>0.27b</td>
</tr>
<tr>
<td>Sicala 40</td>
<td>308.4c</td>
<td>104c</td>
<td>375</td>
<td>0.28b</td>
</tr>
<tr>
<td>Sicot 71C</td>
<td>302.9bc</td>
<td>95abc</td>
<td>322</td>
<td>0.28b</td>
</tr>
<tr>
<td>Sicot 71B</td>
<td>296.7bc</td>
<td>120d</td>
<td>317</td>
<td>0.38c</td>
</tr>
</tbody>
</table>

l.s.d. 41.24 13 n.s. -

Means followed by the same letter within the column are not significantly different 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. Boll retention was analysed by binomial logistic regression and analysis of deviance. N.s. – Not significantly significant at \( P>0.05 \).

Lint/boll (boll size) was lowest for DP 16 and Namcala (Fig. 3a). Both cultivars released in the 1990s, Sicala 40 (3.0 g) and Sicot 189 (2.9 g) had higher lint/boll \( (P>0.05) \) than Namcala (2.7 g). Sicot 71 (3.3 g) had highest \( (P<0.05) \) while Sicot 71B (2.5 g) had the lowest \( (P<0.05) \) lint/boll in this study. Lint/boll can be broken down into its components, seeds/boll and lint/seed. There was no consistent trend in seeds/boll among the conventional cultivars (Fig. 3b). Sicot 71B had the lowest \( (P<0.05) \) number of seeds/boll (28 seeds). The increase in boll size was mainly due to the increase in lint/seed (Fig. 3c). The modern cultivars, Sicala 40 (0.096 g) and Sicot 71 (0.095 g) had a 20% increase in lint/seed compared with the reference cultivar average (0.079 g). Lint/seed for Sicot 71B (0.088 g) was higher \( (P<0.05) \) than DP 16 (0.078 g), Namcala (0.080 g) and Sicot 189 (0.078 g), but lower \( (P<0.05) \) than both Sicala 40 and Sicot 71.

Location had no impact on lint yields \( (P<0.05) \), Table 3). The cooler location at Carroll had more \( (P<0.05) \) fruiting sites/m\(^2\) (414) and lint/boll (3.17 g), but lower \( (P<0.05) \) boll retention (0.24) (Table 3). Both the warmer locations at Myall Vale (103 bolls) and Boggabilla (98 bolls) had higher bolls/m\(^2\) due to higher boll retention, but lint/boll was lower \( (P<0.05) \).
Fig. 1. Daily maximum (●) and minimum (■) temperatures through the 2004/2005 cotton growing season at (a) Boggabilla, (b) Myall Vale and (c) Carroll.

Fig. 2. Fruit retention for six cotton cultivars [Namcala (□), DP16 (■), Sicot 189 (∆), Sicala 40 (▼), Sicot 71 (○) and Sicot 71B (●)] through the 2004/2005 fruit development season at (a) Boggabilla, (b) Myall Vale and (c) Carroll. Probabilities were analysed using binomial logistic regression and analysis of deviance.
Mean lint/boll (g)  
2.2  
2.4  
2.6  
2.8  
3.0  
3.2  
3.4  

Mean seeds/boll  
24  
26  
28  
30  
32  
34  
36  
38  

Mean lint/seed (g)  
0.075  
0.080  
0.085  
0.090  
0.095  
0.100  

Fig. 3. Mean (a) lint/boll, (b) number of seeds/boll and (c) lint/seed for six cultivars (Namcala, DP16, Sicot 189, Sicala 40, Sicot 71 and Sicot 71B) averaged across three locations (Boggabilla, Myall Vale 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.

Boll retention  

Fig. 4. Relationship between boll retention on the (a) number of fruiting sites/m$^2$ and (b) mean seeds/boll for six cultivars (Namcala ($\blacklozenge$), DP16 ($\triangle$), Sicot 189 ($\triangle$), Sicala 40 ($\blacksquare$), Sicot 71 ($\clubsuit$) and Sicot 71B ($\blacktriangle$)) in three locations (Boggabilla, Myall Vale and Carroll).

Lint yield (g/m$^2$)  

Fig. 5. Relationship between seeds/boll on lint/boll (g) for six cultivars (Namcala ($\blacklozenge$), DP16 ($\triangle$), Sicot 189 ($\triangle$), Sicala 40 ($\blacksquare$), Sicot 71 ($\clubsuit$) and Sicot 71B ($\blacktriangle$)) in three locations (Boggabilla, Myall Vale and Carroll).

Lint/seed (g)  

Fig. 6. Relationship between (a) bolls/m$^2$, (b) lint/seed (g) and (c) boll retention (%) on lint yield (g/m$^2$) for six cultivars (Namcala ($\blacklozenge$), DP16 ($\triangle$), Sicot 189 ($\triangle$), Sicala 40 ($\blacksquare$), Sicot 71 ($\clubsuit$) and Sicot 71B ($\blacktriangle$)) in three locations (Boggabilla, Myall Vale and Carroll).
**Table 3.** Mean lint yield (g/m²), bolls/m², fruiting sites/m², lint/boll (g), seeds/boll and lint/seed (g) at maturity for three locations (Boggabilla, Myall Vale and Carroll) averaged across six cultivars (Namcala, DP16, Sicala 40, Sicot 189, Sicot 71 and Sicot 71B).

<table>
<thead>
<tr>
<th>Location</th>
<th>Yield (g/m²)</th>
<th>Bolls/m²</th>
<th>Sites/m²</th>
<th>Boll retention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boggabilla</td>
<td>259.0</td>
<td>98ab</td>
<td>316a</td>
<td>0.34b</td>
</tr>
<tr>
<td>Myall Vale</td>
<td>268.9</td>
<td>103b</td>
<td>294a</td>
<td>0.36b</td>
</tr>
<tr>
<td>Carroll</td>
<td>282.4</td>
<td>91a</td>
<td>414b</td>
<td>0.24a</td>
</tr>
<tr>
<td>l.s.d.</td>
<td>n.s.</td>
<td>9.1</td>
<td>58</td>
<td>-</td>
</tr>
</tbody>
</table>

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. Boll retention was analysed by binomial logistic regression and analysis of deviance. N.s. = Not significantly significant at $P=0.05$.

Australian cotton breeders have been successful in improving cotton lint yields in cultivars released since the early 1970s (Constable et al. 2001). 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 Plant Industry have increased an average of 12.9 kg lint/ha/year, representing a 1.8% yield increase per year (Constable et al. 2001). However, American cultivars showed 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 kg lint/ha/year in 1998 (Lewis et al. 2000). In America, DP 16 produced approximately 0.072 g lint/seed, a value similar to the 0.078 g lint/seed in our study. Cultivars from the mid to late 1990s, DP 50 and Suregrow 125 produced only 0.06 g lint/seed (Lewis et al. 2000). There was a decrease in lint/seed and an increase in seeds/boll produced in American cultivars of the mid 1990s (Lewis et al. 2000) while in Australia, seeds/boll 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 kg of seed compared with a kg of lint (cellulose) (West and Todd 1956) since cotton seed contains approximately 29% triglyceride, or oil (Lewis et al. 2000). A negative relationship was also found between lint yield and seed oil percentage (Mert et al. 2005). By selecting for high seeds/boll (Harrell and Culp 1976), lint yields can become more variable and less reliable (Lewis et al. 2000). Australian and American cultivars could have been selected in different directions, Australian cultivars keeping seed numbers fairly constant and increasing lint percentage (lint yield divided by seed cotton yield), which could have indirectly increased lint/seed and lint/boll, while American cultivars may have been increasing seeds/boll and reducing lint/seed. Environmental influences such as droughts, pests and diseases 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. This is not surprising as the Australian breeding program has a strong emphasis on increasing lint percentage.

**Relationship between 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 $R^2$ (0.48, Fig. 6), which is in agreement with Worley et al. (2004). An American study indicated that boll size was often unrelated to yield (Heatholt et al. 1993). Other studies indicate that while lint/seed was thought to make a relatively smaller contribution to yield, it was necessary to maintain or increase this component in order to secure the increased contributions of selection for an increase in seeds/boll (Harrell and Culp 1976; Worley et al. 1974).

The negative relationship between boll retention and the number of fruiting sites was possibly due to competition for assimilates which is finite in supply and must be partitioned between the various sinks (Constable 1991; Pettigrew 1994). Hence, the optimum number of fruit sites may be ~350/m². Bolls are shed because there are not enough resources to carry all of the bolls through to maturity. As boll retention rates increased, there was 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 more bolls were retained, there were fewer seeds/boll. The number of seeds/boll is set early in development (Oosterhuis 1990) [at square initiation (ovules) and at flowering (successful pollination)] and high retention rates during reproductive development may have reduced seeds/boll. The reduced seeds/boll was associated with reduced lint/boll (see Fig 5). Lint/seed appears to be a relatively stable trait as it is correlated with lint yield (Fig. 6b), but not correlated to boll retention. Greater lint/seed occurred through production of more fibres per seed (Bednart et al. 2007). The trade-off with high retention rates is that the number of seeds/boll could be potentially low, thus keeping boll size small. Breeding should therefore focus on increasing lint/boll, a relatively stable component that can be increased concomitantly with retention rates, especially in Bollgard II cultivars with high boll retention rates.

**Conclusions**

The data in this study showed a negative linear relationship between boll retention and seeds/boll, and between boll retention and fruiting sites/m². Hence, for high yielding cultivars with high boll retention rates, breeding efforts should select for larger boll sizes indirectly by selecting for high lint percentage. The information gained from this study will help cotton breeders to target specific yield components such as larger bolls (lint/boll) and lint/seed by selecting for high lint percentage.

**Acknowledgements**

We thank the Cotton Catchment Communities Cooperative Research Centre for funding for this project, Kellie Gordon and Tom O’Connor of CSIRO Plant Industry for their help with data collection, Mick O’Neill and Karen Vize of the University of Sydney for statistical advice, and Jeff Amthor for useful comments on this manuscript.

**References**


