FINAL REPORT

(due within 3 months on completion of project)

Part 1 - Summary Details

Cotton CRC Project Number: **1.04.07**

Project Title: Irrigated Cotton Farming Systems for Central Queensland

Project Commencement Date: 01 July 2005 **Project Completion Date:** 30 June 2008

Cotton CRC Program: The Farm

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Table of Contents

Background

Central Queensland (CQ) has had a long history of cotton production, with a modern industry spanning over 30 years. The hot tropical climate of CQ presents both constraints and opportunities for cotton production. Production constraints have traditionally included more severe insect problems and weather-related stresses relative to cooler growing areas. Grower records show that over the last 30 years cotton yields and profitability vary dramatically between seasons, among farms and even fields within farms. Reasons for this high variability are thought to include external factors such as variable weather conditions and variable crop management practices. On the flip side, the warm climate translates into a relatively long growing season, which in turn facilitates flexibility in sowing times and opportunities for compensatory yield.

Prior to the GM cotton era which began in 1997, cotton production was constrained mainly by insect problems, particularly *Helicoverpa* spp. caterpillars. The commercialization of second-generation GM cotton (Bollgard II) technology gave growers relief from the traditional insect nemesis, viz., *Helicoverpa*, but highlighted new production constraints and a new threat to the industry. The main production constraints highlighted by Bollgard II were (a) a lack of knowledge on the field parameters underpinning the productive advantages of Bollgard II technology, and (b) the emergence of sucking pests that replaced *Helicoverpa* spp. in the pest spectrum. The new threat to the industry in CQ was the risk of *Helicoverpa* populations developing resistance to the Bt toxins in Bollgard II varieties.

There is evidence to suggest that the southern growing valleys have made significant advances in yield and quality over the last 5 years but CQ had not made the same relative improvements in crop production. The specifics of crop nutrition, irrigation and growth management research outputs and guidelines for growers in southern Queensland and New South Wales differ to those for CQ growing conditions. In addition, drought conditions over the last several years and the steadily increasing costs of primary inputs, insecticides and water, combined with a stagnating or falling world price for cotton, have considerably eroded the profitability of growing cotton in CQ.

Successful use of the new technology required new production-related knowledge that was limited in the CQ cotton growing community. The specifics of cotton agronomy, nutrition, water management and other aspects of production gained from growing conventional cottons is no longer fully relevant to Bollgard II production systems. Higher fruit retention characteristic of Bollgard II varieties combined with a different pattern of fruit setting compared to conventional varieties necessitated a re-evaluation of all field parameters as a pre-requisite to the development of higher yielding production systems for CQ based on Bollgard II technology.

A pilot project on the interaction between sowing date and yield in Bollgard II cotton production systems during the 2004/05 season in the Emerald Irrigation Area (EIA) highlighted the scope for exploiting the long growing season enjoyed by CQ growers. The outcomes of the pilot project indicated the potential commercial viability of crops planted in a wide window from September to December.

Project 1.04.07 was developed to determine the best fit of Bollgard II technology in the CQ cotton production, examine alternative tools for Bt resistance management in *Helicoverpa* spp and address the principal insect-related production constraint on the CQ cotton industry, viz., silverleaf whitefly - *Bemisia tabaci* biotype B (SLW).

Objectives

Broad Aims

1. Quantify physiological and agronomic management parameters for Bollgard II systems in CQ.
2. Characterise the interaction between agronomic management practices, insect pest and disease problems
3. Evaluate aspects of Bollgard II efficacy and resistance management in CQ.
4. Develop management guidelines for key pests of Bollgard II, particularly silverleaf whitefly, in CQ.

Specific Objectives

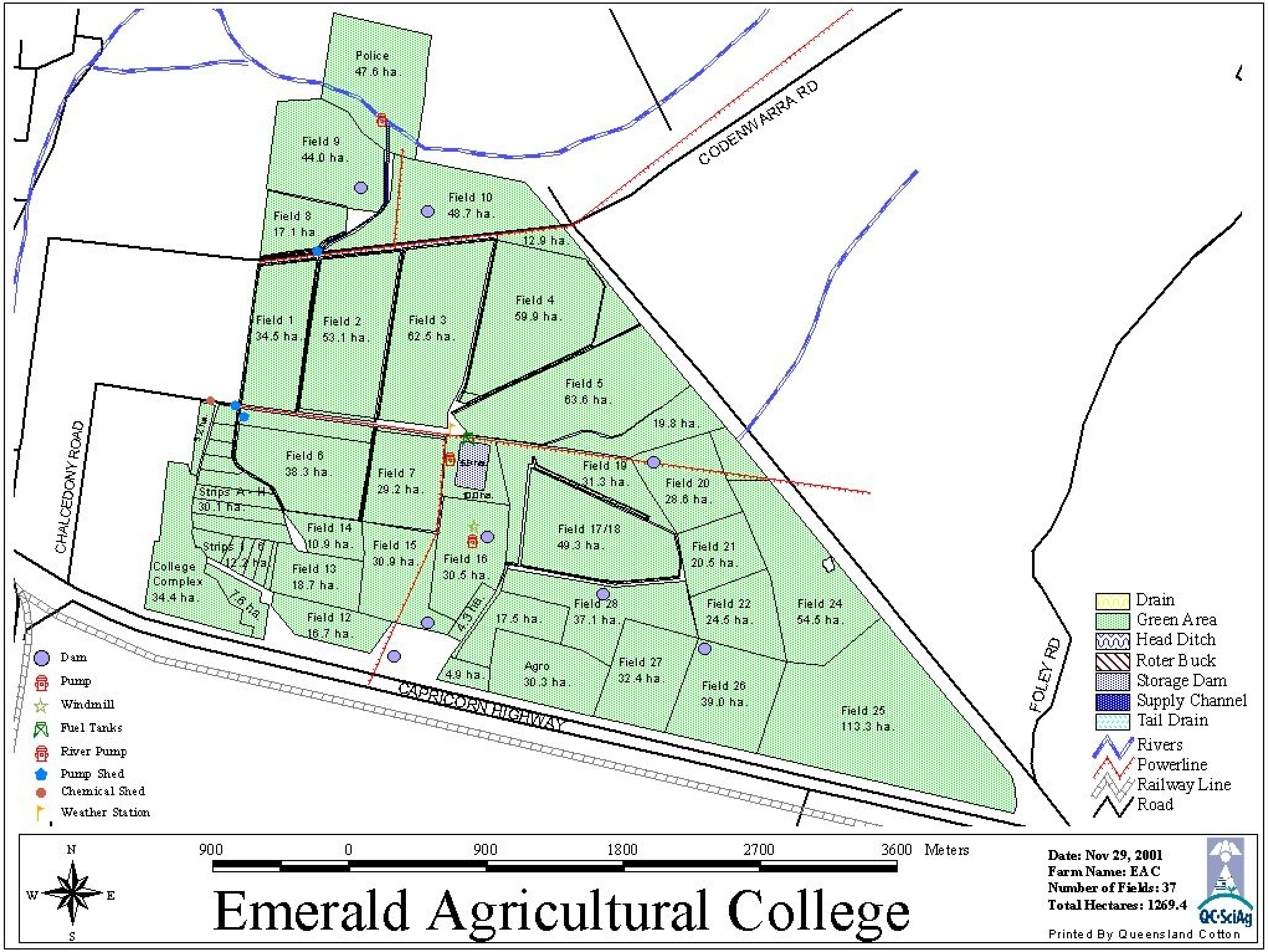
Bollgard II Agronomy:

i. Quantify the impact of sowing date, crop rotation, cultivar types, nutrition, water use and growth habit on lint yield and quality in Bollgard II production systems.
ii. Develop new agronomic management practice guidelines for growers based on current research.

Pest Management for Bollgard II:

1. Develop numerical and binomial sampling strategies for SLW that are appropriate to the CQ cotton production environment.
2. Investigate the impacts of sucking pest management practices on SLW population dynamics in cotton.
3. Evaluate the potential of new technology (Magnet®) for management of Bt resistance in *Helicoverpa* spp.
4. Foster development and on-farm implementation of new and existing IPM tools in the region.

Fig. 1.



Police
47.6 ha.
Field 9
44.0 ha.
Field 8
17.1 ha.
Field 10
48.7 ha.
12.9 ha.
Field 1
34.5 ha.
Field 2
53.1 ha.
Field 3
62.5 ha.
Field 4
59.9 ha.
Field 5
63.6 ha.
19.8 ha.
Field 6
38.3 ha.
Field 7
29.2 ha.
Field 19
31.3 ha.
Field 20
28.6 ha.
Strips A - H
30.1 ha.
Field 14
10.9 ha.
Field 15
30.9 ha.
Field 16
30.5 ha.
Field 17/18
49.3 ha.
Field 21
20.5 ha.
College
Complex
34.4 ha.
Field 13
18.7 ha.
Field 12
16.7 ha.
17.5 ha.
Field 28
37.1 ha.
Field 22
24.5 ha.
Field 24
54.5 ha.
4.9 ha.
Agro
30.3 ha.
Field 27
32.4 ha.
Field 26
39.0 ha.
Field 25
113.3 ha.
CODENWARRA RD
CHALCEDONY ROAD
CAPRICORN HIGHWAY
FOLEY RD
Dam
Pump
Windmill
Fuel Tanks
River Pump
Pump Shed
Chemical Shed
Weather Station
Drain
Green Area
Head Ditch
Roter Buck
Storage Dam
Supply Channel
Tail Drain
Rivers
Powerline
Railway Line
Road
N
S
W
E
900 0 900 1800 2700 3600 Meters
Emerald Agricultural College
Date: Nov 29, 2001
Farm Name: EAC
Number of Fields: 37
Total Hectares: 1269.4
Printed By Queensland Cotton

Fig. 2.

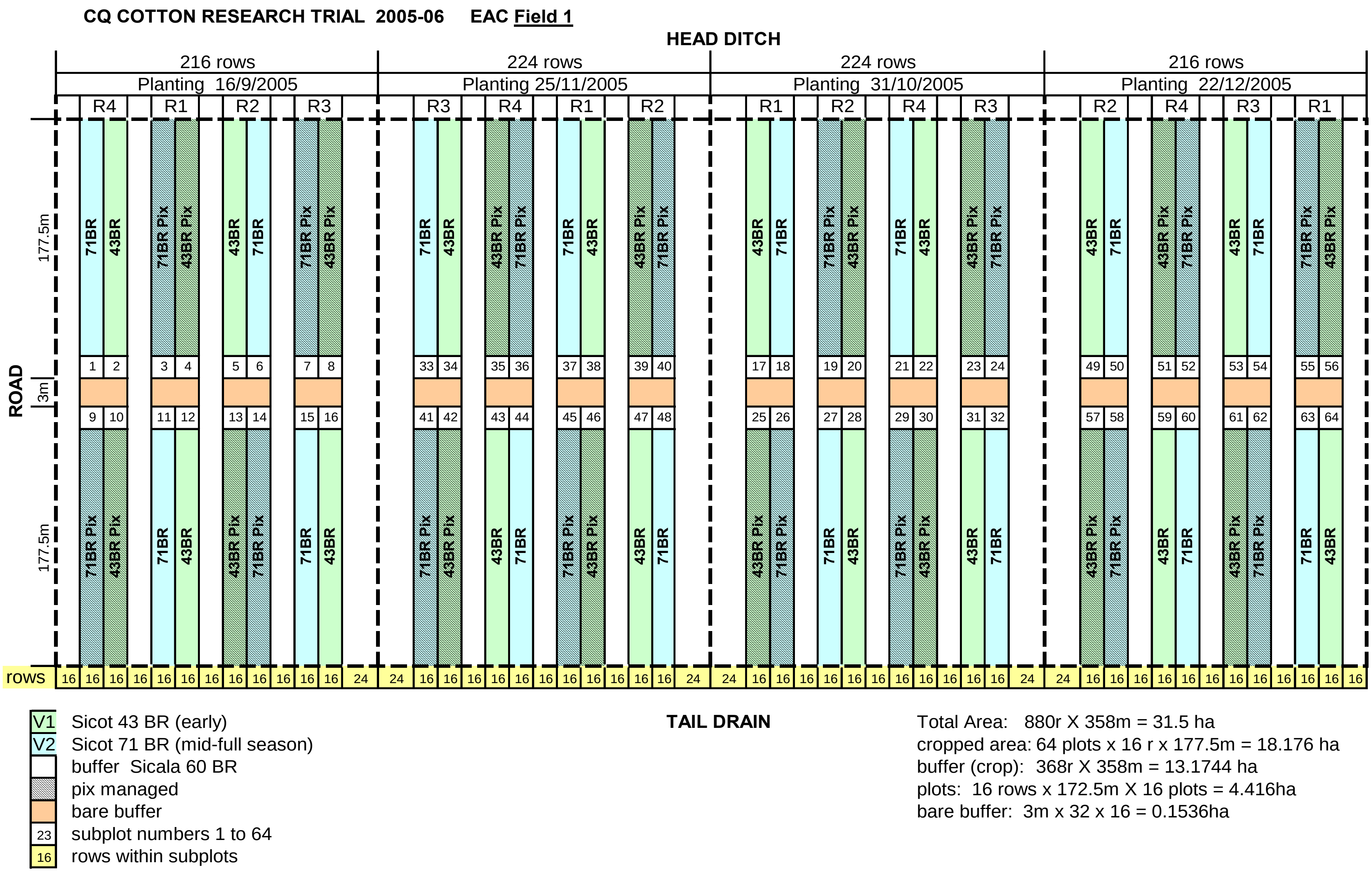
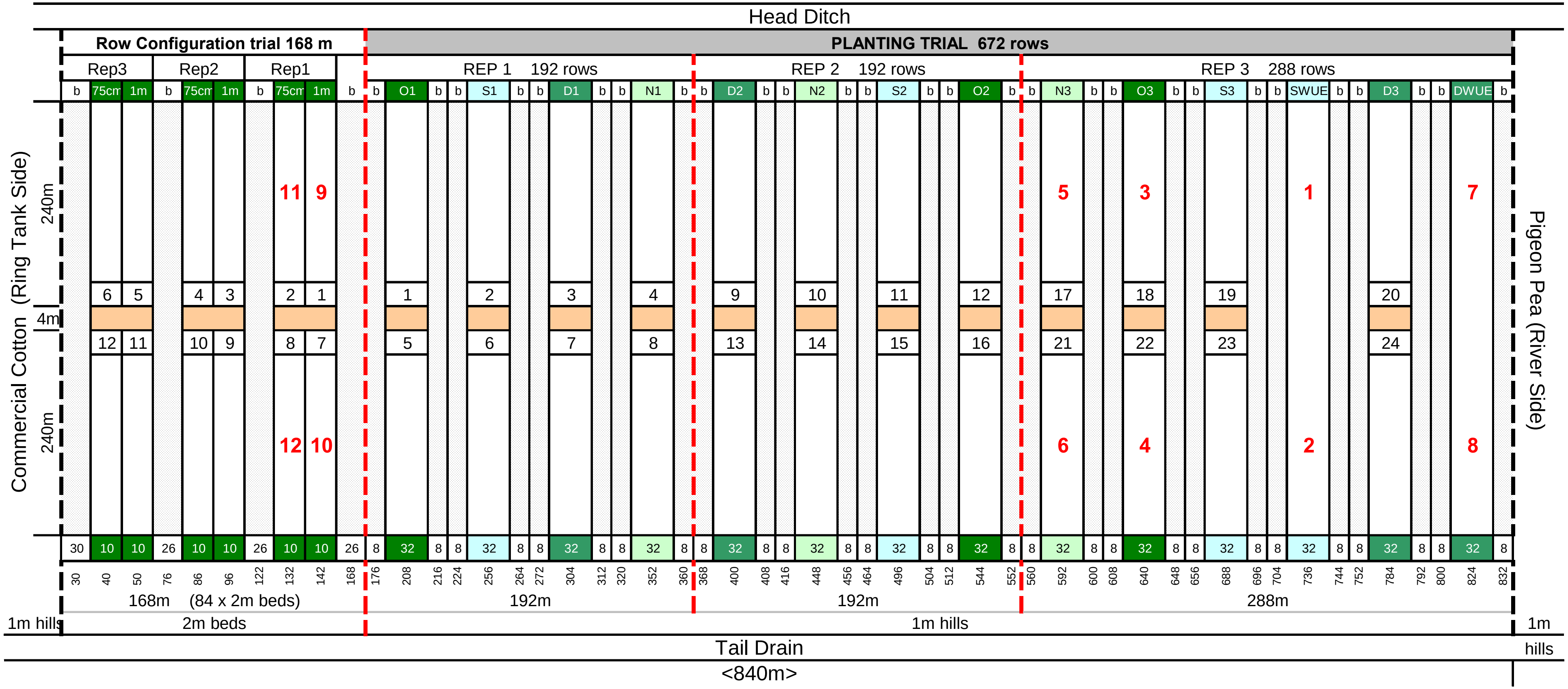

CQ COTTON RESEARCH TRIAL 2005-06 EAC Field 1
HEAD DITCH
216 rows
Planting 16/9/2005
224 rows
Planting 25/11/2005
224 rows
Planting 31/10/2005
216 rows
Planting 22/12/2005
ROAD
RIVER
177.5m
3m
177.5m
rows
TAIL DRAIN
V1 Sicot 43 BR (early)
V2 Sicot 71 BR (mid-full season)
buffer Sicala 60 BR
pix managed
bare buffer
23 subplot numbers 1 to 64
16 rows within subplots
Total Area: 880r X 358m = 31.5 ha
cropped area: 64 plots x 16 r x 177.5m = 18.176 ha
buffer (crop): 368r X 358m = 13.1744 ha
plots: 16 rows x 172.5m X 16 plots = 4.416ha
bare buffer: 3m x 32 x 16 = 0.1536ha

Fig. 3.

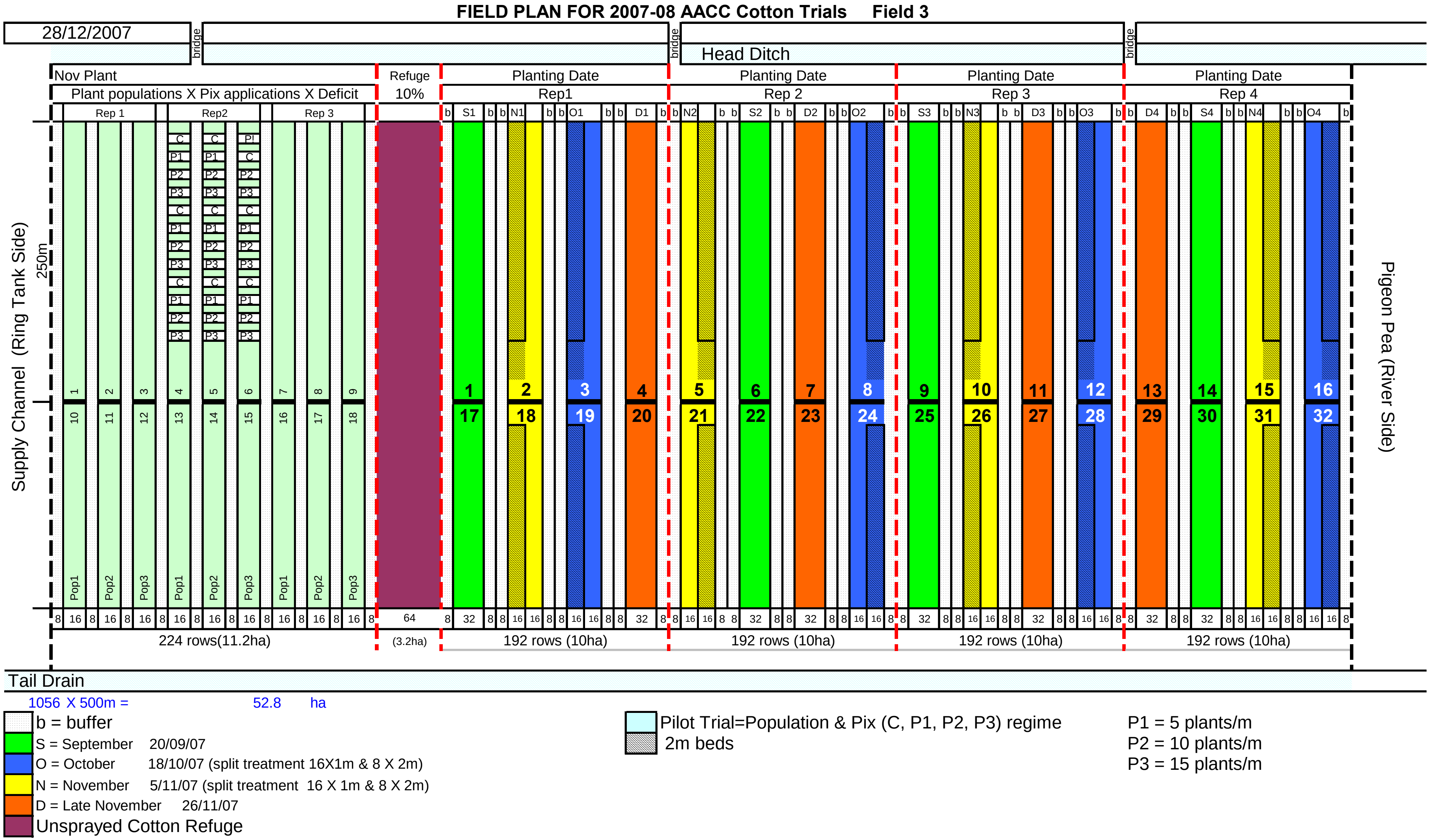
FIELD PLAN FOR 2006-07 AACC Cotton Trials Field 3



		rows		rows
b	buffer Siokra V-16BR (14.94ha)	332	Row configuration 27/9 [2.7ha]	60
S	Sept sowing (15/9/06) [5.76ha]	128	TOTAL cropping area (37.8ha)	840
O	Oct sowing (17/10/06) [4.32ha]	96	main crop Sicot 71BR (22.86ha)	448
N	Nov sowing (13/11/06) [4.32ha]	96	WUE Water Use Efficient Trials (2.88ha)	64
D	Dec sowing (11/12/06) [5.76ha]	128		

1 diviner probe numbers

Fig. 4.


FIELD PLAN FOR 2007-08 AACC Cotton Trials Field 3
28/12/2007
bridge
Head Ditch
Nov Plant
Plant populations X Pix applications X Deficit
Refuge
10%
Planting Date
Rep1
Rep 2
Rep 3
Rep 4
Rep 1
Rep2
Rep 3
S1 N1 O1 D1 N2 S2 D2 O2 S3 N3 D3 O3 D4 S4 N4 O4
C
P1
P2
P3
Pop1
Pop2
Pop3
250m
Supply Channel (Ring Tank Side)
Pigeon Pea (River Side)
64
224 rows(11.2ha)
(3.2ha)
192 rows (10ha)
Tail Drain
1056 X 500m = 52.8 ha
b = buffer
S = September 20/09/07
O = October 18/10/07 (split treatment 16X1m & 8 X 2m)
N = November 5/11/07 (split treatment 16 X 1m & 8 X 2m)
D = Late November 26/11/07
Unsprayed Cotton Refuge
Pilot Trial=Population & Pix (C, P1, P2, P3) regime
2m beds
P1 = 5 plants/m
P2 = 10 plants/m
P3 = 15 plants/m

Methods

Bollgard II Agronomy:
Field assessments of key Bollgard II cotton agronomic variables and their interactions were conducted on the Australian Agricultural College Corporation (AACC) Emerald Campus farm using controlled, large-plot experimental designs.

Year 1: 2005-06
Field layout - The focus of the field assessments was on the interaction between sowing date, cultivar type and application of plant growth hormone (Pix®) on yield and quality. The assessments were conducted in Field 1 (Fig. 1) using a pseudo-replicated split-plot design (Fig. 2) with four sowing dates (main plots = 16 September, 31 October, 25 November and 22 December), two cultivar types (subplots = early season (Sicot 43BR) and mid-full season (Sicot 71BR)) and two Pix treatments (sub-subplot = Pix or no-Pix). Each sowing date treatment (main plot) was replicated four times. The length of each main plot equalled that of the field. The field layout was designed to detect any impacts of topography (top half versus bottom half of the field) on crop physiology and yield. Due to the practical difficulties associated with irrigation of multiple plots at different location throughout the field and constraints on basic tillage operations resulting from wet tail drain areas, replicates of each sowing date were aggregated into blocks (Fig. 2).

Irrigation - All blocks were watered up and planted into moisture. A 60mm deficit was used for irrigation scheduling. This was measured by a Diviner soil moisture system with 2 tubes in every planting date.

Fertilizer – a base rate of fertiliser was applied through anhydrous ammonia and a granular custom blend. On the 2nd in-crop irrigation 60kg of anhydrous was applied through the water. Total Fertiliser included 274kg N/ha, 30kg P/ha and 60kg K/ha.

Planting – 120 000 seeds/ha planted with John Deere Maximerge twin disc planter. Risolex® was applied as water injection solution. Seed was treated with Dynasto® & Amparo®.

Herbicide – Sprayseed® was applied at planting, Roundup® herbicide over the top application and a second Roundup application through a shielded sprayer with Diuron. One inter-row cultivation was carried out between Roundup applications.

Insecticide – Checked by commercial consultant.

Defoliation – Applied at 90% open bolls, all applied with ground rig.

Pix Management -The application of Pix was managed on a commercial decision making process with a local consultant assessing the requirements. Pix was applied to half the plots within the planting date block and the other half were left untreated as controls.

Physiological Measurements
Height and number of nodes (from 4 nodes to cut-out)
1st position retention
Full plant maps @ 1st flower and cut-out.
Light meter readings at 1st flower and cut-out
Maturity picks from 20% open boll, til harvest.
Segmented Hand harvests (box maps), prior to picking
Machine picker yields

Dates of 1st Square, 1st Flower, cut-out, 1st cracked boll and defoliation.
Fibre samples taken for quality analysis.

Year 2: 2006-07

Field layout - The focus of the field assessments in the second year was to validate the impacts of sowing date on crop yields documented in year 1 and to quantify the effects of row configurations and water use efficiency on yield. All field assessments were conducted in Field 3 (Fig. 1). A single cotton variety, Sicot 71BR was used in all the assessments.

The sowing date experiment was conducted using a fully randomized block experimental design (Fig. 3) with four sowing dates (main plots = 15 September, 17 October, 13 November and 11 December). Each sowing date treatment (main plot) was replicated thrice. The plots were split into top and bottom halves to detect effects of topography.

An assessment of two row configurations (75 cm wide and 1m wide) was conducted using a split-plot design with three replicates in a block adjacent to the sowing date experiment (Fig. 3). The row-configuration assessment plots were planted on 27 September. A pilot water use efficiency (WUE) assessment trial was incorporated into the sowing date experimental design as extra main plots in the September and December sowing date treatments. The WUE component was linked in with the WUE III initiative in CQ led by Mr. Lance Pendergast.

The length of all main plots equalled that of the field. The practical difficulties associated with complete randomisation of sowing date treatments experienced in year 1 were avoided in year 2 by the use of a double tail drain system; each main plot was equipped with a separate drainage portal facilitated by an earth bank separating it from the tail drain.

Fertiliser application - Base blend was applied at 360kg/ha containing Muriate of Potash, Starter Z, MAP and Sulphate of Ammonia. 100 kg of Urea was applied as a side dressing and irrigated in. 50 kg of Nitrogen was applied through the irrigation in two applications.

All other land preparation and operations details were similar to year 1.

Year 3. 2007-08

Field layout – Sowing date was retained as the main focus of the field assessments in the third year. All assessments were conducted in Field 3 (Fig. 1) using Sicot 71BR. The field layout for the sowing date assessment was identical to the one used in year 2 (Fig. 4) with four sowing dates (main plots = .20 September, 18 October, 13 November and 28 November).

A separate assessment (Year 3 Pilot) was conducted to determine the interactions between plant population density (main plots = 7 sown seeds/m (low), 12 sown seeds/m (med), 17 sown seeds/m (high)), Pix rate and timing of application, and irrigation deficit (60 cm or 80 cm). The Pix treatments were: C=Control, P1 = early Pix at 7-9 nodes, P2 = P1 + Pix at first flower, P3 = Pix application as determined by crop consultant. Pix treatments were replicated four times at each level of plant population density (Fig. 4).

Fertiliser application - Base blend was applied at 360kg/ha containing Muriate of Potash, Starter Z, MAP and Sulphate of Ammonia. 100 kg of Urea was applied as a side dressing and irrigated in. 12 kg of Anhydrous Ammonia was applied through the irrigation in two applications.

All other land preparation and operations details were similar to year 2.

Pest Management for Bollgard II:

Bt Resistance Management – New options for pre-emptive management of Bt toxin resistance in *Helicoverpa armigera* populations were investigated in the Dawson-Callide valleys by Dr. Paul Grundy in 2004-05 and 2005-06. A full report is presented in **Appendix 1**.

Silverleaf Whitefly Management – Data on the field ecology and inter-seasonal population dynamics of SLW collected in project DAQ 120C from 2002-03 – 2005-06 were used to develop comprehensive sampling and management guidelines for growers and consultants. A full report (scientific publication) is presented in **Appendix 2**.

Results

Year 1: 2005-06

Sowing Date (SD) codes:
September planted = 1
October planted = 2
November planted = 3
December planted = 4

Cultivar type (CT) codes:
Sicot 71BR = cv 1
Sicot 43BR = cv 2

The data were subjected to analysis of variance procedures and repeated measures analyses using an ante-dependence structure of order 0 or 1 (ANTTEST procedure in GENSTAT), as appropriate. The adjacent text box shows the numerical codes used to refer to sowing date (SD) and cultivar type (CT) treatments used in the experimental design in the following sections.

Sowing Date Experiment:

Plant stand:

- Plant density (metre-row $^{-1}$) estimates for SD 1-4 were 7, 8, 10 and 6, respectively. Plant stands were fairly uniform in crops 1-3 but patchy in crop 4 (Fig. 5). Within each sowing date, there were no significant differences between cultivars types and among Pix and no-Pix designated treatment plots (ANOVA on split plots, P > 0.20).

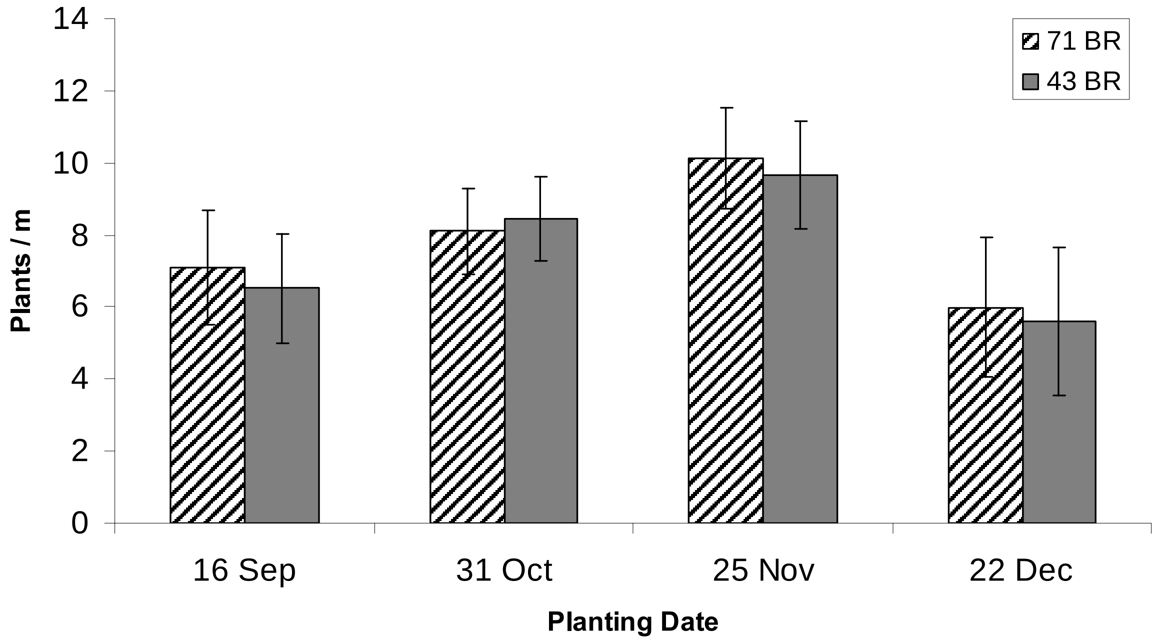


Fig. 5. Mean plant density estimates for the sowing (planting) date experiment at the Australian Agricultural College Farm in 2005-06.

Height:

- Seasonal growth profiles of all SDs were similar but both cultivars from SD 1 were consistently shorter than their counterparts from SD 2-4 (Figs. 6 A, D).
- It was deemed necessary to apply Pix in both September and December planted crops but not in the November or October planted crops. The application of growth regulator (Pix) to SD 1 and 4 (September and December) did not have a significant effect on plant height (ANTTEST procedure, $P \geq 0.10$). Plants in Pix treated plots of Sicot 71 BR were marginally (3-4 cm) shorter than in untreated plots but this trend was not observed in corresponding plots of Sicot 43 BR (Figs. 6 B, C, E, F).

- The Pix x Cultivar interaction was significant at 70-90 DAP in SD 1 and 90 DAP in SD 4 (ANTTEST procedure, $P \leq 0.05$) indicating a small but significant differential response by the two cultivars to plant growth hormone treatment. Sicot 71 BR was generally around 5 cm shorter than Sicot 43 BR in split-plot comparisons.
- There were no differences in height between cultivars in SDs 2 and 3 (Pix was not applied).

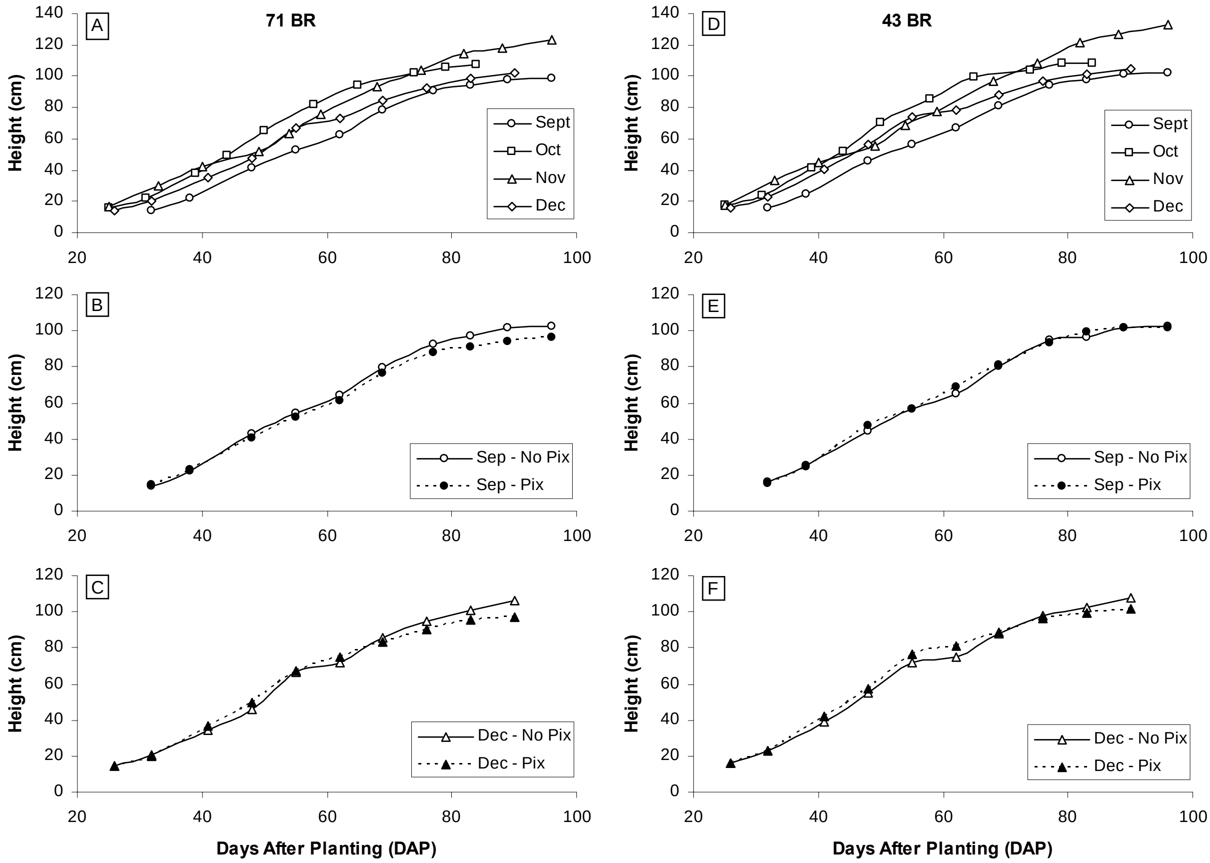


Fig 6. Differences in crop height among treatment of the sowing date experiment at the Australian Agricultural College Farm in 2005-06. A) Seasonal crop height differences between sowing dates for Sicot 71 BR; D) Seasonal crop height differences between sowing dates for Sicot 43 BR; B) Seasonal crop height differences between plots with and without application of Pix for Sicot 71 BR in the September sowing treatment; E) Seasonal crop height differences between plots with and without application of Pix for Sicot 43 BR in the September treatment; C) Seasonal crop height differences between plots with and without application of Pix for Sicot 71 BR in the December sowing treatment; F) Seasonal crop height differences between plots with and without application of Pix for Sicot 43 BR in the December treatment.

Total Nodes:

- Seasonal profiles of total number of nodes were similar in all SDs. The profiles for both cultivars in SD 1 differed from their counterparts in SDs 2-4 by 0.5-1 node (Figs. 7 A, D).
- The application of growth regulator (Pix) to SDs 1 and 4 (September and December) did not have a significant effect on total nodes (ANTTEST procedure, $P \geq 0.10$) for both cultivars (Figs. 7 B, C, E, F).
- There were no differences in total nodes between cultivars in SDs 2 and 3 (Pix was not applied).

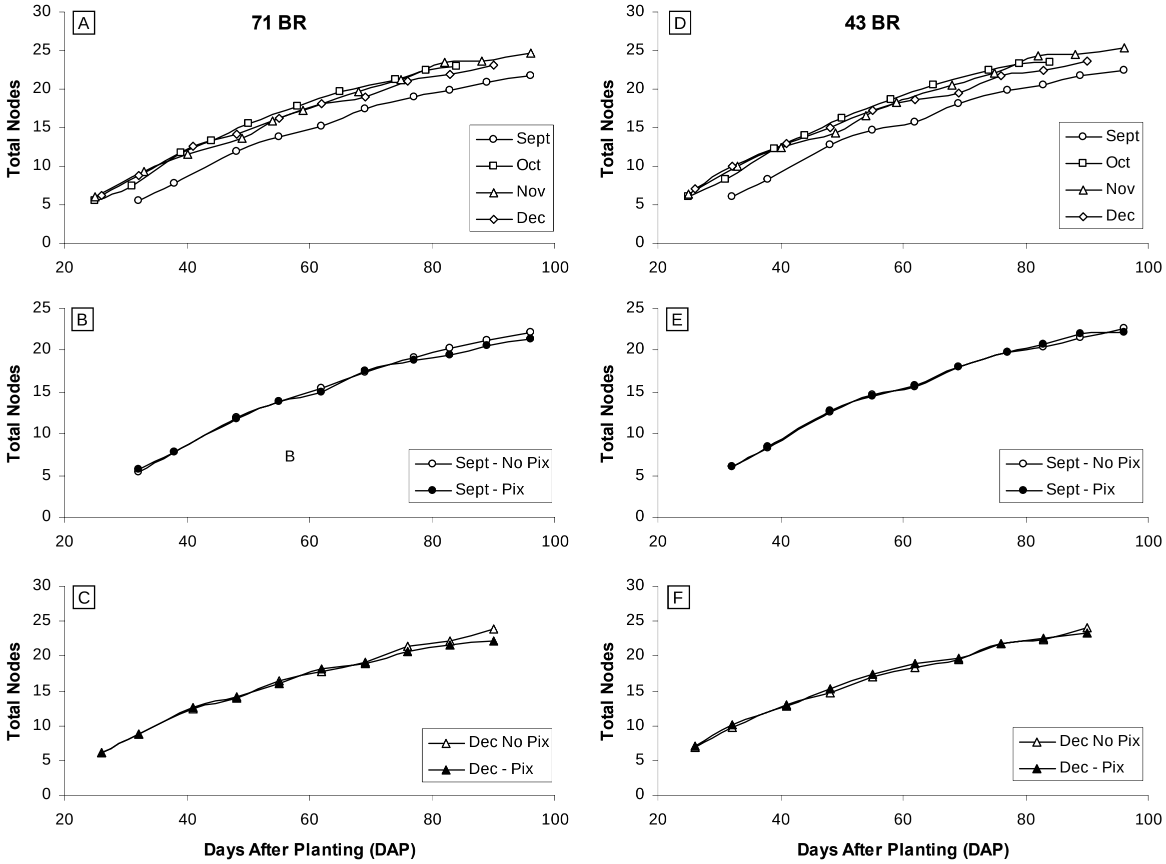


Fig 7. Differences in node development among treatment of the sowing date experiment at the Australian Agricultural College Farm in 2005-06. A) Seasonal node development differences between sowing dates for Sicot 71 BR; D) Seasonal node development differences between sowing dates for Sicot 43 BR; B) Seasonal node development differences between plots with and without application of Pix for Sicot 71 BR in the September sowing treatment; E) Seasonal node development differences between plots with and without application of Pix for Sicot 43 BR in the September treatment; C) Seasonal node development differences between plots with and without application of Pix for Sicot 71 BR in the December sowing treatment; F) Seasonal node development differences between plots with and without application of Pix for Sicot 43 BR in the December treatment.

Fruit Retention (%):

- Fruit retention profiles were variable among the four SDs, reflecting differences in temperature and rainfall/overcast weather regimes experienced by each crop. The profiles for SDs 1 and 2 were largely flat (stable) throughout the season, with fruit retention dropping to 70% at the end of the season (Figs. 8 A, B). SD 4 started the season at well above 80% fruit retention, finishing the season at just under 70% (Fig. 8 D). By comparison, SD 3 started shedding fruit around 55 days after planting, ending the season at 50% retention (Fig. 8 C).
- Within each SD, there were no significant differences between the individual profiles for Sicot 71BR and Sicot 43BR for most of the growing season (Figs 8 A-D) (ANTTEST procedure, $P \geq 0.10$). Similarly, within cultivars there were no significant differences between replicates. This suggests a fairly homogeneous growing environment across the field housing the trial.
- The fruit retention profiles of plots with and without Pix treatment were virtually identical in both cultivars in crops 1 and 4 (Figs. 9 A-D) indicating that application of Pix did not have any effect on % fruit retention.
- Exposure to extreme heat (= heat shock, > 38 °C) varied with time of planting. SD 1 was exposed to 13 days of extreme heat, largely after the first 80 days of growth (Fig. 10 A).

SDs 2 and 3 were each exposed to 18 days of extreme heat largely within the first 75 days of growth (Fig. 10 B, C) whereas SD 4 was exposed to 11 days most of which occurred prior to seedling emergence (Fig. 10 D).

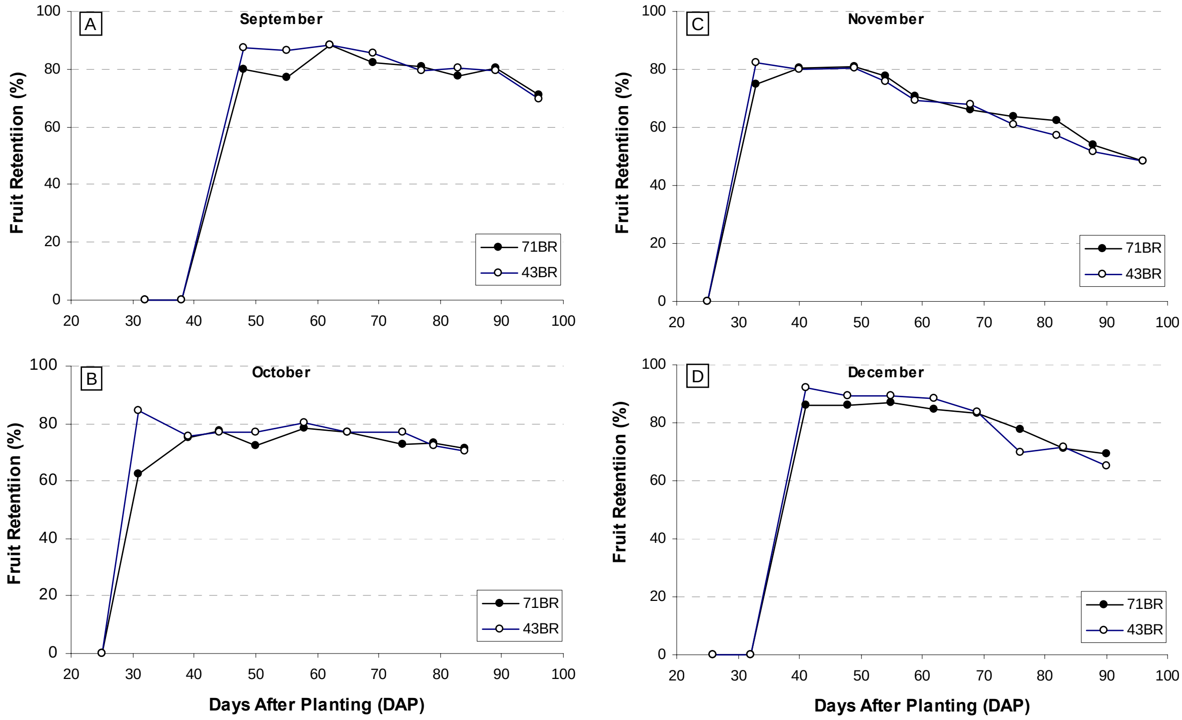


Fig. 8. Seasonal fruit retention profiles for Sicot 71 BR and Sicot 43 BR in the sowing date experiment at the Australian Agricultural College Farm in 2005-06. A) September, B) October, C) November, D) December.

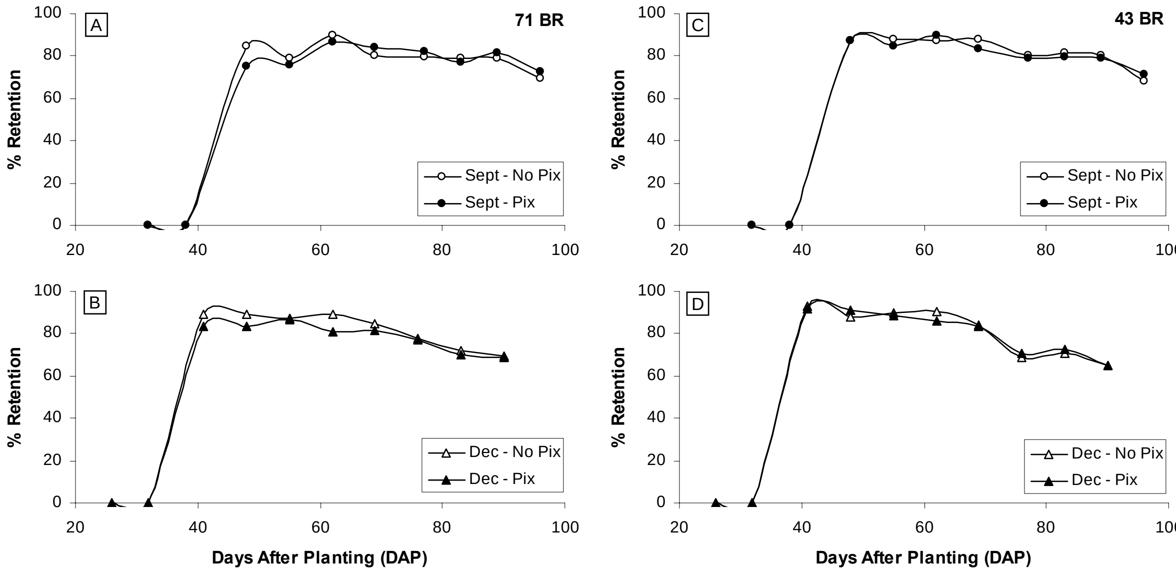


Fig 9. Differences in fruit retention among treatment of the sowing date experiment at the Australian Agricultural College Farm in 2005-06. A) Seasonal retention profile differences between plots with and without Pix application for Sicot 71 BR in the September sowing date treatment; C) Seasonal retention profile differences between plots with and without Pix application for Sicot 43 BR in the September sowing date treatment; B) Seasonal retention profile differences between plots with and without Pix application for Sicot 71 BR in the December sowing date treatment; D) Seasonal retention profile differences between plots with and without Pix application for Sicot 43 BR in the September sowing date treatment.

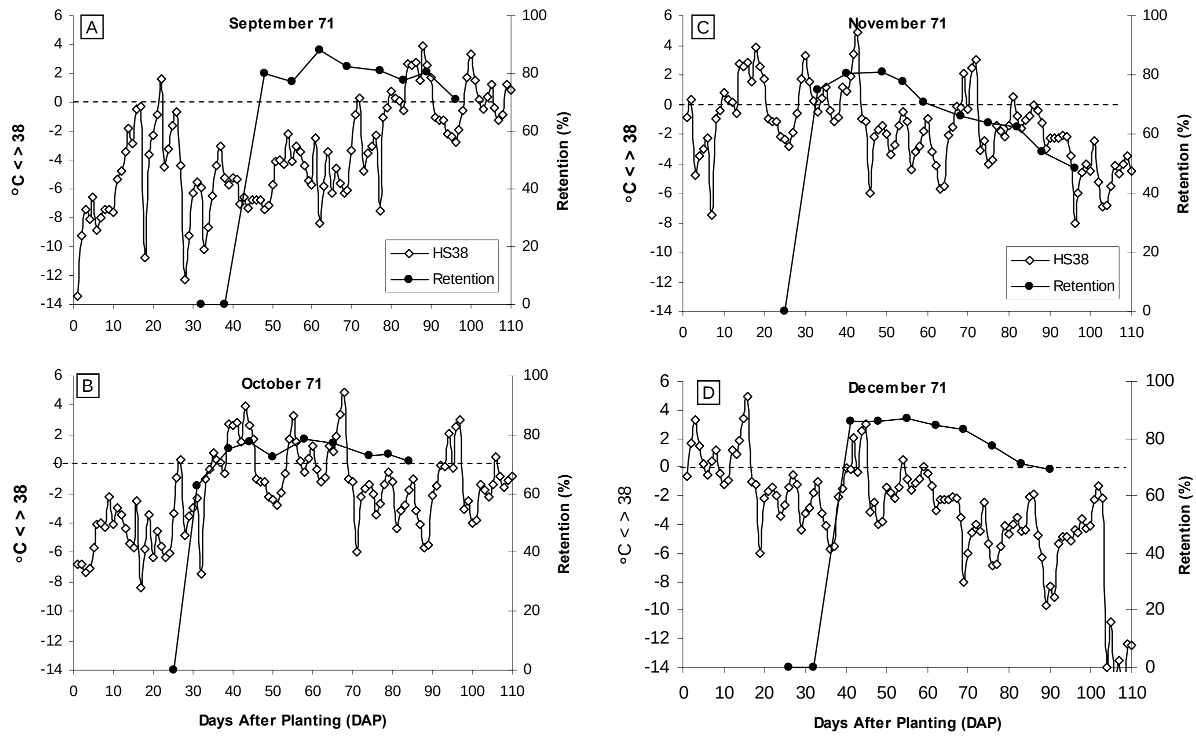


Fig. 10. Fruit retention profiles for crops in the sowing date treatment at the Australian Agricultural College Farm in 2005-06 superimposed on daily maximum temperature fluctuation expressed as a deviation above or below 38 °C (interpreted as the heat stress threshold for cotton). A) September; B) October; C) November; D) December.

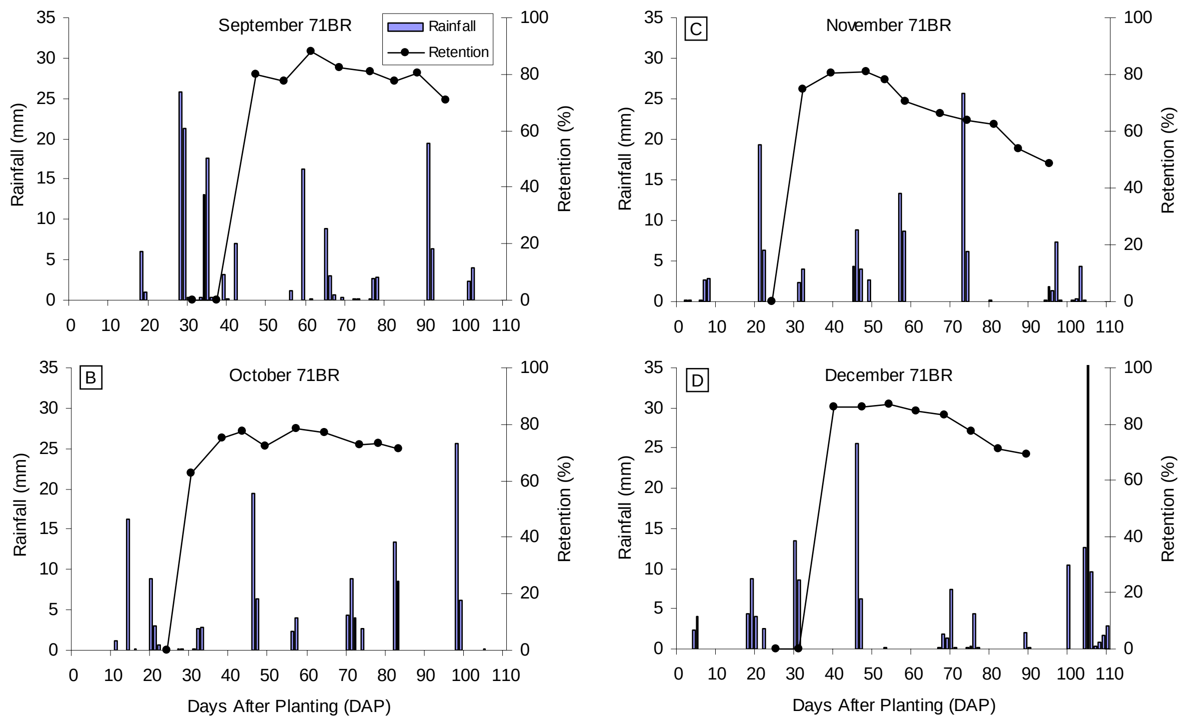


Fig. 11. Fruit retention profiles for crops in the sowing date treatment at the Australian Agricultural College Farm in 2005-06 superimposed on daily rainfall. A) September; B) October; C) November; D) December.

- Rainfall events experienced by the four SDs (Figs. 11 A-D) in conjunction with corresponding drops in maximum temperature over 2 or more days (Figs. 10 A-D) are likely markers of overcast weather which in turn offers an explanation for sharp falls in fruit retention. The sharp drop in %fruit retention in SD 3 at around 55-60 days after planting (Fig. 10 C) coincides with a drop in maximum daily temperature over several days and a rainfall event (Fig. 11 C), making it highly likely that overcast conditions contributed significantly to fruit shedding. This phenomenon is again apparent at 70-75 days after planting.

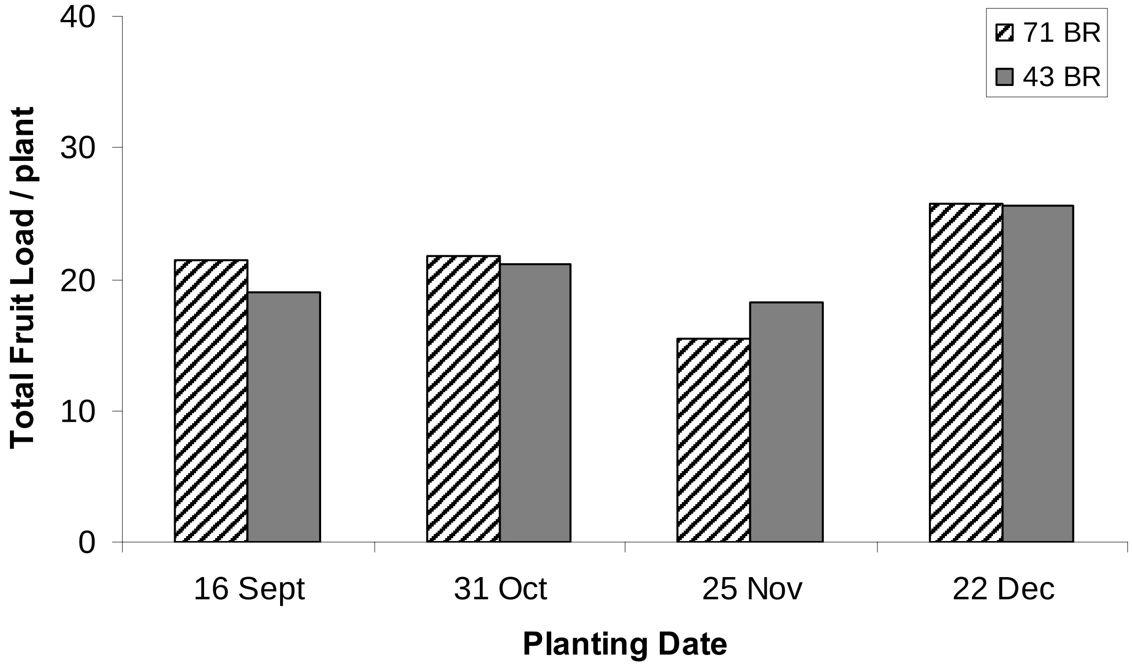


Fig 12. Total fruit load Fruit by cultivar in the sowing date treatments at the Australian Agricultural College Farm in 2005-06.

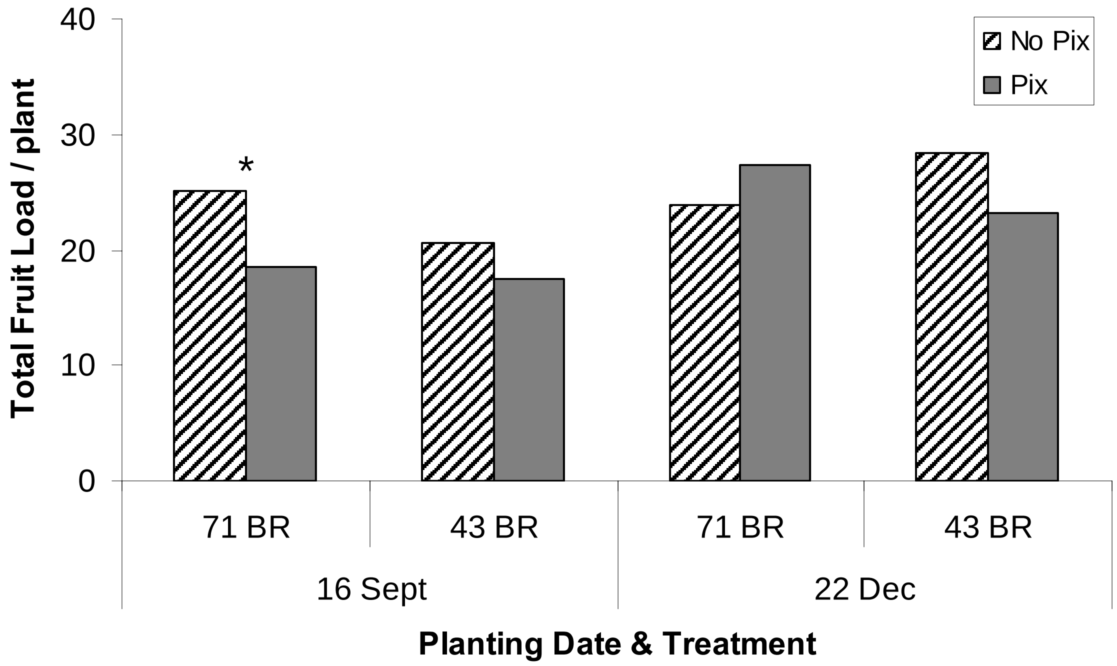


Fig 13. Total fruit load Fruit by cultivar for plots with and without Pix application in the sowing date treatments at the Australian Agricultural College Farm in 2005-06.

- SD 4 experienced a general decline in daily maximum temperatures after the first 60 days (Fig. 10 D), thereby limiting the availability of sufficient heat units during boll filling.

Total Fruit Load:

- SD 4 had the highest total fruit load (sum of squares, flowers and bolls estimated at cut-out) followed by SDs 1 and 2 whereas SD 3 had the lowest (Fig. 12). Differences in total fruit load between cultivars were not statistically significant within any of the crops (ANOVA on split plots; df=1,3, $P > 0.10$).
- Total fruit load was significantly lower in Pix-treated plots of Sicot 71BR than in corresponding untreated plots (Fig. 13; ANOVA on split plots; df=1,6, $P = 0.002$) whereas differences in fruit load between treated and untreated plots of Sicot 43BR were not significantly different (ANOVA on split plots; df=1,6, $P > 0.10$).
- The differential reaction of the two cultivars to Pix appears to have been small but negative.

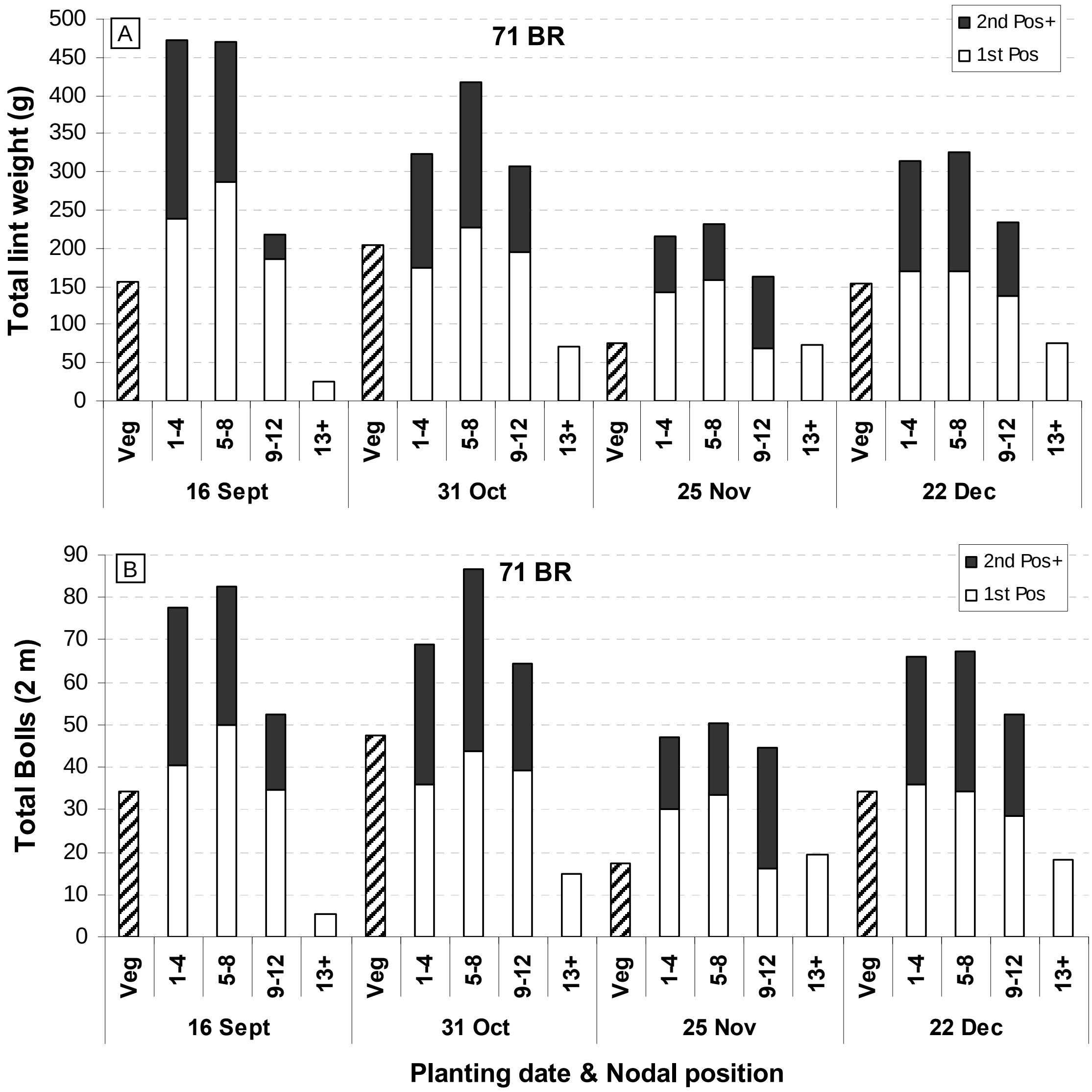


Fig. 14. Compartmentalization of lint weight and total boll numbers by nodal position using the CSD Box Mapping procedure for Sicot 71 BR in the sowing date treatments at the Australian Agricultural College Farm in 2005-06.

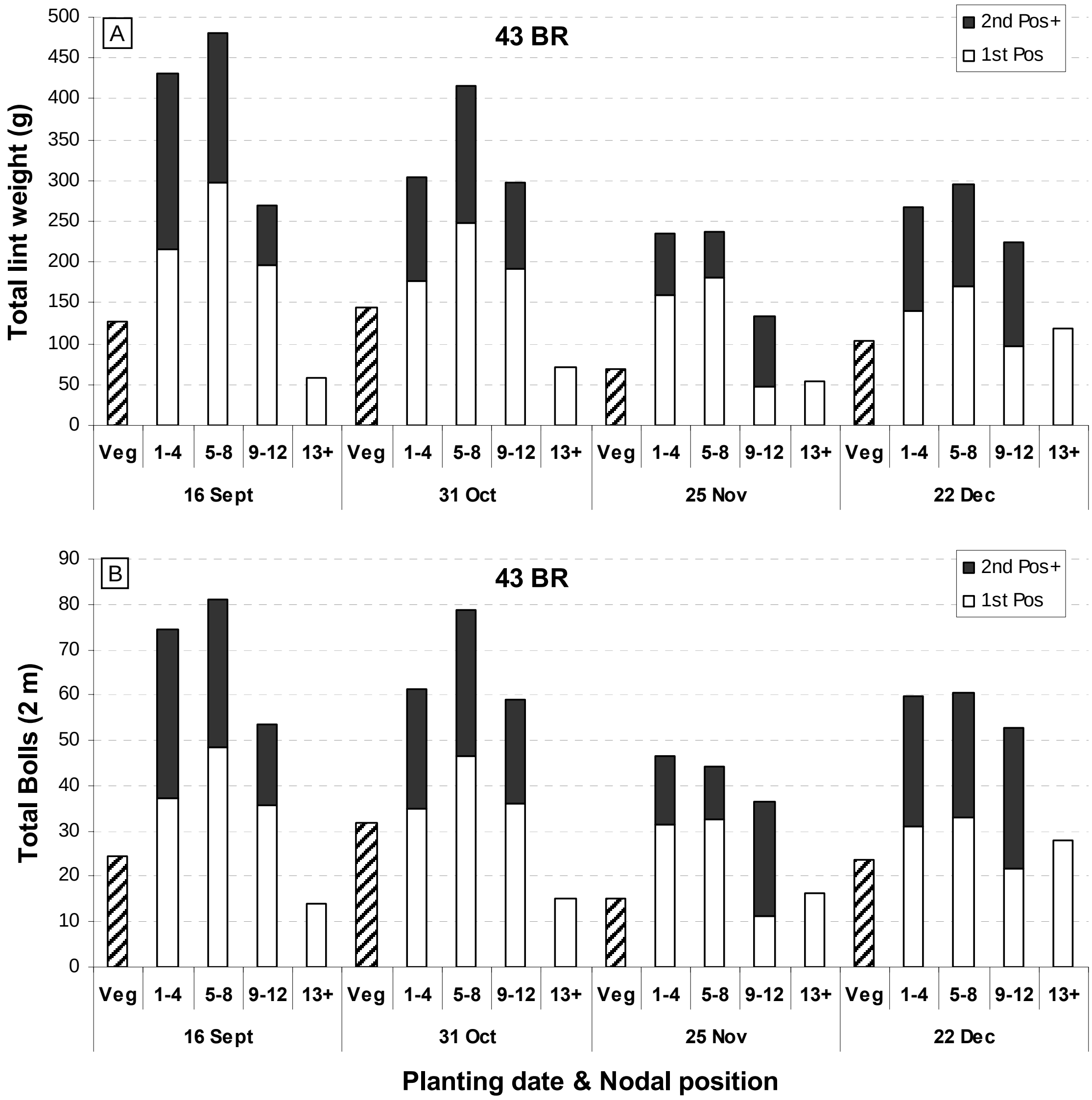


Fig. 15. Compartmentalization of lint weight and total boll numbers by nodal position using the CSD Box Mapping procedure for Sicot 43 BR in the sowing date treatments at the Australian Agricultural College Farm in 2005-06.

Plant Yield Maps (Box Maps):

- The compartmentalisation of total lint weight and boll numbers (yield parameters) according to nodal position on the plant and planting date for Sicot 71BR and Sicot 43BR following the protocol used by Cotton Seed Distributors (CSD) agronomists is shown in Figs. 14 and 15, respectively.
- Both cultivars in SD 1 (16 September) produced the bulk of their yield on the first eight nodes, as evidenced by the drop in lint yield and boll numbers at nodes 9-12 and 13+ whereas in SD 2 (31 October) yield was concentrated in the middle (nodes 5-8).
- In SD 3, both cultivars has a disproportionately large load of 2nd position bolls at nodes 9-12 with a correspondingly small load at nodes 1-4 and 5-8 in conjunction with a small vegetative boll load (Figs 14 B, 15 B). These findings collectively describe a crop with limited growth potential that tried to put on a top crop at the end. A relatively dense plant stand (cf Fig 5) may have contributed to the erosion of yield potential by encouraging apical growth at the expense of vegetative growth at lower nodes.
- In both cultivars average boll weight was markedly higher in SD 1 than in the other SDs (Fig. 16).

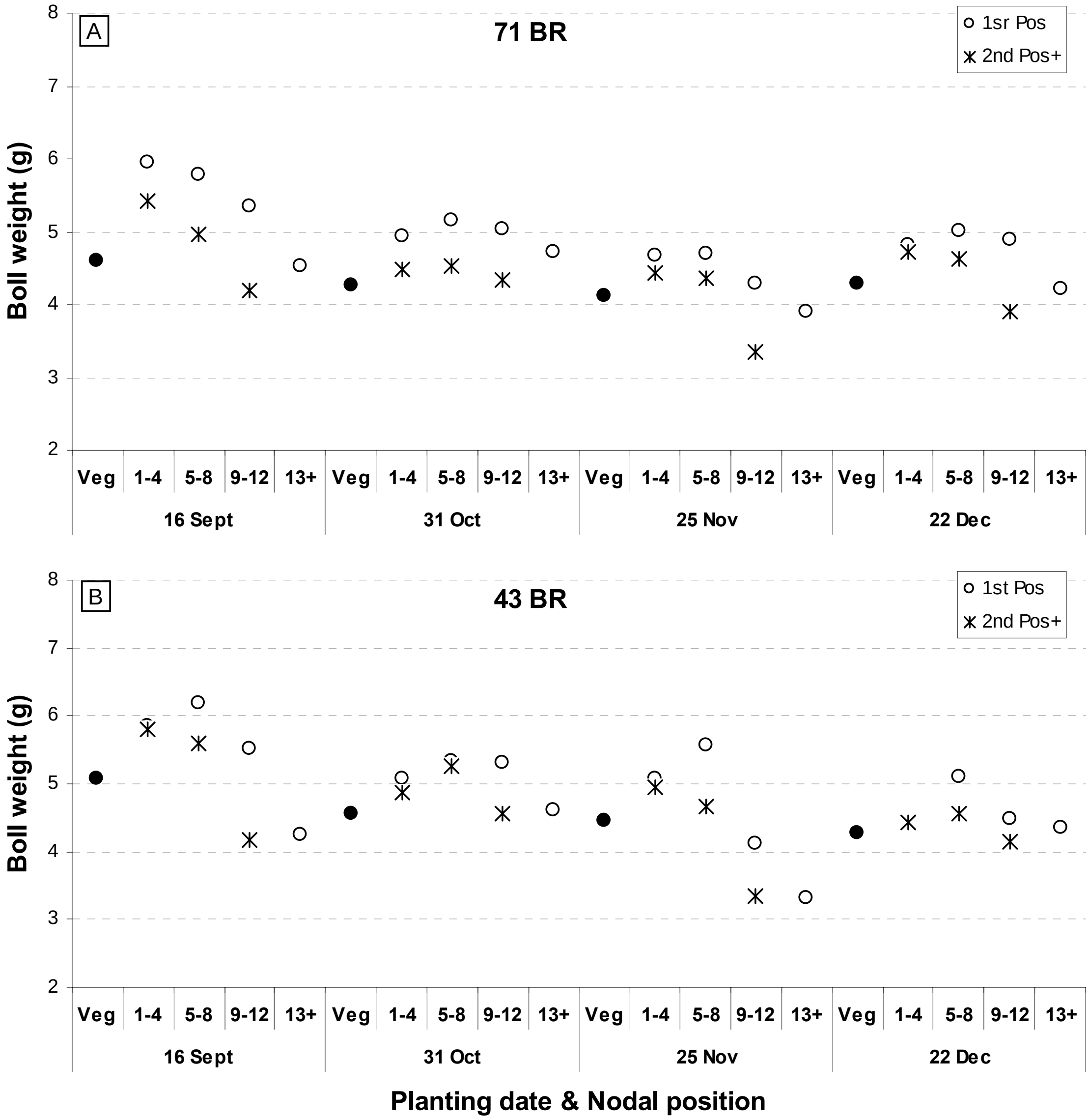


Fig. 16. Compartmentalization of boll weights by nodal position using the CSD Box Mapping procedure for (A) Sicot 71 BR and (B) Sicot 43 BR in the sowing date treatments at the Australian Agricultural College Farm in 2005-06.

- The effect of smaller boll size in SD 2 relative to SD 1 is evident in the contrast between crops with respect to marginal lint weights and boll loads (Fig. 17 A-D); Sicot 71BR produced the same marginal lint weights in SDs 1 and 2 but boll load was higher in SD 2 (cf Figs 17 A, B). Sicot 43BR produced higher marginal lint weights in SD 1 but equal boll loads in both crops (cf Figs. 17 C, D).

Final machine picked yields:

- Sicot 43BR out-yielded Sicot 71BR in SD 1 (ANOVA on split plots; Cultivar stratum, df=1,3, $P = 0.03$) but there were no significant differences between cultivars in any of the other SDs (Fig. 18).
- There were no significant differences in machine picked yield between Pix-treated and untreated plots within cultivars within each SD (ANOVA on split plots; Cultivar stratum, df=1,3, $P > 0.10$; Fig 19).
- In SDs 1, 3 and 4, plots in the bottom (tail drain) half of the paddock consistently under-yielded corresponding plots in the top half (ANOVA on split plots; Rep x Plot x Subplot stratum, df=1,15, $P = 0.024$; Fig. 20) presumably as a result of significant water logging.

- Sicot 43BR yielded 10.1, 9.8, 5.8 and 5.6 bales/ha in SDs 1-4 respectively.
- Sicot 71BR yielded 9, 9.7, 5.4 and 6 bales/ha in SDs 1-4 respectively.

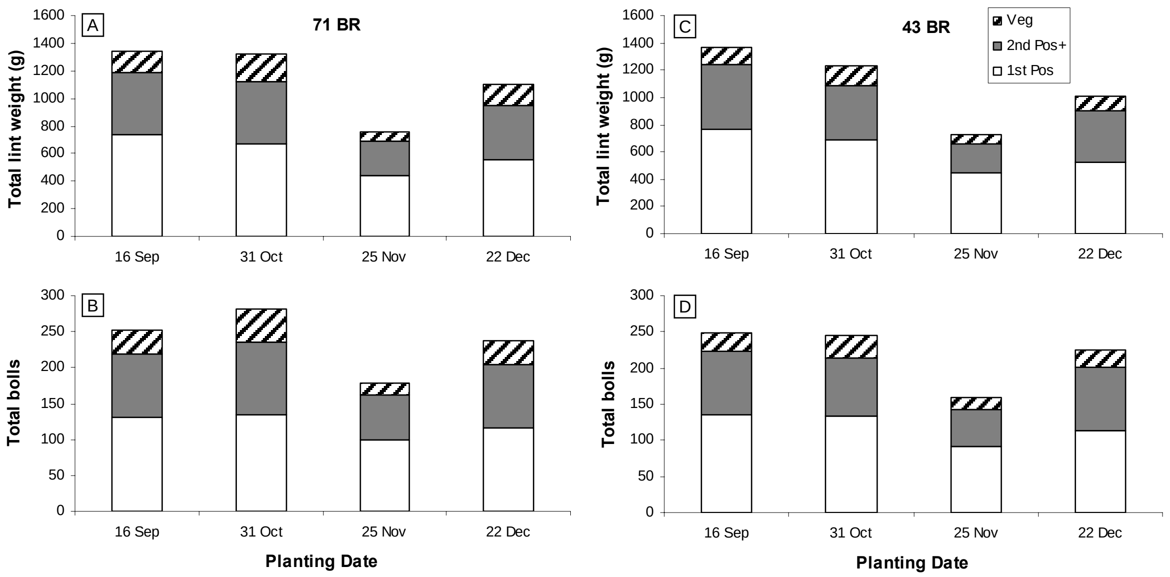


Fig. 17. Compartmentalization of total lint weight and total bolls into first and second nodal position and vegetative boll categories for Sicot 71 BR (A, B) and Sicot 43 BR (C, D) in the sowing date treatments at the Australian Agricultural College Farm in 2005-06.

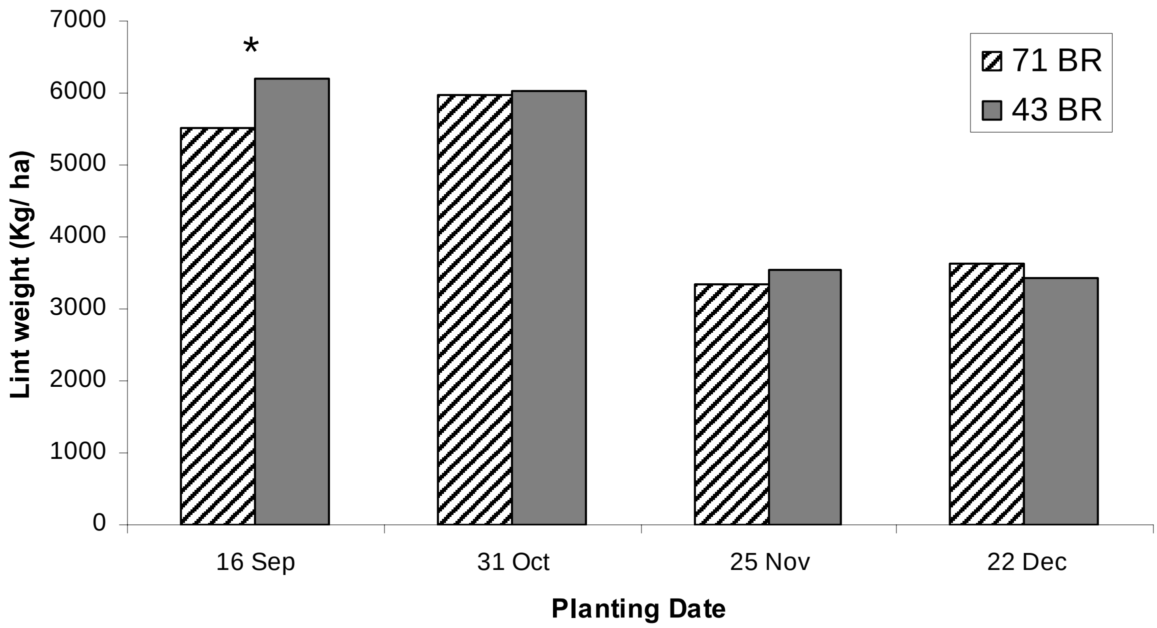


Fig. 18. Mean yield (lint weight) for Sicot 71 BR and Sicot 43 BR in the sowing date treatments at the Australian Agricultural College Farm in 2005-06. * indicates statistically significant differences between cultivars.

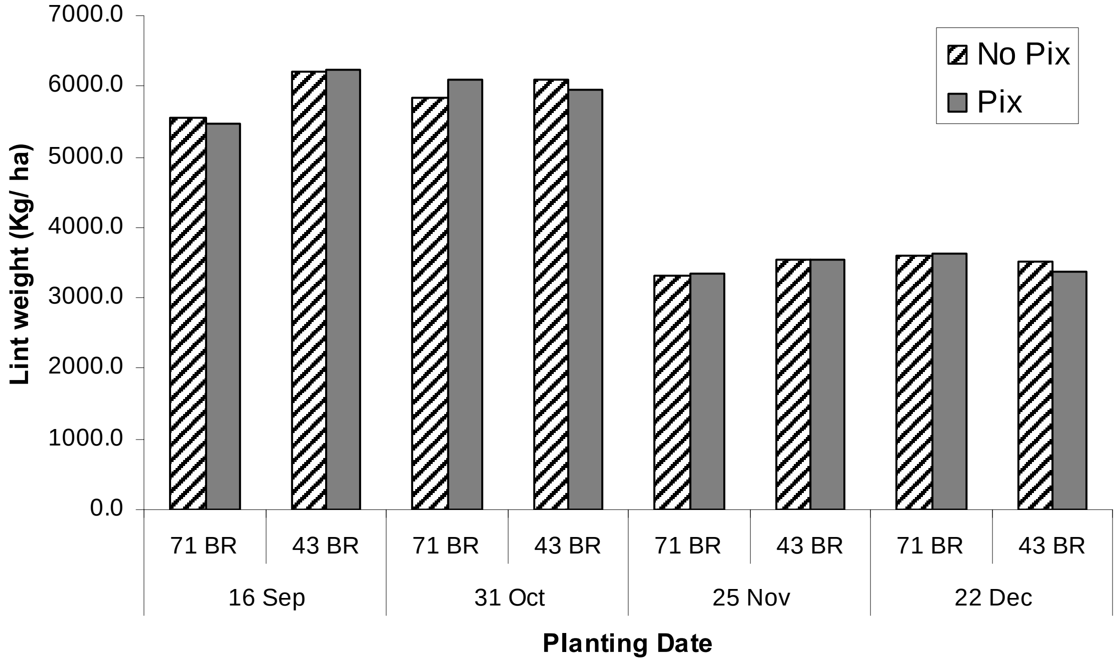


Fig. 19. Mean yield (lint weight) for plots with and without Pix application within Sicot 71 BR and Sicot 43 BR in the sowing date treatments at the Australian Agricultural College Farm in 2005-06. No significant differences between adjacent columns within any treatment.

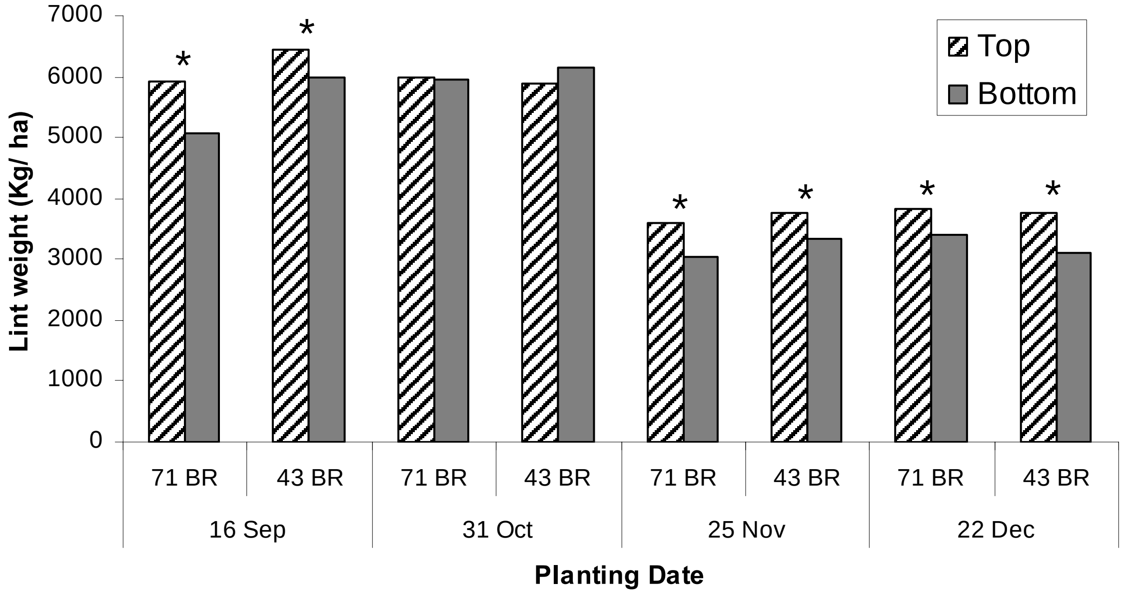


Fig. 20. . Mean yield (lint weight) for top (head ditch end) and bottom (tail drain end) subplots within Sicot 71 BR and Sicot 43 BR main plots in the sowing date treatments at the Australian Agricultural College Farm in 2005-06. * indicates statistically significant differences between adjacent columns within main treatment/plot.

Length of Season (Days to Maturity)

- The days to 60% maturity confirm the similarity of the two cultivar types in terms of physiological responses in the CQ environment (Table 1).
- The results also confirm the lack of response to growth regulator (Pix) application.

Table 1. Number of days from planting to maturity for plots with and without growth regulator (Pix) application within Sicot 71 BR and Sicot 43 BR cultivar treatments in the sowing date experiment at the Australian Agricultural College Farm in 2005-06.

Days to 60% maturity

Treatment	43 No Pix	43 Pix	71 No Pix	71 Pix
16 Sep	131	129	132	131
31 Oct	123		126	
25 Nov	128		131	
22 Dec	153	162	150	148

Days to 80% maturity

Treatment	43 No Pix	43 Pix	71 No Pix	71 Pix
16 Sep	137	136	138	137
31 Oct	131		133	
25 Nov	152		151	
22 Dec	175	176	171	162

Machine Picked Lint Quality

- All quality indicators and gin turnout were low for SD 3 (Nov) which is consistent with the picture presented by the other physiological data.
- Gin turnout were very good (above 40%) for SDs 1 and 2 (Sept and Oct) and respectable (40%) for SD 4 (Fig. 21).
- Although gin turnout and length were good for SDs 1 and 2, micronaire was in suboptimal range (above 4.5; Figs. 22, 23).
- Crop 4 was low yielding but lint quality was clearly in the optimal parameter range for all variables – low micronaire, good length and respectable turnout (Figs. 22, 23).

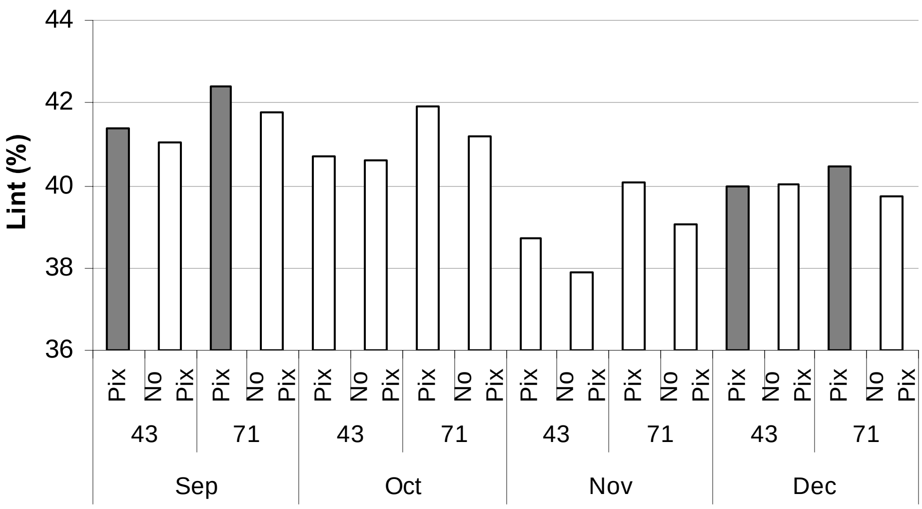


Fig. 21. Average gin turnouts (% Lint) for subplots (with and without Pix application) within Sicot 71 BR and Sicot 43 BR main plots in the sowing date treatments at the Australian Agricultural College Farm in 2005-06.

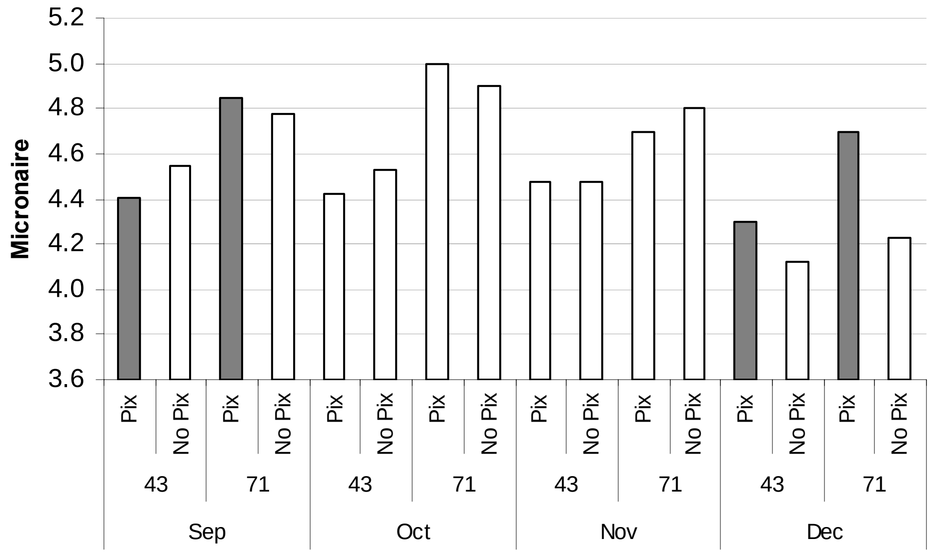


Fig. 22. Micronaire classing for subplots (with and without Pix application) within Sicot 71 BR and Sicot 43 BR main plots in the sowing date treatments at the Australian Agricultural College Farm in 2005-06.

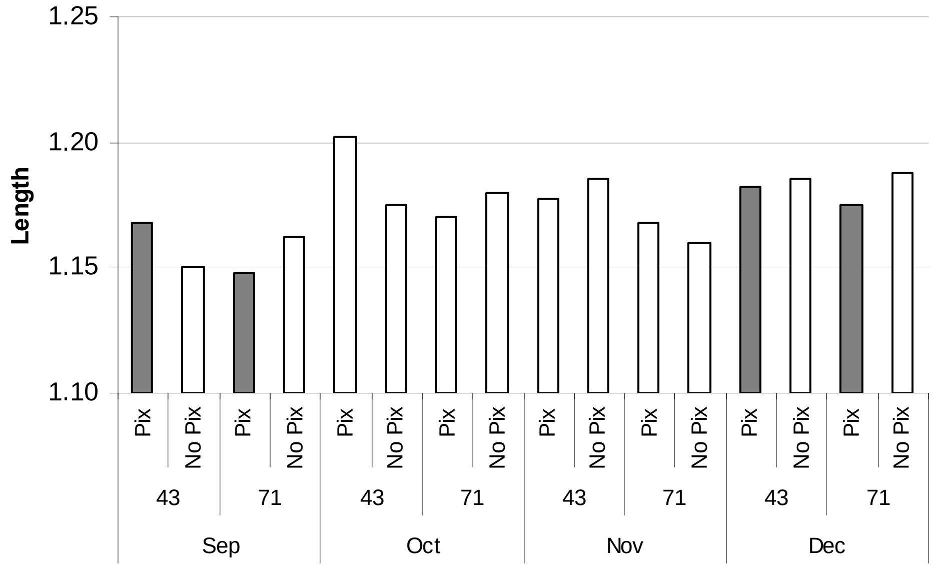


Fig. 23. Fibre length classing for subplots (with and without Pix application) within Sicot 71 BR and Sicot 43 BR main plots in the sowing date treatments at the Australian Agricultural College Farm in 2005-06.

Year 2: 2006-07

Sowing Date Experiment:

Plant stand:

- Mean plant density, in the range of 12-12.5 plants/metre-row, was not significantly different between SDs 2-4 (October–December) but significantly lower at 9.5 plant/metre-row in SD 1 (September) (ANOVA, df=3, 20, P < 0.001).

Heights &Nodes:

- SD 1 plots were consistently shorter than their SD 2 and 4 counterparts whereas SD 3 showed the greatest potential for rapid growth under warm conditions (Fig. 24A).
- A comparison of crop final heights at cut-out revealed statistically significant differences between crops from the different sowing dates: SD 1 < SD 4 < SD 2 < SD 3 (ANOVA, df=3, 8, P < 0.001).
- SD3 had the highest average number of fruiting nodes at cut-out (15.67) whereas SD 1 and SD 4 had the least ()12.53 and 13.07, respectively.
- The order of statistical significance among the treatments for average number of fruiting nodes was: SD 1 = (SD 4) < SD 2 < CD 3 (ANOVA, df=3,8, P = 0.002).

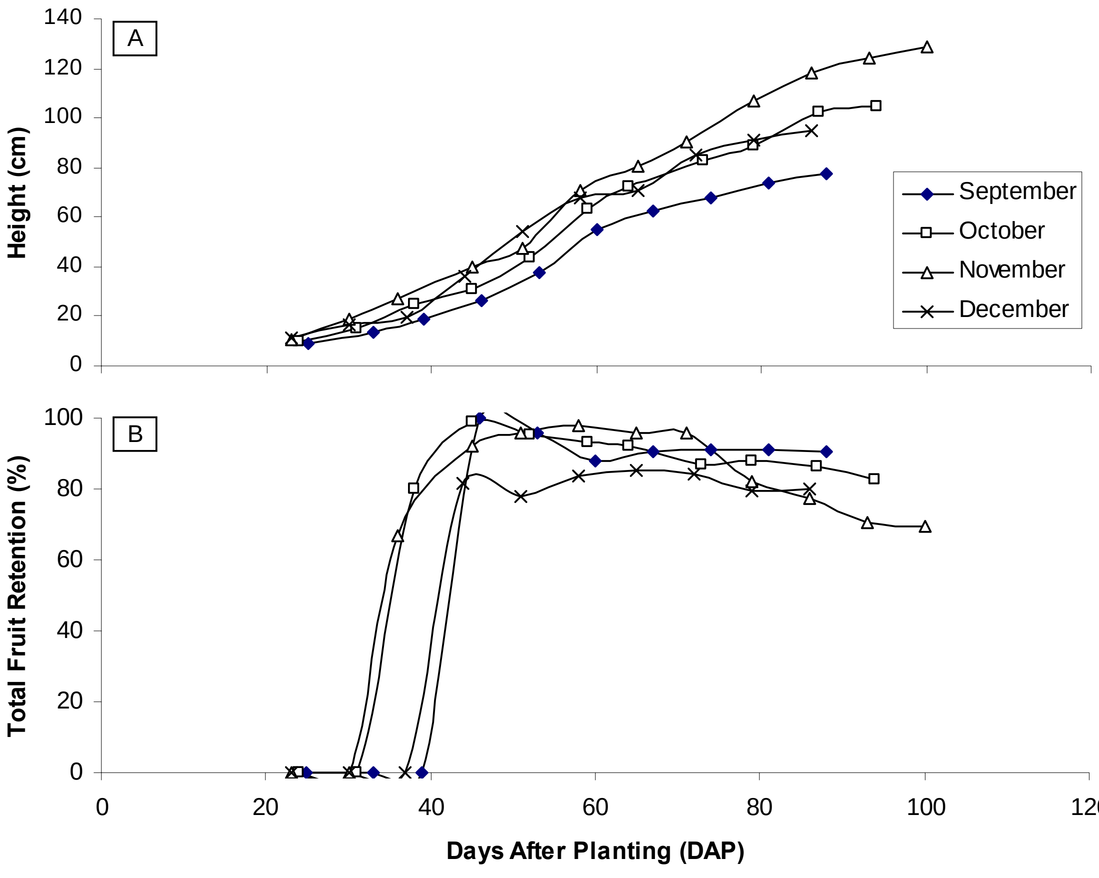


Fig. 24. Seasonal crop height (A) and total fruit retention (B) differences among sowing date treatments for Sicot 71 BR at the Australian Agricultural College Farm in 2006-07.

Fruit Retention (%) & Total Fruit Load:

- The profile of % Fruit retention varied within (over time) and among sowing dates. Prior to about 70 DAP, the fruit load (%) profile was lowest in SD 4 and highest in SD 3 (Fig. 24B).
- Beyond 80 DAP, the % fruit retention profile for SD 3 dropped sharply and did not recover.
- This trend was confirmed by the discrepancies between whole plant maps at first flower and cut-out which showed that SD3 ended up with the lowest total fruit load relative to fruiting positions at 53%.
- By comparison, SDs 1 and 4 held on to around 80% of all fruit and SD2 held on to 65%.

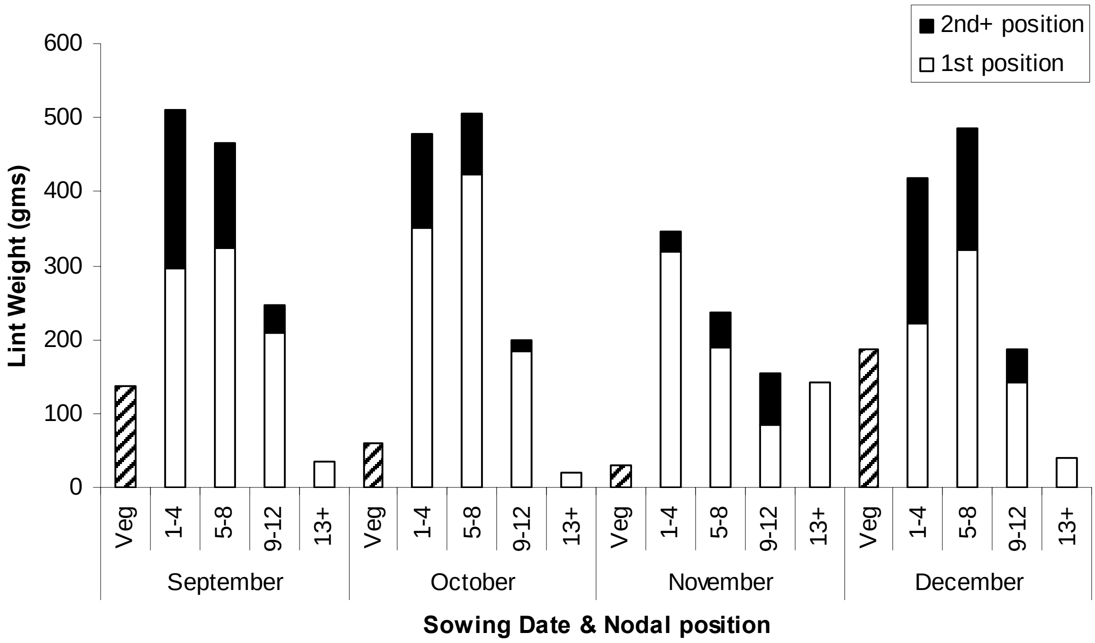


Fig. 25. Compartmentalization of lint weight by nodal position using the CSD Box Mapping procedure for Sicot 71 BR in the sowing date treatments at the Australian Agricultural College Farm in 2006-07.

Plant Yield Maps (Box Maps):

- The compartmentalisation of yield, as indicated by the box mapping procedure, is reflective of different environmental conditions experienced by each sowing date.
- Overall boll numbers, adjusted for differences between nodal position groups (group used as a blocking variable in ANOVA procedure) we re not significantly different among SDs 1-4 (ANOVA, df=3,85, P = 0.19).
- Lint weight varied among the four planting dates. Overall adjusted lint weight (nodal position grouping variable used as blocking factor) in SD3 was significantly lower than in SDs 1, 2 and 4 had similar weights (ANOVA, df=3,85, P =0.01).
- A graphical comparison of the four sowing dates (Fig. 25) shows that the bulk of the yield was produced at nodes 1-8, with a predominance of first position bolls in SD2 and greater contribution of secondary and tertiary fruiting positions in SDs 1 and 4. The contribution of vegetative bolls to total yield was also greater in SDs 1 and 4. This pattern of yield distribution was at odds with SD3 wherein not only was overall yield depressed compared to the other SDs but the contribution of a top crop (13+ nodal positions) to yield is apparent.

Final machine picked yields & fibre quality:

- Statistical analysis of the machine picked yield data (blocked on location, ie., top or bottom of field) indicated two yield groups (Fig,. x4; ANOVA, df=3,43, P < 0,001).
- SD s 1 and 2 were placed in the high yielding group yielding around 9.5 bales/ha (LSD test, P > 0.05) whereas SDs 3 and 4 were in the second group (LSD test, P > 0.05) yielding under 8.45 bales/ha.
- A two-way ANOVA procedure on the yield data to ascertain the importance of location indicated a non-significant main effect (P = 0.49) and location x sowing date interaction (P = 0.07).
- Lint quality was described as base grade or better for all plots/treatments.

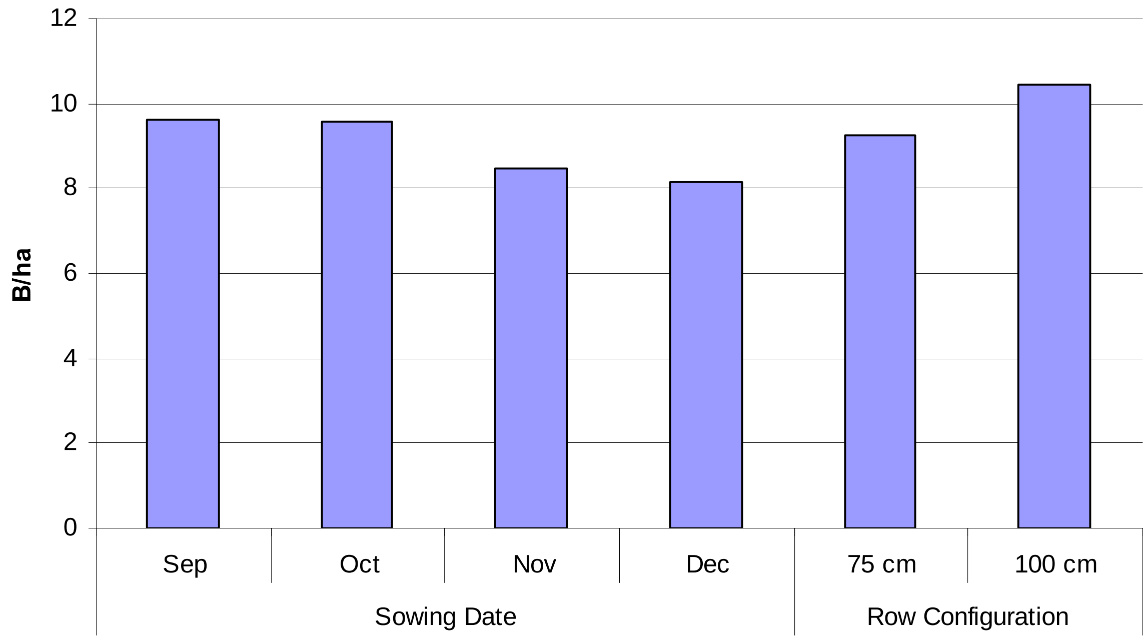


Fig. 26. Yield comparison between treatments of the sowing date and row configuration experiments at the Australian Agricultural College Farm in 2006-07.

Row-Configuration Experiment

Final machine picked yields:

- The 2-m bed treatment out-yielded the 1-m row treatment by 1.2 bales/ba (Fig. x4; ANOVA, df=1,9, P = 0.003).
- A yield advantage of the 2-m bed treatment over the 1-m row counterpart was apparent at all nodal positions (Fig. xx).
- A two-sample t-test comparing yields for the 2-m bed configuration with SD1 (September sowing date) yields again confirmed an approximately 1 bale/ha advantage of the former over the latter (Test statistic t=-3.15 on 16 d.f., P = 0.006).

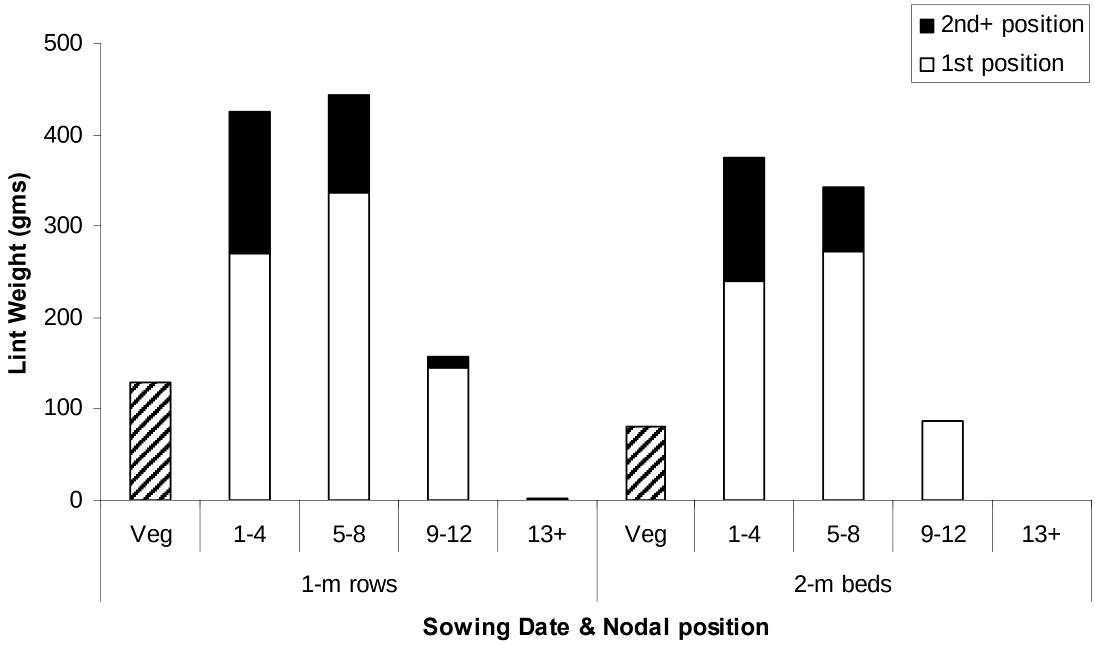


Fig. 27. Compartmentalization of lint weight by nodal position using the CSD Box Mapping procedure for Sicot 71 BR in the row configuration treatments at the Australian Agricultural College Farm in 2006-07.

WUE assessment

A number of unsuccessful attempts to conduct Irrimate® Surface Irrigation evaluations were carried out throughout the 2006-07 season.

Despite the best of intentions by personnel assigned the task of delivering irrigations by the agricultural college a lack of experience with the infrastructure usually resulted in problems maintaining a consistent delivery throughout the individual irrigation events. The most common problem was maintaining a uniform head-ditch height. Large fluctuations in head-ditch height occurred due to the inability to match the delivery-pump rate with the combined siphon outflow. As many irrigation events were conducted unattended overnight there was a tendency to err on the side of safety i.e., to set the pump rate such that the head-ditch height would decrease rather than risk it increasing and breaking out. Unfortunately the head-ditch design required a precise adjustment as its design provided little capacity for buffering and insufficient freeboard. As a consequence it was common for a number of siphons in each set to stop and be restarted at a later time when first noticed. Head ditch height problems were compounded by insufficient bed formation. Furrow break-outs were common. Irrimate® surface irrigation evaluations are able to account for this to a limited degree but not to the extent that occurred. Attempts to overcome these problems by doubling up the number of siphon and flume meters to quantify irrigation water delivered and tail-drain runoff (and thereby calculate field application rate) were unsuccessful.

Year 3: 2007-08.

Research outputs for this cotton season were severely compromised by inclement weather conditions that resulted in flooding in much of the Emerald Irrigation Area in January and February 2008. September, October and November planted experimental crops (SDs 1-3, including the Year 3 Pilot experiment) received more than double the rainfall experienced in previous seasons (Table 2). A December sown treatment option was precluded by rain and wet soil condition throughout much of December. The experimental site was inaccessible throughout January 2008.

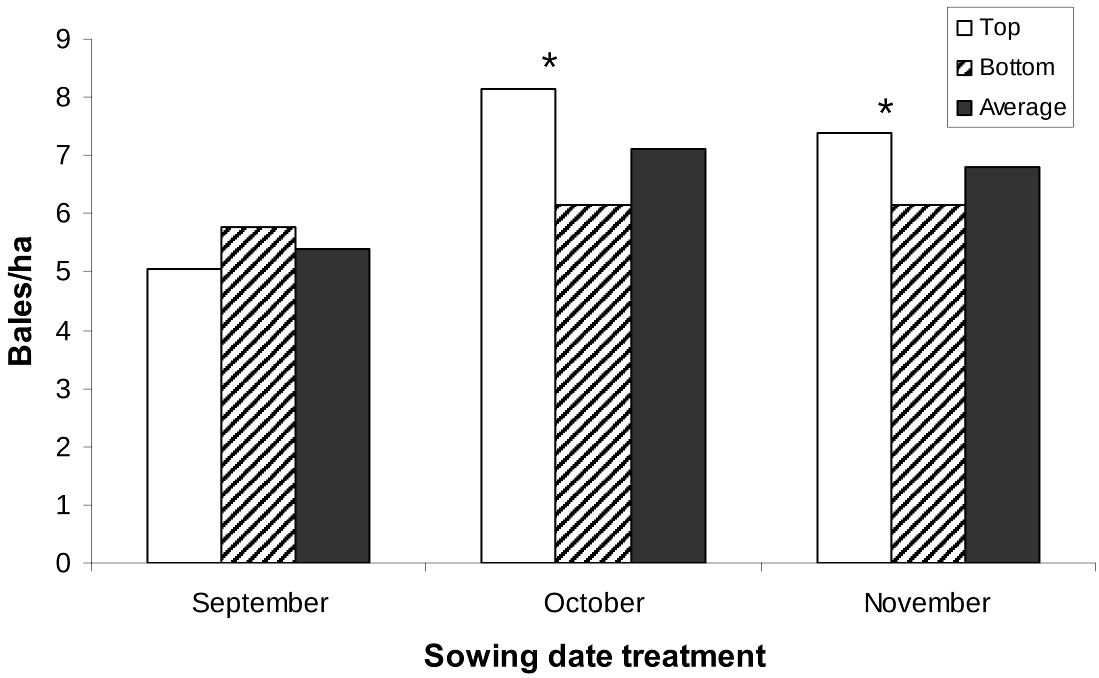


Fig. 28. Yield comparison between treatments of the sowing date experiment at the Australian Agricultural College Farm in 2007-08.

Machine harvested final yields for SDs 1-3 and the Year 3 Pilot plots were not reflective of the physiological data collected throughout the season following the same protocols used in years 1 and 2 of the project. Only final yield data are presented here.

- SD 1 was most heavily affected by inclement weather conditions and yielded only 5.8 bales/ha. Yield for SD 2 and 3 were 7.1 and 6.8 bales/ha, respectively (Fig. 28). Lint quality in all plots was described as base grade or better. Average gin turnout was also relatively low at 37.5%.
- Yields of the population density plots in the Year 3 Pilot experiment, consistent with those from the sowing date experiment, were all in the vicinity of 7 bales/ha. Neither the population density plots nor the Pix application plots provided any useful data as a result of agronomic problems arising from weather conditions, as indicated above.

Table 2. In-crop management parameters for Sowing Date experimental cotton plots: 2005-08

	Sowing Treatment			
Variable	September	October	November	December
2005-06				
Sowing date	16-Sep	31-Oct	25-Nov	22-Dec
In-crop irrigations	5	6	7	4
In-crop rainfall (mm)	160	154	129	170
Insecticide sprays	3	3	4	3
Pix applications	1	0	1	1
2006-07				
Sowing date	15-Sep	17-Oct	13-Nov	11-Dec
In-crop irrigations	6	3	5	3
In-crop rainfall	358	358	344	264
Insecticide sprays	3	3	3	2
Pix applications	0	2	2	2
2007-08				
Sowing date	20-Sep	18-Oct	5-Nov	n/a
In-crop irrigations	3	2	2	n/a
In-crop rainfall	534	750	710	n/a
Insecticide sprays	1	2	4	n/a
Pix applications	0	0	0	n/a

Table 3. Key physiological development information for Sowing Date experimental cotton plots in the 2005-06 season.

Trial Block	Crop Development	Dates	No. Of Days	Day Degrees
September	Planted	16/09/2005	0	0
	1st Square	21/10/2005	35	449
	1st Flower	15/11/2005	25	808
	Cut-out	21/12/2005	36	1411
	Cracked Boll	6/01/2006	16	1711
	90% Open Boll	13/02/2006	38	2393
October	Planted	31/10/2005	0	0
	1st Square	28/11/2005	28	424
	1st Flower	22/12/2005	24	853
	Cut-out	26/01/2006	35	1496
	Cracked Boll	8/02/2006	13	1730
	90% Open Boll	25/03/2006	45	2454
November	Planted	25/11/2005	0	0
	1st Square	20/12/2005	25	462
	1st Flower	13/01/2006	24	908
	Cut-out	24/02/2006	42	1676
	Cracked Boll	10/03/2006	14	1895
	90% Open Boll	29/04/2006	50	2539
December	Planted	22/12/2005	0	0
	1st Square	19/01/2006	28	536
	1st Flower	10/02/2006	22	926
	Cut-out	22/03/2006	40	1594
	Cracked Boll	17/04/2006	26	1934
	90% Open Boll	18/06/2006	62	2365

Table 4. Key physiological development information for Sowing Date experimental cotton plots in the 2006-07 season.

Trial Block	Crop Development	Dates	No. Of Days	Day Degrees
September	Planted	15/09/2006	0	0
	1st Square	21/10/2006	36	408
	1st Flower	20/11/2006	30	818
	Cut-out	14/12/2006	24	1185
	Cracked Boll	15/01/2007	32	1656
	1st Defoliation	20/02/2007	36	2182
October	Planted	17/10/2006	0	0
	1st Square	20/11/2006	34	475
	1st Flower	13/12/2006	33	827
	Cut-out	19/01/2007	37	1375
	Cracked Boll	12/02/2007	24	1728
	1st Defoliation	16/03/2007	32	2235
November	Planted	14/11/2006	0	0
	1st Square	15/12/2006	31	475
	1st Flower	11/01/2007	27	861
	Cut-out	23/02/2007	43	1497
	Cracked Boll	9/03/2007	14	1727
	1st Defoliation	20/04/2007	42	2304
December	Planted	18/12/2006	0	0
	1st Square	20/01/2007	33	498
	1st Flower	15/02/2007	26	878
	Cut-out	16/03/2007	29	1342
	Cracked Boll	16/04/2007	31	1745
	1st Defoliation	1/05/2007	14	1914
Row configuration	Planted	28/09/2006	0	0
	1st Square	2/11/2006	35	444
	1st Flower	30/11/2006	28	854
	Cut-out	26/12/2006	26	1248
	Cracked Boll	24/01/2007	29	1672
	1st Defoliation	3/03/2007	38	2228

- Crop physiological development information for the sowing date experiments is summarised in Tables 2-4.
- Sowing date has a profound impact on cotton physiology and ultimately on yield. The differences between sowing date treatments documented in this project show clearly that the impact of sowing date is large enough to overwhelm other potential factors such as nutrition, pix management and possibly others.
- The traditional sowing window that extends from the middle of September to the end of October is the most optimal in terms of yield.
- Late planted crops (November and December) will, in most years, incur a yield penalty ranging from 1-4 bales/ha.
- The yield penalty incurred by December planted crops can be explained satisfactorily in terms of steadily declining heat units throughout crop development and a cool/cold finish in late May or June in comparison to early (September/October) planted crops that mature under warm/hot conditions.
- November-planted crops have a tendency to for excessive apical growth and mid-season fruit loss that is not readily explained by anomalous weather conditions or other external factors.
- In-field phonological differences between cultivar types (determinate/indeterminate, mid-season/full season) are not manifested adequately under CQ environmental conditions. Varieties that differ considerably in growth habit under milder growing conditions in more southerly latitudes may be virtually indistinguishable under CQ conditions.

Outcomes

The project has successfully delivered on the majority of expected outcomes listed under the broad aims of the original proposal.

From a Bollgard II Agronomy research perspective, the project outputs address several major questions that are captured within the broad aims. These questions are highly relevant to the profitability and sustainability of cotton production enterprises in CQ.

Within Aim (1), important issues for local growers are:

i. What is the ideal time to plant Bollgard II in order to maximize the yield potential offered by the GM technology? The outputs of the project clearly show that cotton crop planted in the traditional sowing window from the middle of September to the end of October consistently produce the highest yields. This is a clear outcome that stands up even in the face of the exaggerated inter-seasonal climate variability typical of CQ.

ii. How will planting outside the traditional planting affect yield and quality? The project's outputs provide a clear and quantitative assessment of the impacts of sub-optimal planting opportunities on profitability. By defining the yield penalty (1-4 bales/ha) for late planted cotton crops, growers can make well informed cropping choices.

iii. How important is varietal and/or cultivar type selection for cotton production in CQ? The equivalence of cultivar types with clearly distinguishable, genetically based growth habits in the CQ environments, as demonstrated in the comprehensive experimental evaluation in Year 1 of the project, gives growers important information for making varietal choices. The results suggest that in the CQ environment differences in growth habit may be less important than overall yield potential as a selection tool for the development of new cultivars.

Not all agronomic objectives were successfully achieved. The scope of the project was proven to be overly ambitious in some areas. It became apparent very quickly after the first year that the extreme inter-seasonal variability with regard to the main meteorological variables (temperature, rainfall) experienced in CQ made it impossible to interpret the outputs of a single season's research as meaningful. This made it imperative that experimental layouts involving key crop physiological and agronomic variables be repeated for a minimum of three years to obtain meaningful insights into the main effects of and interaction between variables such as sowing date. The operational resources required to successfully run large, replicated and labour-intensive agronomic experimented severely limited the number of discrete variable that could be included in any experimental design. For this reason, variables such as nutrition, water use efficiency and rotations fell beyond the practical scope of the research program.

Within the entomological aims (2-4) the majority of specific objectives and outcomes have been delivered. Dr. Paul Grundy's research program outputs from the Dawson/Callide irrigation area show conclusively that Magnet® technology is highly effective in attracting and killing adult moths in the field. This work demonstrates the unquestionable potential for development of alternative and highly effective resistance management strategies for Bollgard II using novel technologies and strategies based on products such as Magnet® (see Appendix 1 for a full account of the outputs and outcomes). Paul's work shows

The basic field ecology and population dynamics of SLW has previously been studied and documented under project DAQ 120C funded by the Cotton Research & Development Corporation. The development of sampling protocols and a management strategy for SLW in this project (published in the 2008-09 Cotton Pest Management Guide) represents a major achievement in the area of crop protection for the national cotton industry. Validation of the SLW research and management options in the Dawson irrigation area cotton and southern Queensland during 2006-07 documents the robustness and rigour of the entomological research outcomes achieved through this project. A full account of the SLW research and management strategy for SLW in Australian cotton is given in Appendix 2.

Conclusion

The agronomic outcomes of this project give CQ growers fundamental information which is vital for making cropping decisions and selecting options in the highly variable CQ environment. Prior to this research, the CQ production was though to support economically viable cotton production in a wide sowing window from the middle of September to early January. The outcomes of this project provide clearly defined quantitative impacts associated with alternative sowing options outside the traditional early sowing window thereby empowering growers to make properly evaluated cropping decisions with regard to cropping systems, rotations, double/opportunity cropping options, varietal selection, cropping in water limited situations, etc. The factors that contribute to observed yield impacts in late planted crops are not fully understood. There is considerable potential to manipulate these factors in order to make alternative cropping opportunities more economically viable. A focussed research program on the physiology of late planted cotton in CQ would be immensely beneficial for the development of resilient mixed farming systems involving cotton and other field crops.

The entomological outcomes of this project represent strategic and tactical tools that are highly relevant to the viability and profitability of the cotton industry in Australia. The future of the cotton industry is inextricably linked to the survival and efficacy of GM cotton. Magnet® and similar technologies and tools will be increasingly important in strategies to preserve the shelf life and efficacy of current and future generations of GM technology. More research will be required to address logistical and operational issues related to these new technologies before they can be fully exploited in commercial production systems.

From an economic perspective, SLW is the sleeping giant in terms of insect nemeses of cotton, particularly from the standpoint of climate change and an increasingly warmer production environment. An effective sampling and management strategy for SLW which has been delivered by this project will go a long way towards minimising production costs in an environment characterised by rapidly rising input costs. SLW has the potential to permanently debilitate the national cotton industry by influencing market sentiment and quality perceptions.

Extension Opportunities

The agronomic outcomes of the project have already been largely disseminated to local industry through seasonal shed meetings, farm walks and cotton industry/grower body meetings. A formal report of the findings will be published in the Australian Cotton Grower magazine. A full report will also be published in a CQ Trial Book that is being developed by the Cotton Industry Development Officer in Emerald, Susan Maas, for the period 2005-08.

Although the immense potential of Magnet in Bollgard II resistance management strategies targeting Helicoverpa spp. has been clearly demonstrated in the outcomes of this project, its practical usefulness is far from being fully established. This is because significant logistical issues related to area-wide application, post-application evaluation and reporting, long-term management and other issues need to be addressed before the product can play a useful role in industry.

The SLW outcomes of the project have already been published in an international, peer reviewed journal, featured in the hands-on sessions at the recent Cotton Conference at the Gold Coast, on the CRC website and the annual Cotton Pest Management Guide. Future extension of these outcomes will be through IPM workshops that target new comers to the cotton industry and growers in areas where SLW becomes a problem in the future.

Publications

Richard V. Sequeira & Steven E. Naranjo (2008). Sampling and management of *Bemisia tabaci* (Genn.) biotype B in Australian cotton. ***Crop Protection*** 27 (2008) 1262– 1268.

Executive Summary

This project has delivered outcomes that address major agronomic and crop protection issues closely linked to the profitability and sustainability of cotton production enterprises in CQ. From an agronomic perspective, the CQ environment was always though to support economically viable cotton production in a wide sowing window from the middle of September to early January prior to this research. The ideal positioning of Bollgard II varieties in the CQ planting window was, therefore, critical to the future of the local cotton industry because growers needed baseline information to determine how best to take advantage of the higher yield potential offered by the Bt cotton technology, optimise irrigation water use and fibre characteristics.

The project's outputs include a number of key agronomic findings. Over three growing seasons, Bollgard II crop planted in the traditional sowing window from the middle of September to the end of October consistently produced the highest yields. The project delivers a clear and quantitative assessment of the impacts of planting outside the traditional cropping window - a yield penalty of between 1-4 bales/ha for November and December planted cotton. Whilst yield penalties associated with December-planted crops are clearly linked to declining heat units in the second half of the crop and a cool finish, those associated with November-planted cotton are not consistent with the theoretical yield potential for this sowing date. Further research to understand and minimize the physiological constraints on November-planted cotton would give CQ cotton growers far greater flexibility to develop mixed/double/rotation cropping farming systems that are relevant to the rapidly evolving nature of Agricultural production in Australia. The equivalence of cultivar types with clearly distinguishable, genetically based growth habits, demonstrated in this project, gives growers important information for making varietal choices.

The entomological outcomes of this project represent strategic and tactical tools that are highly relevant to the viability and profitability of the cotton industry in Australia. The future of the cotton industry is inextricably linked to the survival and efficacy of GM cotton. Research done in the Callide irrigation area demonstrates the unquestionable potential for development of alternative and highly effective resistance management strategies for Bollgard II using novel technologies and strategies based on products such as Magnet®. Magnet® and similar technologies will be increasingly important in strategies to preserve the shelf life and efficacy of current and future generations of GM technology. However, more research will be required to address logistical and operational issues related to these new technologies before they can be fully exploited in commercial production systems.

From an economic perspective, SLW is the sleeping giant in terms of insect nemeses of cotton, particularly from the standpoint of climate change and an increasingly warmer production environment. An effective sampling and management strategy for SLW which has been delivered by this project will go a long way towards minimising production costs in an environment characterised by rapidly rising input costs. SLW has the potential to permanently debilitate the national cotton industry by influencing market sentiment and quality perceptions. Field validation of the SLW population sampling models and management options in the Dawson irrigation area cotton and southern Queensland during 2006-07 documents the robustness of the entomological research outcomes achieved through this project.

Appendix 1.

Moth Busting for Bt Resistance Management

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Summary

Targeting the last generation of *Helicoverpa armigera* that typically escape cotton fields prior to pupae busting with the use of summer trap crops has been an integral component of the central Queensland *Bt* resistance management strategy. A superior method for targeting these escapes might be to use area-wide applications of the attract and kill product Magnet® on late season cotton fields. Experiments that aimed to assess the potential efficacy of area-wide applications of Magnet® laced with insecticide for *Helicoverpa* moth control in the Dawson Valley suggest considerable potential for such a strategy with significant reductions in *Helicoverpa* being recorded after each application. Further experimentation to test the validity of area wide Magnet® applications as an alternative strategy to trap cropping will be conducted during the 2006/07 season. This paper outlines the progress of the research to date.

Background

Growers of Bollgard® cotton varieties in central Queensland (CQ) are required to undertake a number of preventative resistance management actions. Typically this involves growing an unsprayed refuge of pigeon pea with an additional later sowing of pigeon pea as a trap crop. The refuge generates additional susceptible *Helicoverpa* to dilute potentially insecticide-resistant individuals emerging from Bollgard® crops whilst the trap crop attracts the last *Helicoverpa* generation to emerge from cotton so that potentially resistant offspring can be aggregated and destroyed with cultivation (Sequeira 2001).

The trap cropping strategy has been implemented in CQ since 1997. Patches were required to comprise the greater of 1% or 2 hectares of total farmed area. These patches are sown with pigeon pea after the main cotton crop is established and are ideally managed so that the trap crop is at peak attractiveness to *Helicoverpa* moths as the cotton crop enters post cut out decline (Sequeira 2001). In the 8 years since the introduction of this strategy, several complications have emerged. Firstly the efficacy of trap crops for attracting *Helicoverpa* moths emerging from adjacent cotton fields and capturing their progeny has been difficult to quantify. Secondly the drought conditions of the last 4 years have resulted in some growers not irrigating pigeon pea trap crops in a manner that ensured correct timing of peak attractiveness. Thirdly weed management in pigeon pea has been problematic. The efficacy of poorly irrigated or weedy pigeon pea trap crops is questionable.

With the dependence on Bt varieties likely to remain well into the foreseeable future, the need to seek improvements to the current resistance strategy will remain a research priority. Trap crops represent a potential weak link within the Bt resistance management strategy for CQ. However, alternative methods for targeting end of season moth escapes have not existed until the recent development of the attract and kill product Magnet®, that when laced with insecticide and applied to crop foliage works to lure foraging moths with floral volatiles to feed on toxic residues.

With the imminent commercialisation and registration of Magnet®, potential exists to develop an alternative strategy to trap cropping for targeting last generation *Helicoverpa* spp moth populations. The application of Magnet® in widely spaced strips to all Bollgard® fields within a region post crop cutout with a view to “busting” moths as they emerge may offer the following advantages:

Strategic – Can be better timed to coincide with the emergence of last generation moths.

Direct – Kills female and male resistance gene-carrying moths directly and it takes the trap to the source crop rather than being remotely located.

Measurable – Unlike trap cropping, the impact of Magnet® on local *Helicoverpa* populations can be measured.

Economic – Magnet® cost is offset by savings from not trap cropping.

Uniform – The whole region would be treated at the same time in the same way.

Easy – The product can be applied aerially.

Proactive – The CQ industry will have a refined unique strategy and be seen as taking proactive responsibility in preserving Bt technology.

This paper details the first part of an ongoing experiment to examine the potential area-wide deployment of Magnet® to target *Helicoverpa* populations on a regional scale.

Materials and Methods

Pilot Study 2004-05 Season

An initial pilot study was conducted in the Dawson Valley to examine the potential impacts of treating a large discrete area of cotton with Magnet®. Two 800 hectare patches of Bollgard® cotton approximately 5 km apart (separated by pastoral and native vegetation) were chosen for the experiment. Magnet® mixed with methomyl was applied by aircraft on the afternoon of 15 February 2005 to one of the patches (Gibber Gunyah district) in 1 metre wide bands, spaced approximately 72 m apart over the entire area.

Helicoverpa spp. moth populations were assessed pre and post treatment using light traps and flush counts. Four light traps were placed randomly in each of the two treatment patches and cleared of insects daily. Each trap's contents were stored in ethanol and returned to the laboratory for later examination. Flush counts were made on randomly selected fields throughout the two patches every 1-2 days to estimate moth densities per hectare of cotton. Flush counts were conducted by throwing handfuls of soil at the crop along a 100 m transect and counting *Helicoverpa* moths as they emerged. The flush count technique was initially "calibrated" by following disturbed moths and identifying them, indicating that at least 85% of the flushed moths were likely to be *Helicoverpa* species. Eight transects were conducted in each of the two patches on each sampling occasion.

2005-06 Experiment

A more intensive experimental design was used for the study in the 2005-06 season to overcome the logistical problems of replication over large areas and possible interactions between the Magnet® treated patches and the control. Replication of the treatments over time and two additional treatments were used. Additional treatments consisted of a Magnet® without insecticide treatment to allow for comparison with the Magnet®/Insecticide treatment without the influence of any direct or indirect sink effects as well as two control patches, one remote (15 km away) and the other directly adjacent to and within 5 km of the Magnet® treated areas (Figure 1). Each of the treatment areas comprised of approximately 800 hectares of cotton that were separated from each other by pastoral land and native vegetation.

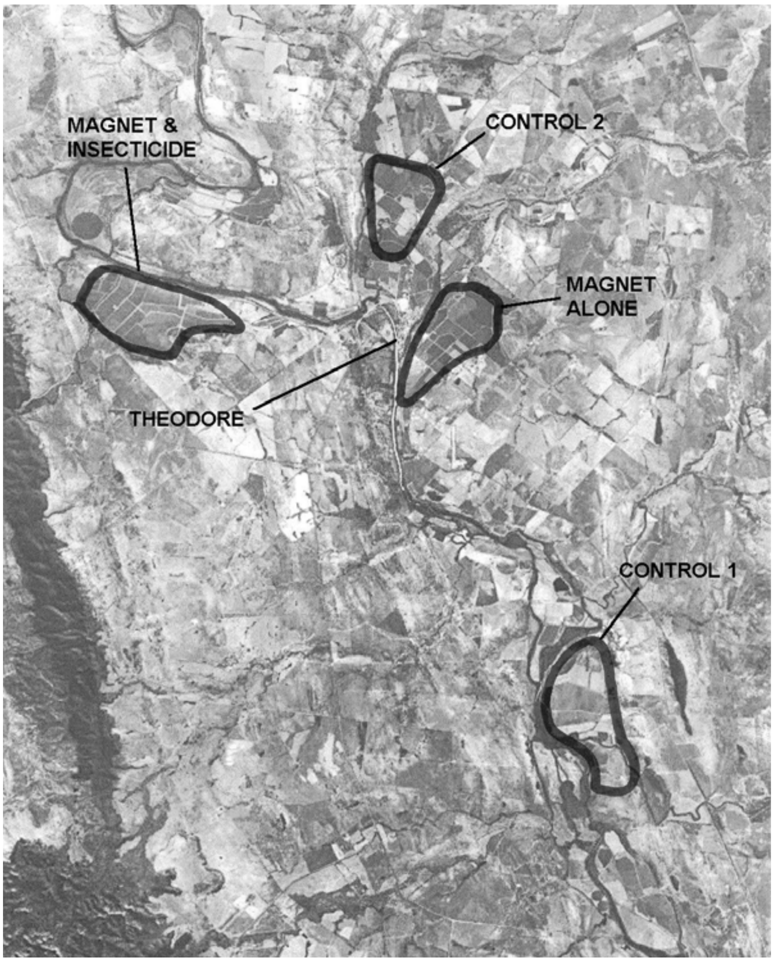

Figure 1. An aerial photo showing the Theodore channel irrigation area showing the approximate location of the two Magnet® treatment areas as well as the distant (control 1) and nearby controls (control 2).

Magnet® treatments would commence once the crop had reached row closure and moths had become abundant in the region. Consecutive treatment applications would then be made once the impacts of the previous treatment had ceased across the 4 patches. The first application of Magnet was made on 5 Dec 2005 with the treatments being applied aerially in 1-2 metre wide bands spaced approximately 145 m apart. Thiodicarb was used as a mixing partner at the Magnet label recommended rate. A second replication was conducted on 12 Dec 2005 using the same application method. No further replications could be made due to a lack of moths in the region after this time.

Moth populations were monitored using the same techniques as for the pilot study. *Helicoverpa* spp. egg densities per metre of crop row were recorded on Bollgard ® crops throughout the 4 treatment patches during the experiment. 15 patches of conventional unsprayed cotton (8 rows by 50 metres) were established randomly throughout the two Magnet® treatments and the distant control to also examine if the repeat applications of Magnet® had any influence on pupae recruitment over time. Sampling for pupae was conducted every 2-3 weeks during the season.

2005-06 Experiment

The same experiment as conducted in 2005-06 was repeated in 2006-07 utilising the same methods and treatment layout.

Results

Pilot Study 2004-05 Season

The Magnet® treatment had an immediate impact on moth population densities with a reduction of 97% recorded during the first 48 hours post-treatment (Fig 2). Light trap catches during the experiment also suggested a reduction in *Helicoverpa* numbers post-treatment compared to the control (Fig 3). A similar impact was also recorded for *Spodoptera litura* (a secondary cotton pest) — of which the larvae were observed abundantly throughout Bollgard® II crops during the 2004/05 season (Fig 4).

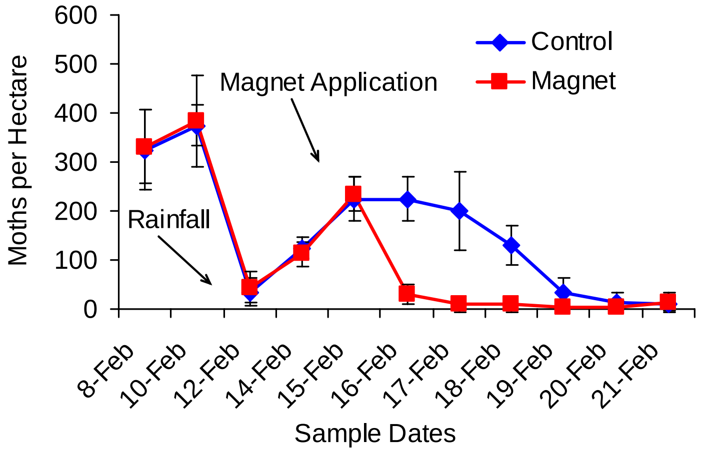

Figure 2. The mean estimated number of *Helicoverpa* moths recorded per hectare using flush counts in the control and Magnet® and insecticide treatment areas.

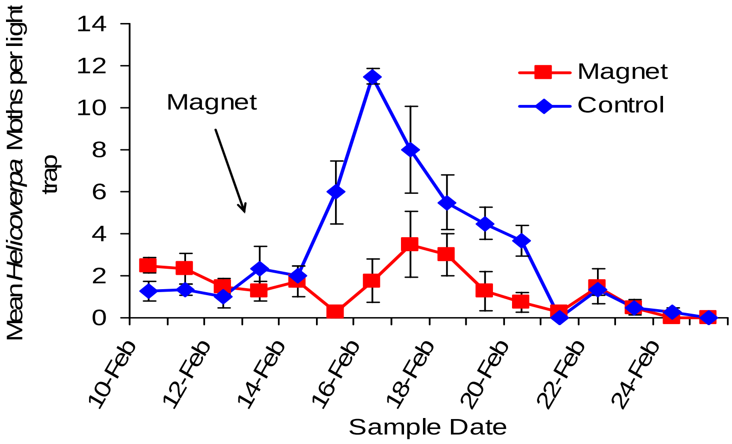

Figure 3. Mean number of *Helicoverpa* moths caught per trap in the control and Magnet® and insecticide treatment areas.

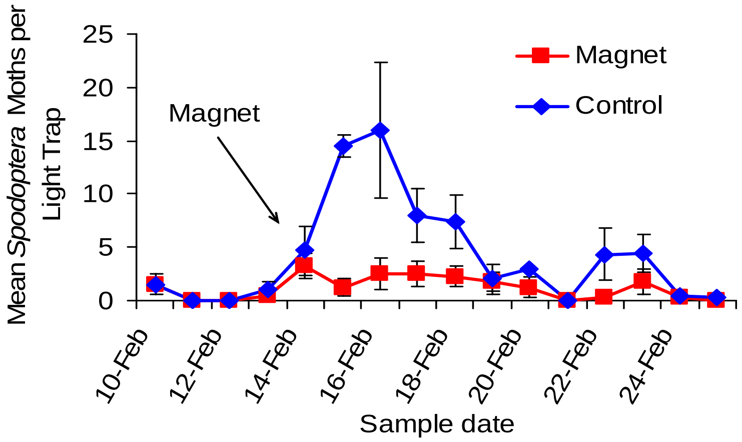

Figure 4. Mean number of *Spodoptera litura* moths caught per trap in the control and Magnet® and insecticide treatment areas.

2005-06 Experiment

The Magnet® treatments were applied twice during the first half of the season after which moths became scarce throughout the region, preventing additional applications. The first two applications coincided with the presence of *H. punctigera* that were migrating into the region at very high densities during a period of north-westerly wind patterns December. Collections of dead moths from the Magnet®/insecticide treated area suggested that the populations during the period of the first two applications consisted of >90% *H. punctigera* with the remainder being *H. armigera*.

The application of Magnet® both with and without insecticide caused significant changes to the local moth densities compared with the untreated controls. Significant increases in moth density were observed following the application of Magnet® WITHOUT insecticide on each occasion. Alternatively, significant decreases in moth numbers observed when Magnet® was applied WITH insecticide compared to either control (Fig 5). This contrast is best illustrated by Figure 6.

The oviposition trends observed in each of the treatment patches over time exhibited similar patterns to those recorded for moth abundance (Fig 7). However, the rate of oviposition was very low in compared to the high numbers of moths recorded in the area at the time. Pheromone traps placed throughout the area for both *Helicoverpa* species failed to capture any *H. punctigera* moths despite their high abundance. A collection of 200 eggs was conducted on 15 December and returned to the laboratory and grown out for identification. Of those that successfully hatches and allowed subsequent identification, 88% were *H. armigera*.

Sampling conducted in each of the 15 unsprayed conventional cotton patches found very few pupae of which none were viable (all either diseased or parasitised).

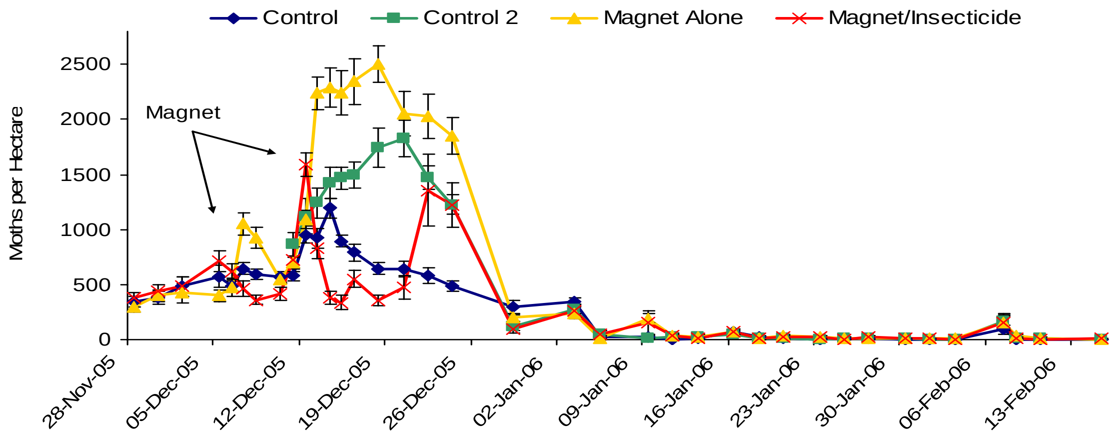

Figure 5. The mean densities of moths per hectare assessed using flush counts in both controls and the Magnet® with and without insecticide treatments. Sampling in the control 2 was commenced later than the other three areas when it was recognised that a nearby second control would provide an additional comparison to the more distant first control area.

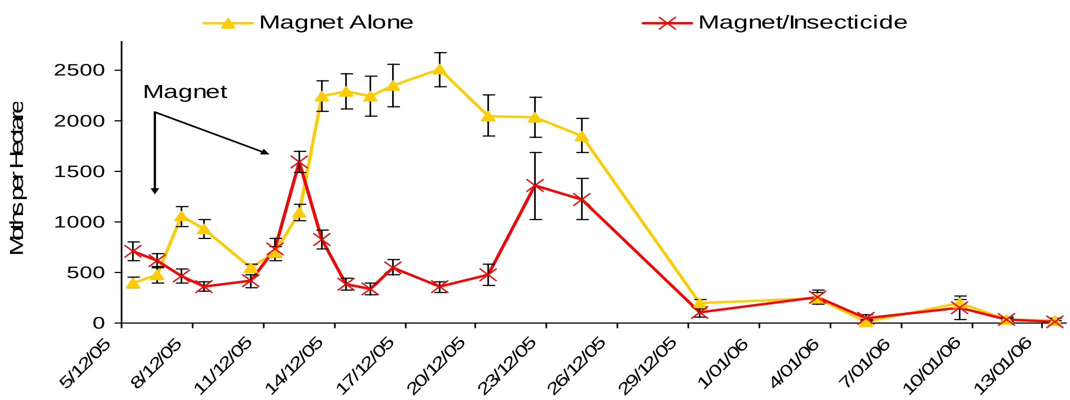

Figure 6. The same data as for figure 5 with the two controls omitted. The two treatments depicted are the use of Magnet® with and without an insecticide.

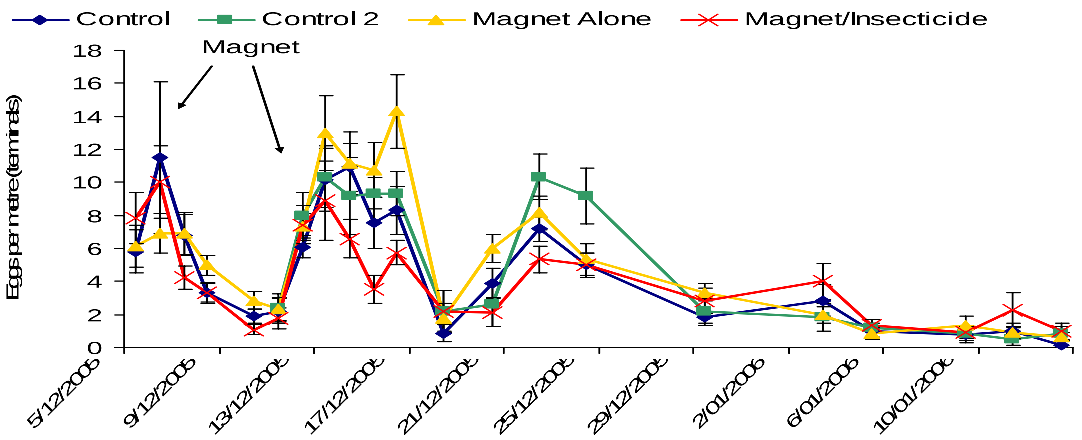

Figure 7. The mean densities of *Helicoverpa* spp. eggs laid on the terminal shoots per metre of crop row in both controls and the Magnet® with and without insecticide treatments. Sampling in the control 2 was commenced later than the other three areas when it was recognised that a nearby second control would provide an additional comparison to the more distant first control area.

2006-07 Experiment

Replication of the 2005-06 experiment was unable to be completed due to the very low abundance of *Helicoverpa* moths during the entire cotton season. Moth numbers were deemed to low to warrant area-wide applications of Magnet® (Fig 8).

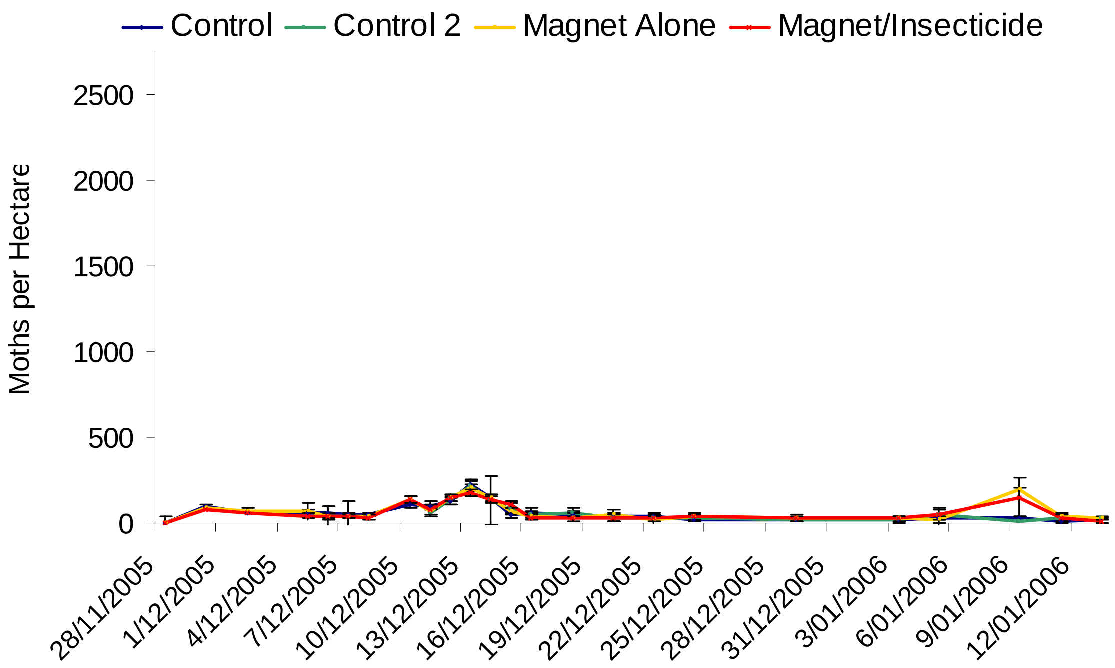

Figure 8. The mean densities of moths per hectare assessed using flush counts in both controls and the Magnet® with and without insecticide treatments areas.

Discussion

The results from the first two experiments suggest that Magnet® laced with insecticide and aerially applied over large areas caused significant reductions in *Helicoverpa* moth densities. The pilot trial in 2005-06 suggested that Magnet® caused an immediate large decrease in moth populations throughout the treated area. The patterns of moth abundance in response to the application of Magnet® with and without insecticides provided additional insight on the impacts of area-wide applications. Whilst the application of Magnet® with insecticide on each occasion gave significant reductions in local moth densities, the application of Magnet® alone at the same time suggested that the product also served to attract or retain additional moths within the treated area, potentially masking the real treatment impact. Unfortunately low moth numbers during the 2006-07 season prevented further testing as per the strategy tested in 2005-06 and therefore the remainder of the discussion will refer to the 2005-06 experiment.

The question of whether Magnet® served to attract additional moths or just retained a high proportion of the moths passing through the region at the time of treatment is not entirely clear. The apparent lack of influence that the Magnet® had on the controls during the experiment further suggest that the patterns observed were more likely to be a function of retaining migrating moths rather than attracting moths away from nearby cropping areas such as control 2.

The low egg densities recorded on the Bollgard crops compared to the very high numbers of moths observed within the region during December 2005 was unusual (Fig 2 & 4). Identification of dead moths collected off the ground from the Magnet®/insecticide treated area suggested that the 90% or more of the moths inhabiting the region during December were *H. punctigera*. Yet of the eggs collected during the same period 88% of the progeny were *H. armigera* suggesting that the high densities of *H. punctigera* were generally reproductively inactive whilst passing through the area. This conclusion is possibly further supported by the total lack of response by *H. punctigera* moths to sex pheromone traps located throughout the area during the December period (data not presented here).

It was anticipated that the impact of the Magnet® during 2005-06 might have been detectable in terms of changing pupae recruitment over time. However, the complete absence of viable pupae in the 15 patches of conventional cotton prevented comparisons. Observations within the unsprayed cotton plots suggested that beneficial insects were very abundant as well as epizootics of NPVs. The natural mortality induced by these agents combined with the generally low levels of oviposition may explain the lack of viable pupae.

In terms of treatment response, the first application had less impact than the second during the 2005-06 experiment. The main factors for the observed difference in performance may be explained by the greater losses of applied product due to the younger crop (reduced canopy leaf area) and the advent of rainfall 3 days after application. With regard to utilising regional applications of Magnet®, there would be more than sufficient crop canopy to capture aerially applied magnet on late season crops. However, the susceptibility of Magnet® to post-application dilution from rainfall could be a significant problem for which risk management strategies would need to be developed should such a strategy be implemented.

The lack of continued moth activity during January and February 2006 and again during the 2006-07 season prevented further applications and therefore the results at this stage are incomplete.

These results provide some insights as to the potential for using Magnet as an area-wide management tool however future research would need to consolidate these findings.

Acknowledgement

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Appendix 2.

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Sampling and Management of *Bemisia tabaci* (Genn.) Biotype B in Australian Cotton

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Abstract.

Data on seasonal population abundance of *Bemisia tabaci* biotype B (silverleaf whitefly) in Australian cotton fields collected over four consecutive growing seasons (2002/03 – 2005/06) were used to develop and validate a multiple-threshold based management and sampling plan. Non-linear growth trajectories estimated from the field sampling data were used as benchmarks to classify adult silverleaf whitefly (SLW) field populations into six density-based management zones with associated control recommendations in the context of peak flowering and open boll crop growth stages. Control options based on application of insect growth regulators (IGRs) are recommended for high density populations (>2 adults/leaf) whereas conventional (non-IGR) products are recommended for the control of low to moderate population densities. A computerised re-sampling program was used to develop and test a binomial sampling plan. Binomial models with thresholds of T=1, 2 and 3 adults/leaf were tested using the field abundance data. A binomial plan based on a tally threshold of T=2 adults/leaf and a minimum sample of 20 leaves at nodes 3, 4 or 5 below the terminal is recommended as the most parsimonious and practical sampling protocol for Australian cotton fields. A decision support guide with management zone boundaries expressed as binomial counts and control options appropriate for various SLW density situations is presented. Appropriate use of chemical insecticides and tactics for successful field control of whiteflies are discussed.

Keywords: *Bemisia tabaci*; cotton; management zones; binomial sampling plan

1. Introduction

In 2001 the whitefly, *Bemisia tabaci* (Gennadius), emerged as a significant threat to Australian field crops following a major outbreak of the pest in the cotton growing area surrounding the township of Emerald (23º23' S, 14810' E) in central Queensland (Moore et al., 2004). Extensive whitefly surveys by CSIRO entomologists throughout the central Queensland (CQ) region in 2001 and 2002, and diagnostic testing for biotype determination using RAPD PCR techniques (De Barro and Driver, 1997) revealed only the B biotype in all population samples (P. De Barro, unpublished data).

The threat posed by the B biotype, also referred to as the Silverleaf whitefly (SLW), to cotton is two-fold. Firstly, the sugary secretion (honeydew) deposited on open cotton bolls by adults and nymphs feeding on the abaxial surface of leaves makes the lint sticky and unmarketable. Yield losses can also occur due to whitefly feeding, especially when population densities are high (De Barro, 1995; Naranjo et al., 1998). Secondly, rapidly evolving resistance to chemical control agents (Dennehy et al., 2005; Horowitz et al., 2005) makes management of SLW infestations challenging.

In 2002, the CQ cotton industry responded to the SLW threat by implementing a field sampling and management plan developed and used successfully in Arizona (USA) cotton crops (summarized in Ellsworth and Martinez-Carrillo, 2001) to equip cotton growers with an emergency, stop-gap pest management framework. Briefly, the Arizona SLW management plan involves use of highly effective insecticides (insect growth regulators, IGRs) in conjunction with adult and nymph density action thresholds, and an efficient binomial sampling scheme anchored within a broadly based integrated pest management framework (Naranjo et al., 1996, 1998; Ellsworth and Martinez-Carrillo, 2001; Naranjo, 2001; Palumbo et al., 2001).

Since the introduction of the Arizona SLW protocols in 2002, control of SLW in CQ commercial cotton has been underpinned by the use of the IGR pyriproxifen (Admiral®), in conjunction with the dual Arizona action thresholds of 3-5 adults/leaf and 0.5-1 nymphs per 3.88 cm^2 circular leaf area based on a sample size of 30 leaves (Naranjo et al., 1996; Ellsworth and Martinez-Carrillo, 2001). Field reports from crop consultants have consistently indicated that whilst the IGRs have proven to be highly effective in controlling SLW populations, varying degrees of lint contamination still occurs in commercial cotton fields.

The recurrence of SLW and lint contamination each growing season indicated the need for an indigenous pest management framework tailored to local crop production practices, plant phenology and pest population characteristics in order to provide effective long-term control of the problem in Australian cotton. In this paper we present a new decision support framework and control recommendations for SLW in Australian cotton based on population abundance data collected under the auspices of a research project initiated in 2002 to investigate the invasion ecology and population dynamics of the invader. The field density data, collected over four consecutive cotton seasons (September – March; 2002/03 – 2005/06) in commercial cotton fields, were used to characterize seasonal population growth trajectories which, in turn, were used as the basis for the development of intervention and control guidelines. A new binomial sampling scheme is presented and discussed in relation to effective SLW management.

2. Materials and Methods

2.1. Sampling

Population density of SLW adults and nymphs was estimated at seasonally fixed geo-referenced sampling sites in commercial cotton fields scattered throughout the Emerald irrigation area. Sampling was conducted at fortnightly intervals in crops planted between 15 September and 30 October over three consecutive cotton seasons (2002/03 - 2004/05) at 90, 34 and 24 sampling sites, respectively. Each sampling site was located within a 5-20 ha field of cotton. Large fields (> 20 ha) were arbitrarily subdivided into two or more units that were sampled separately.

GPS coordinates marked the centre of each site. No samples were collected within 20 m from the edge of the field. Population density was estimated by sampling one leaf from each of 30 plants at each sampling site. The leaves were sampled in a zigzag or U-shaped pattern, allowing approximately 5 m between individual plants. The abundance of adults was estimated by whole leaf sampling whereas the abundance of large nymphs was estimated within a 3.88 cm^2 area defined by a circular disc placed in sector 2 formed by the left and middle major veins on the abaxial surface of each leaf (Fig. 1; Naranjo and Flint, 1994, 1995).

In 2002/03, following the implementation of Arizona SLW protocols (Naranjo *et al*. 1997) in CQ commercial cotton, sampling was restricted to the 5^{th} node leaf (node 1 = 1^{st} fully unfurled terminal leaf). Adult density was estimated by gently turning over a single leaf and counting the total number of insects on the abaxial side. The same leaf was subsequently used to estimate the density of large nymphs (instars III and IV) using the disc method. In subsequent seasons the estimation of SLW density was based on a more flexible sampling protocol to account for variation in plant phenology and SLW distribution within and between fields and plants; adult density was assessed on a randomly selected 3^{rd}, 4^{th} or 5^{th} node leaf whereas the density of large nymphs was assessed on a 5^{th}, 6^{th} or 7^{th} node leaf using a 3.88 cm^2 disk.

The validity of the leaf sampling protocol, including the justification for choice of sampling nodes for adult and juvenile SLW, accuracy of the leaf disc method for estimating juvenile abundance and temporal changes in within-plant distribution associated with plant maturity, was tested in a separate series of field assessments that will be reported elsewhere.

2.2. Population Growth Trajectories

Non-linear regression curves were used to quantify changes in the mean and maximum estimated field population density of adult SLW between sampling dates in each growing season. Population density data for nymph were analysed separately. A physiological time scale based on accumulated heat units (Day-Degree, DD hereafter) above the cotton development threshold of 12 °C (Constable and Shaw, 1988) was used to characterise and compare population growth trajectories among seasons. The daily accumulation of heat units was calculated using the formula:
$DD = [(T_{max} + T_{min}) - 24]/2$, where T_{max} and T_{min} are maximum and minimum daily temperatures for Emerald recorded by the Australian Bureau of Meteorology.

In the calculation of DD, all commercial fields sampled for estimation of SLW abundance were assumed to have been sown on 23 September with emergence on 01 October each year. A single planting date was deemed to be a reasonable simplification because the bulk of commercial cotton in the Emerald irrigation area was in the cotyledon/seedling stage by the first week of October during the sampling period (2002/03-2004/05).

An exponential model was used to describe population growth trajectories:

$$\text{Log Density}_{(X)} = \mathbf{A} + \mathbf{B}\,(\mathbf{R}^{X}) \qquad (1),$$

where **A**, **B** and **R** are parameters, and X is DDs.

The raw leaf count data were $\log_{10}(X+1)$ transformed prior to analysis. Sampling site means were used as the basic units of density for generating population growth trajectories. GENSTAT Release 8 (Payne et al., 2005) was used for all statistical analyses of the data. Curve fitting was done using the NONLIN procedure in GENSTAT.

The non-linear curves describing changes in population density were used to classify SLW field populations into management categories with associated control recommendations in relation to crop growth stage and the potential for damage.

2.3 Sampling Plan

A fixed-sample size binomial sampling plan was developed and tested using a public-domain computer program, *Resampling for Validation of Sample Plans* (RVSP), developed by Naranjo and Hutchison (1997). The RVSP program has been widely tested and used to develop sampling plans for several insect pests in crops worldwide (Hodgson et al., 2004).

The combined 2002/03 and 2003/04 adult abundance data (counts on individual leaves) were used to develop the sampling plan. Data from adjacent fields within farms were aggregated to yield 67 individual data sets with sample sizes of 60 – 390 leaves. Aggregation of the raw abundance data based on samples of 30 leaves was necessary to generate data sets that were large enough to facilitate re-sampling procedures (see below).

The key elements of a binomial sampling plan – the binomial model and effective sample size - were identified in two stages. In the first stage we investigated the relationship between mean population density (***m***) and the proportion of leaves infested with at least T individuals (**P_T**) using an empirical equation:

$$\ln(\boldsymbol{m}) = \alpha + \beta \ln(-\ln[1 - P_T]) \qquad (2)$$

where α and β are parameters estimated by linear regression (Kono and Sugino, 1958; Gerrard and Chiang, 1970). Binomial models that use **P_T** as a predictor of ***m*** using equation (2) were developed for tally thresholds (T) of 1, 2 and 3 adults per leaf.

In the second stage we compared the performance of the three models at specific values of ***m*** (action thresholds) based on their Operating Characteristic (OC) functions and actual errors in classification for fixed sample sizes of 20, 30 and 40 leaves. The OC function, generated by the RVSP program, is a useful graphical indicator of the model's accuracy in population classification in relation to an action threshold. A four-parameter logistic model was fitted to the OC data to facilitate interpretation (Naranjo et al., 1997):

$$OC(_X) = \mathbf{D} + (\mathbf{A} - \mathbf{D}) / (1 + [m/\mathbf{C}]^{\mathbf{B}}) \qquad (3)$$

where **D**, **A**, **C** and **B** are constants and ***m*** is field population density of adults.

The OC value for each data set indicates the proportion of re-sampled means that are classified as being above or below the action threshold by the binomial model being analysed. Thus, the OC may be interpreted as the probability of taking no action in relation to the action threshold. For fixed sample size plans, the shape of the OC curve may be influenced by the binomial model used and sample size (Naranjo et al., 1996; 1997). The shape of the OC function reflects the accuracy of the model. The steeper the OC function in the vicinity of the action threshold, the greater the accuracy of the underlying binomial model. If the underlying model is sound the OC should be near 0.5 at the action threshold.

The binomial models with satisfactory OC functions were further evaluated for accuracy in population classification based on actual Type I (α) and Type II (β) errors. The RVSP output includes re-sampled estimates of ***m*** and **P_T** for each data set. Individual data sets were re-sampled 500 times with replacement. We used the RVSP output for the 2002-04 data set to classify the outcome of each iteration for each data set as accurate or inaccurate in relation to the action threshold and its binomial (proportion infested) counterpart (see Naranjo et al., 1997 for further details and methodology). The α error rate is the probability of taking control action when none is needed whereas the β error rate is the probability of failing to take action when needed. The latter is considered more important in making pest management decisions because of the associated higher risk of economic damage (Naranjo et al., 1997).

The binomial model with the lowest error rates in population classification was tested using independent field data not used in any facet of model development. In the 2005/06 season independent data were collected from eight commercial cotton fields planted at various times between 15 September and 25 December 2005 specifically for validation of the binomial sampling plan for adult SLW. Each crop was sampled 2-3 times at arbitrary intervals and a total of 30 data sets, each containing 90-200 leaves at the 5^{th} node, were collected over the season.

3. Results

3.1 Population growth trajectories & intervention triggers

Seasonal population density profiles for adult SLW were all consistent with exponential growth described by equation (1) up to approximately 2000 DD (Table 1). A plateau or decline in density is evident at the end of the season, primarily as a result of intervention with chemical insecticides. The abundance of large nymphs generally increased as the crop matured (2000 DD). Seasonal population profiles of large nymphs were highly variable between seasons (Fig. 2 B). The discord amongst nymph population profiles can be explained in part by sampling error inherent in the leaf disc method used to estimate abundance. Independent field assessments indicated that estimates of changes in large nymph density obtained using the leaf disc were poorly correlated with the corresponding whole leaf counts (R. Sequeira, unpublished data). Thus, the nymph abundance data based on leaf disc counts were not sufficiently robust to warrant further analysis and interpretation. The development of a management decision support framework for SLW (see below) was based exclusively on the adult abundance data.

Due to the limited range in field population densities of adults observed within individual seasons and the similarity of the 2002/03 and 2003/04 profiles (Fig. 2 A), the combined data from these seasons were used to estimate generalized population growth trajectories. The 2004/05 data were excluded because SLW densities were too low to be considered economically injurious. A scatter graph of adult density (sampling site mean) in the combined data set (Fig. 3) shows an exponential increase in dispersion with increasing DDs. Non-linear regression curves describing predicted maximum and mean population density for the 2002-04 data partition the *time* (DD) *x density* response area into three discrete regions of low (1), medium (2) and high (3) SLW population density and future growth potential in the context of key crop physiological stages.

We identified peak flowering and open bolls as the key crop physiological stages in relation to SLW management. Changes in the rate of acceleration calculated from differencing transformations ($N_{t+1} - N_t$) of log density indicate that peak flowering of cotton at around 1300 DD (10-14 days after first flower) coincides with an inflection point in SLW population growth trajectories. A sharp increase in the acceleration of growth rate (not shown) is evident at around peak flowering when population density exceeds 1 adult/leaf. At the upper end, the presence of significant SLW populations in fields with open bolls (>1650 DD) makes lint contamination and the resultant threat to the industry inevitable.

We used the partitioned *time x density* response area as a multiple threshold framework to classify SLW populations into management zones with associated control options (Fig. 4). The mean (lower) threshold curve separates regions 1 and 2 whereas the maximum (upper) threshold curve separates regions 2 and 3. Field populations are assigned to regions and zones based upon a consistent density deviation above or below the time-specific threshold density over several sampling intervals.

Intervention with insecticides is not warranted in fields falling into region 1 (zone 1) because the risk of lint contamination is negligible. Fields falling into region 2 may be further grouped into two zones. Application of conventional (non-IGR) insecticides may be useful for population suppression in early crop stages (zone 2A) or in the open boll stage for rapid knockdown (zone 2B). IGRs, alone or in tandem with conventional insecticides, are the recommended control options for fields in region 3 which is further partitioned into three zones. Application of an IGR prior to about 1450 DD (zone 3A) is not recommended due to the possibility of SLW population resurgence and the need for additional intervention in later stages of the crop. The ideal positioning of IGR applications is between 1450 and 1650 DD (zone 3B) prior to the onset of boll opening. In fields with open bolls (>1650 DD) and >2 adults/leaf (zone 3C) the use of an IGR by itself is unlikely to prevent lint contamination due to the inherent time delay in the onset of population decline following application; rapid knockdown of the population using a conventional insecticide followed by IGR application for residual control may be required to limit the extent of lint contamination.

3.2 Sampling Plan

The development of binomial models was based on 54 useful data sets derived from the combined 2002-04 abundance data, with mean densities in the range of 0.01 – 8 adults per leaf. The relationship between proportion infested ($\mathbf{P_T}$) and mean density ($\boldsymbol{m}$) for tally thresholds (T) of 1, 2 and 3 adults per leaf was adequately represented by equation 2, with r^2 values > 0.92 (Fig. 5). The best fit was in the mean density range of about 0.01 - 4 adults/per leaf. Above this range, the relationship was compromised by the paucity of observed sample means.

In a preliminary analysis intended to differentiate the three binomial models, their OC function characteristics were compared at an action threshold of 2.25 adults/leaf (upper limit of zone 3B) which equates to proportion infested values of $P_{T(1)} = 0.65$, $P_{T(2)} = 0.47$ and $P_{T(3)} = 0.28$ (Fig. 5). The T=1 model was characterized by comparatively poor OC function that was relatively flat, with a high degree of scatter (Fig. 6). By comparison, OC functions for the T=2 and T=3 models were similar in shape, with steeper drops in the vicinity of the action threshold and less scatter.

Actual Type I and Type II classification error rates for the 2002-04 data used in parameterization and the 2005-06 independent validation data sets were used to further discriminate between the T=2 and T=3 models in term of accuracy. Errors were assessed at two action thresholds corresponding to the boundaries of management zone 3B (Fig. 5) and three sample sizes. Mean type I and II error rates were well below 10% across all model x action threshold combinations (Table 1). There was no evidence of a sample size effect on error rates. Mean type I error rates were consistently higher than their corresponding type II counterparts, indicative of conservative behaviour by both models. As indicated by the OCs, the T=2 and T=3 models were very similar in terms of Type I and II error rates across action thresholds. However, the relationship between proportion infested and mean density was slightly better for the T=2 model and it would provide better resolution at lower SLW densities.

4. Discussion

We propose a SLW management strategy that provides the requisite scope and flexibility to address the complexity of pest management in Australian cotton production systems. Individualism in crop management practices is one of several factors that make SLW management challenging. Virtually 100% of Australia's annual cotton crop is managed by professional agricultural consultants. Adjacent cotton farms can often be managed by different consultants employing individualistic pest control strategies. This often results in situation where fields with similar SLW densities can be managed differently and fields with significantly different population densities may be treated with the same product.

The cost of insecticide application has had a significant impact on the evolution of SLW management in Australian cotton. Whilst threshold-based intervention with IGRs has provided effective control of SLW populations in commercial cotton fields (Horcott Pty. Ltd., unpublished data), in reality the treatment of sub-threshold populations has become common practice. The use of IGRs for SLW control has declined substantially in recent years. At around $100 per hectare, IGR application contributes significantly to the cost of production.

The decline in IGR use has been matched by an increase in the use of less expensive conventional (non-IGR) insecticides. However, experiences of using non-IGR insecticides for SLW control have been variable. A good example of this is diafenthiuron which appears to provide consistently good field control at low-moderate densities but is variable in efficacy at higher densities.

The spectrum of insect problems endemic to Australian cotton production systems is yet another factor that impinges on management of SLW. In the current GM cotton era, sap sucking bugs, particularly mirids (*Creontiades* spp.), are major and frequent pests requiring 1-2 insecticide sprays on most crops each season. Aphids, mites, jassids and thrips also need to be controlled on many crops each year. These pests are commonly controlled with insecticides such as fipronil, dimethoate and various pyrethroids which also impact on beneficial insect populations. Consequently, the 'bio-residual' factor (Ellsworth and Martinez-Carrillo, 2001; Naranjo, 2001) that makes IGRs so effective in other cotton systems like that in Arizona by providing ongoing control of SLW through natural enemy and other mortality factors after the residual effect of the chemical has evaporated is often in-effective in Australia. Thus, the need to control other pests constrains the timing of IGR use in Australian cotton fields.

Fields treated early (before ~1450 DD) with insecticide (including IGRs) to control SLW have a higher probability of re-colonisation from other sources or resurgence of the population in the 9-10-weeks from peak flowering to defoliation. Pest resurgence is a key consideration in management decisions due also partly to a restriction on insecticides for whitefly control to one application of a single product per season from each chemical group (including IGRs) voluntarily adopted by the Australian cotton industry as part of a national Insecticide Resistance Management Strategy (Forrester et al., 1993; Fitt, 1994).

Collectively, the six management zones and associated control options we propose here address the majority of whitefly population density scenarios and crop consultant behaviors in Australian cotton fields. The proposed proactive management options involving the use of conventional insecticides (zone 2A) or IGRs (zone 3B) aim to minimize the risk of lint contamination whereas reactive population control in the open boll stage (zones 2B, 3C) primarily minimize the level of lint contamination.

Population control with IGRs remains the principal platform of our strategy. IGRs have provided sustainable and IPM-friendly control of whiteflies in Australia, the USA and other cotton producing countries in the world (Ellsworth and Martinez-Carrillo, 2001; Naranjo 2001; Palumbo et al., 2001). The IGRs Pyriproxifen and buprofezin are highly effective against SLW, give excellent control across a broad range of densities and are very selective, allowing unimpeded survival of predators and parasites (Palumbo et al., 2001, Naranjo et al., 2004). With an accumulation rate of around 18-20 DD/day under typical CQ summer conditions, zone 3B provides an optimum IGR application window of at least 10 days between 1450 –1650 DDs.

The boundaries between regions and zones (Fig. 4) are discretionary areas with regard to population management options. For example, SLW field populations with estimated densities and/or growth rates just below the zone-3B boundary would be correctly placed in zone 2A and targeted with conventional insecticides for suppression but more reliably controlled by application of an IGR. Local information pertaining to the crop, weather and the pest and beneficial populations will be important in determining the appropriate course of action in discretionary areas.

Robust sampling procedures and accurate population estimation or classification are fundamental to effective pest management. Binomial sampling can often be more accurate than complete enumeration for classifying populations as above or below a given threshold because presence/absence sampling based on a tally threshold is fairly resistant to the effects of a few outlier observations (Jones, 1994; Naranjo et al., 1996; Hodgson et al., 2004). The re-sampling analysis of the 2005-06 field data provides a robust test of the binomial models under field conditions. Type II error rates (Table 1) which are more important than their Type I counterparts for minimising the risk of crop damage indicate on average >90% accuracy in population classification for both binomial models. Based on our results we recommend a tally threshold of T=2 adults/leaf and a minimum sample size of 20 leaves at terminal nodes 3, 4 or 5 as the most parsimonious and practical sampling plan for Australian cotton fields.

Threshold population densities of adult SLW that define the boundaries between regions and management zones relative to crop growth stage, expressed as binomial counts (% infested), are presented as a SLW control decision support guide for growers and crop managers (Fig. 4). The success of the strategy hinges on rigorous sampling of adult and nymph populations after the onset of flowering. Whilst sampling for adults provides more accurate estimates of SLW abundance in the crop than nymph sampling, the latter is vital for gauging future population growth potential and is critical for validating the population dynamics assumptions that underpin the pest management strategy proposed here.

Our management strategy and sampling plan are expected to be valid in crops that experience pest population growth as a result of endogenous processes and gradual immigration over a period of several weeks or months as opposed to mass immigration events. The pattern of SLW population dynamics in central Queensland cotton planted in the prime commercial window (15 September – 31 October) appears to be consistent with a gradual build up of SLW through a combination of steady, low-level immigration from over-wintering weed hosts and endogenous population growth. The presence of adults and concomitant absence of large nymphs within crops at or beyond cut-out is strongly indicative of mass immigration in which case the management strategy discussed here may not be fully applicable.

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Table 1. Actual Type I (α) and Type II (β) error in classification for adult SLW abundance data from Australian cotton fields using binomial models with tally threshold ≥ T adults/leaf and sample sizes (**n**) of 20, 30 and 40 leaves. The models were evaluated at action thresholds (***m***) of 1.44 and 2.25 adults/leaf. Classification errors were computed manually from the output of the RVSP computer program based on 500 re-sampling iterations for each data set.

		Type I error (%)		Type II error (%)	
Data / Model	**n**	Mean	Max	Mean	Max
2002-04 (combined): 54 data sets					
Model: T=2 ***m***=1.44	20	3.2	29.0	1.2	11.8
	30	3.2	31.6	0.7	10.6
	40	3.0	37.2	0.5	9.2
Model: T=3 ***m***=1.44	20	6.5	36.6	0.4	5.6
	30	3.7	30.2	0.4	5.0
	40	4.6	35.8	0.2	4.4
Model: T=2 ***m***=2.25	20	2.2	35.6	1.9	24.2
	30	1.7	31.6	1.9	26.2
	40	2.1	46.4	1.2	24.4
Model: T=3 ***m***=2.25	20	2.2	19.4	0.9	13.2
	30	1.7	17.2	0.9	12.0
	40	1.2	14.2	0.9	11.6
2005-06: 30 independent data sets					
Model: T=2 ***m***=1.44	20	4.1	24.2	0.6	6.6
	30	5.2	40.8	0.4	7.6
	40	5.0	42.4	0.3	5.0
Model: T=3 ***m***=1.44	20	8.5	65.8	0.1	1.4
	30	6.6	64.6	0.3	5.2
	40	7.9	71.6	0.1	2.6
Model: T=2 ***m***=2.25	20	4.0	33.6	1.0	9.6
	30	3.2	34.4	0.9	10.2
	40	3.6	37.0	0.6	7.8
Model: T=3 ***m***=2.25	20	4.4	29.0	0.5	8.4
	30	3.8	30.4	0.6	9.4
	40	3.1	28.2	0.6	7.2

Figure Captions:

Fig. 1. Abaxial surface of a cotton leaf compartmentalised into sectors by major veins and the positioning of a 3.88 cm^2 disc for sampling Silverleaf Whitefly (SLW) nymphs.

Fig. 2. A) Mean population growth trajectories of adult SLW from cotton fields in three consecutive growing seasons (2002/03 – 2004/05) in the Emerald Irrigation Area. Vertical lines show SEM. Non-linear regression curves were fitted to data from individual seasons using equation (1): Log Density $_{(x)}$ = A + B(R^X). Parameter estimates (± SE) for eq. (1): (a) 2002/03 (▲); R=1.00312 (4 x 10^{-4}), B=0.00077 (6.1 x 10^{-4}), A=0.0352 (8.1 x 10^{-3}), r^2=98.6; (b) 2003/04 (Δ); R=1.00289 (2.4 x 10^{-4}), B=0.00156 (7.1 x 10^{-4}), A=-0.00156 (7.1 x 10^{-4}), r^2=97.8; (c) 2004/05 (**O**); R=1.00135 (4 x 10^{-4}), B=0.01196 (1x 10^{-2}), A=-0.01196 (1x 10^{-2}), r^2=90.4. B). Mean seasonal density profiles of SLW large nymphs for 2002/03 (♦), 2003/04 (Δ) and 2004/05 (□) in cotton fields in the Emerald Irrigation Area. Vertical lines represent SEM.

Fig. 3. Non-linear regression curves fitted to combined adult SLW data for 2002/03 and 2003/04 using equation (1): Log Density $_{(x)}$ = A + B(R^X). Symbols represent mean density at each field sampling location. Upper (dashed) and lower (solid) curves indicate predicted maximum and mean density at each sampling date, respectively. Parameter estimates (±SE) for eq. (1): (a) Mean density curve; R=1.00283 (4 x 10^{-4}), B=0.00155 (1.2 x 10^{-3}), A=0.0139 (1 x 10^{-2}), r^2=96.3; (b) Maximum density curve; R=1.002 (6 x 10^{-4}), B=0.0166 (2 x 10^{-2}), A=0.0869 (6.5 x 10^{-2}), r^2=87.5. The curves define three regions of low, medium and high population density.

Fig. 4. Changes in the predicted maximum (solid curve) and mean (dashed curve) population density of adult SLW in Emerald cotton crops planted on 23 September in relation to crop age (accumulated Day Degrees) estimated from the 2002/03 – 2003/04 combined abundance data. Vertical dashed lines indicate key physiological crop stages and delineate various pest management decision zones. Proportions of infested leaves were calculated using the T=2 binomial model; values are provided along the curves at 50 DD intervals (see text for detail).

Fig. 5. The relationship between mean observed field density of adults and the proportion of sample units infested with ≥ T adult SLW per leaf for the combined data from the 2002/03 and 2003/04 seasons in Emerald cotton fields. The smooth curves were fitted using the exponential form of Equation (2): $\boldsymbol{m} = \ln(\alpha)\cdot(-\ln[1 - P_T]^{\beta})$. Parameter estimates (±SE): (A) T=1, α=0.6898 (6.8 x 10^{-2}), β=1.2721 (4.5 x 10^{-2}), r^2=0.9435; (B) T = 2, α=1.1564 (8.4 x 10^{-2}), β=0.7720 (2.9 x 10^{-2}), r^2=0.9387; (C) T = 3. α=1.5074 (9.4 x 10^{-2}), β=0.6220 (2.8 x 10^{-2}), r^2=0.9252.

Fig. 6. Operating characteristic (probability of taking no action) curves for fixed-sample size binomial models using a tally threshold of T=1, 2 or 3 adults/leaf, corresponding binomial action thresholds (P_T) of 0.65, 0.47 and 0.28 and a sample size of N=30 leaves for the combined 2002-04 SLW adult abundance data. Values of the operating characteristic (OC) were generated by the RVSP re-sampling software (see text for details). The smooth curves represent fitted values of Equation (3); the horizontal and vertical dashed lines indicate an OC value of 0.5 and the action threshold of 2.25 adults/leaf, respectively.

Figures

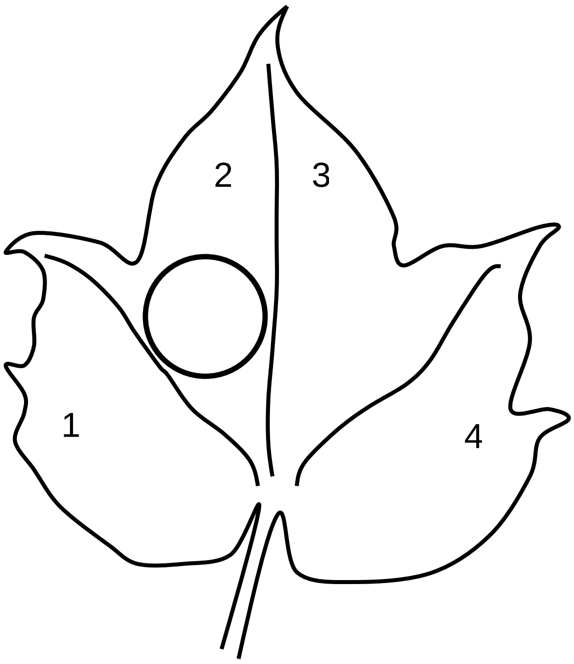


Fig. 1.

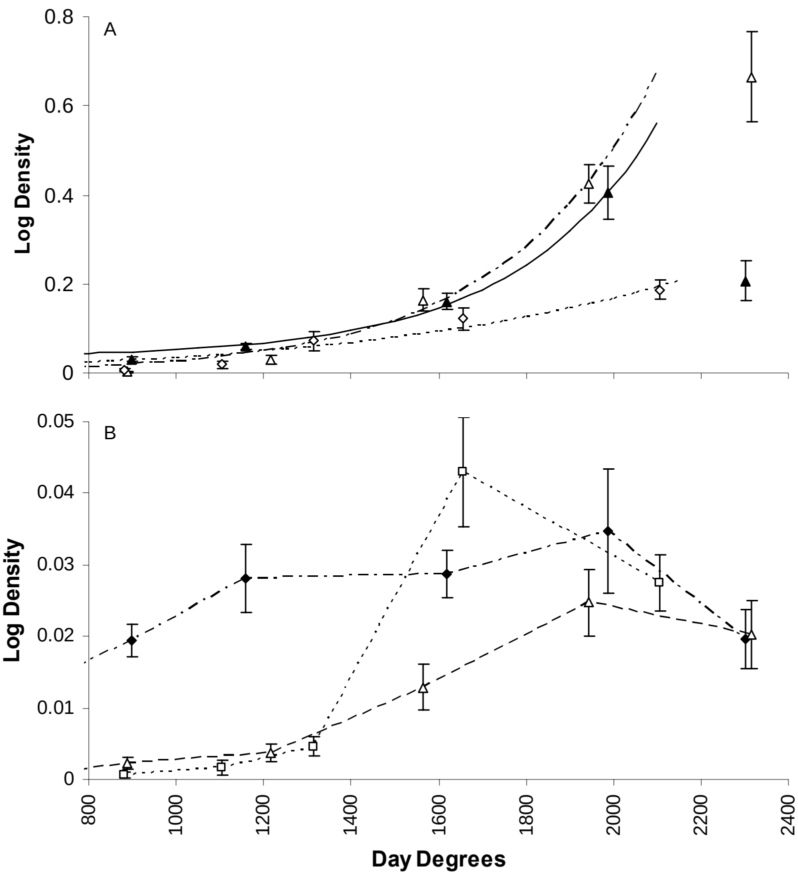
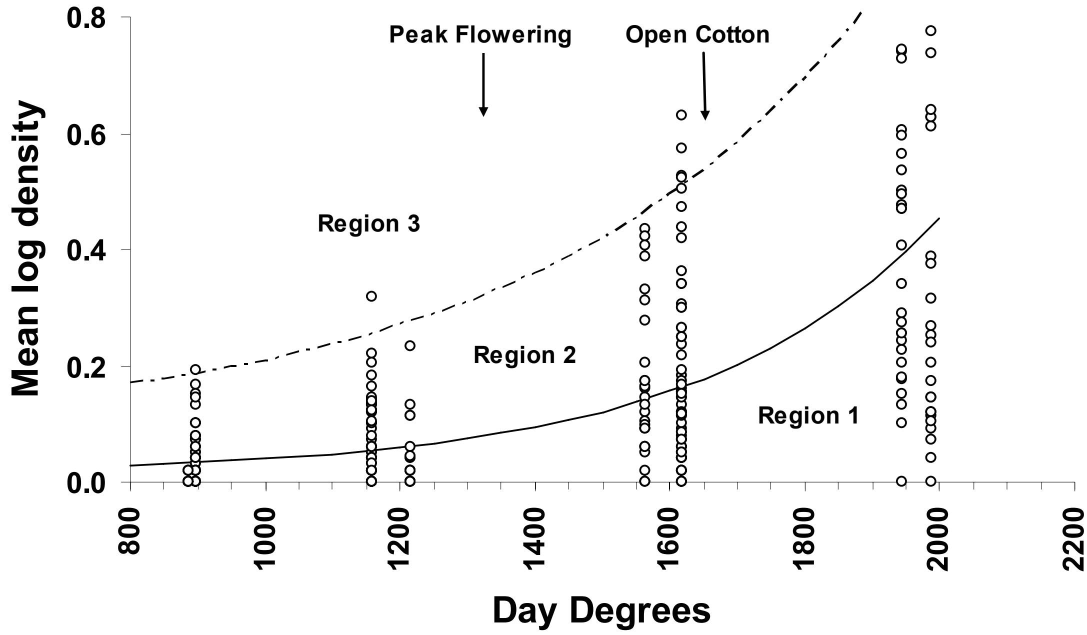
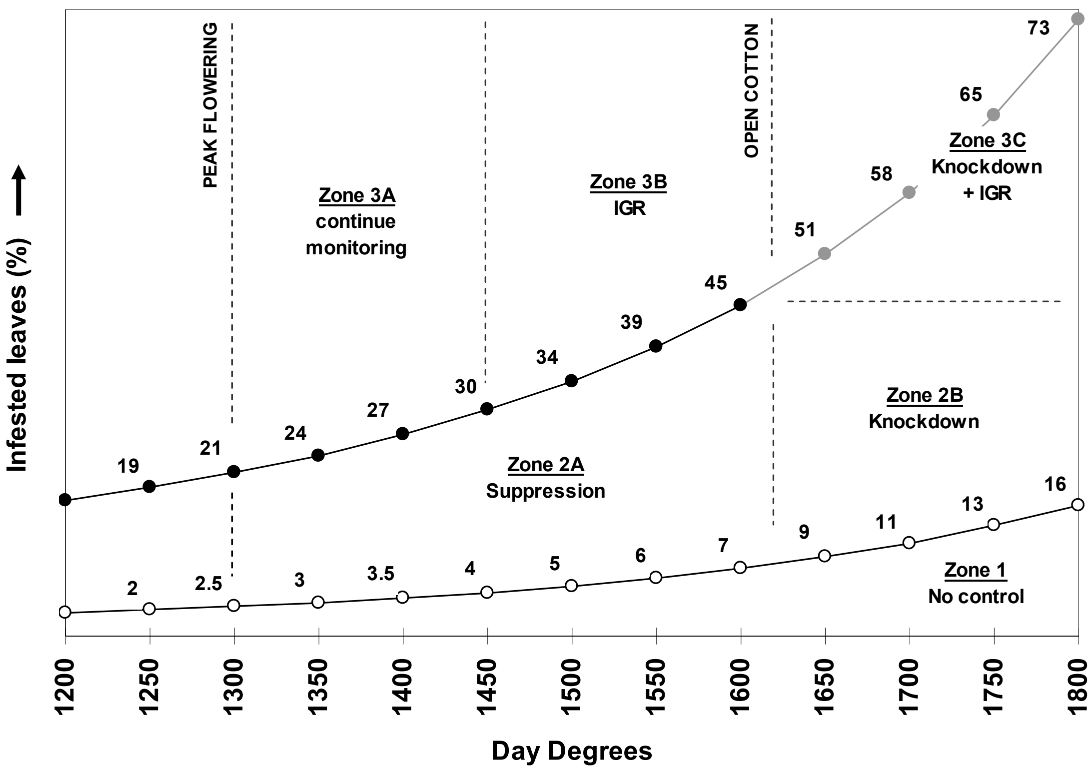


Fig. 2



Peak Flowering
Open Cotton
Region 3
Region 2
Region 1
Mean log density
Day Degrees

Fig. 3.



PEAK FLOWERING
OPEN COTTON
Zone 3A
continue monitoring
Zone 3B
IGR
Zone 3C
Knockdown + IGR
Zone 2A
Suppression
Zone 2B
Knockdown
Zone 1
No control
Infested leaves (%)
Day Degrees

Fig. 4.

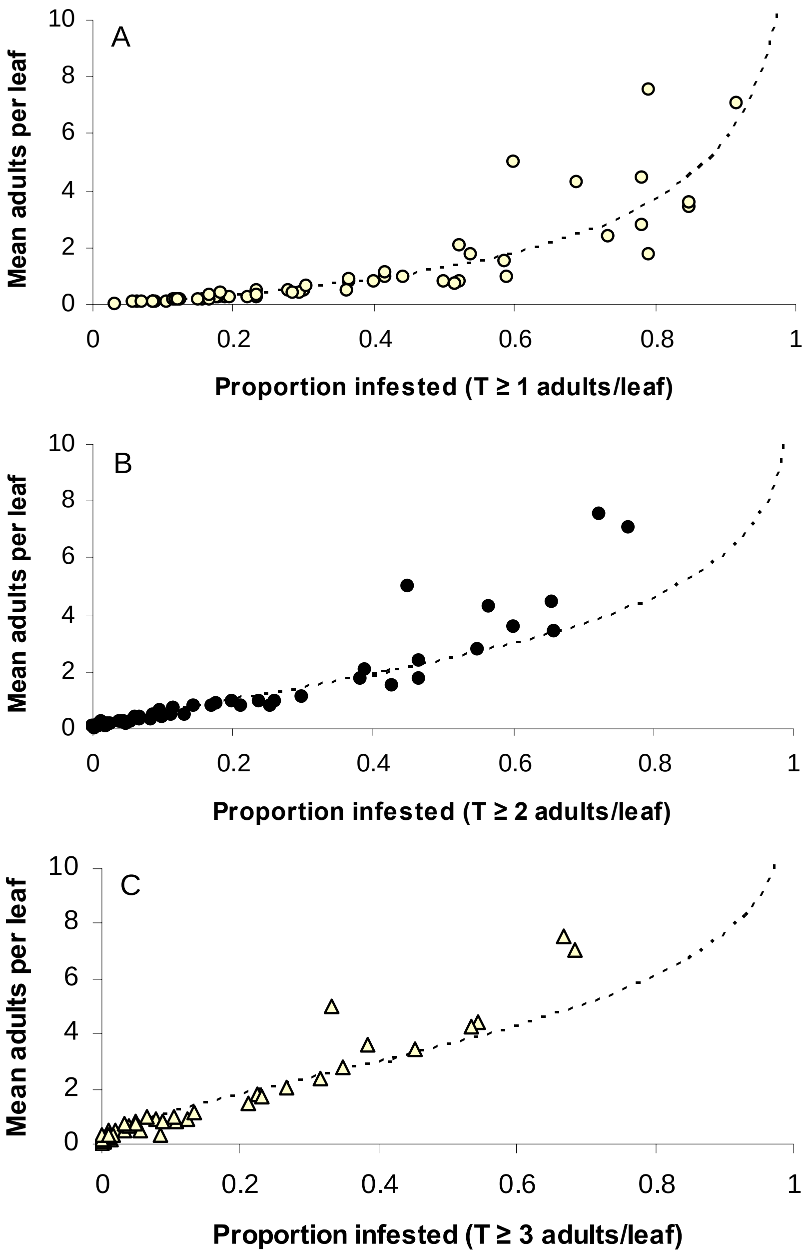

A
B
C
Mean adults per leaf
Proportion infested (T ≥ 1 adults/leaf)
Proportion infested (T ≥ 2 adults/leaf)
Proportion infested (T ≥ 3 adults/leaf)
0
2
4
6
8
10
0
0.2
0.4
0.6
0.8
1

Fig. 5.

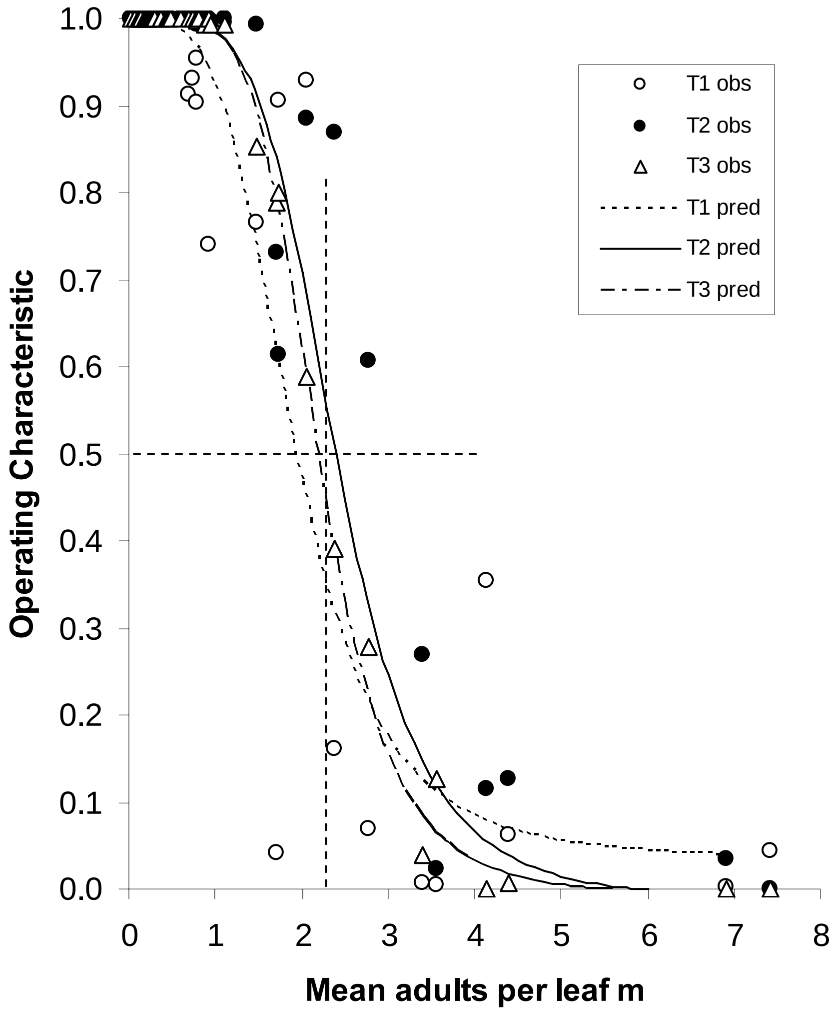

T1 obs
T2 obs
T3 obs
T1 pred
T2 pred
T3 pred
Operating Characteristic
Mean adults per leaf m
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
1
2
3
4
5
6
7
8

Fig. 6.