Chapter 3

Yield and maturity of UNR cotton

3.1 Introduction

UNR, a production system with rows spaced less than 40 cm apart, has shown potential for earlier maturity in low-input systems in the U.S.A. Conceptually, the high density planting of UNR reduces the time to crop maturity, as fewer bolls per plant need to be produced to achieve comparable yields to conventionally spaced cotton crops (Lewis 1971). In practice, this earliness has been difficult to achieve consistently in UNR trials in Australia and the U.S. (Constable 1977a; Kerby *et al.* 1990a). Cotton in Australia is primarily grown in high-yielding, high-input productions systems compared with the lower input production systems in the U.S.A. To date, most trials in Australia comparing UNR to conventionally spaced systems include different management strategies for each system thus confounding comparisons and failing to clearly identify any possible advantages of UNR.

The first step in understanding the performance and growth of UNR cotton production systems using high-inputs in Australia is to determine if they confer maturity or yield benefits. The studies reported in this chapter compare crop maturity, lint yield, yield components, fibre quality, final fruit distribution and plant architecture characteristics for UNR and conventionally spaced cotton grown using high inputs of nutrient, water and insecticides.

The results of six experiments conducted over three years and across a range of environments are presented. One experiment included an additional row spacing treatment (twin row) to UNR and conventionally spaced cotton. Two experiments also compared the effect of the growth regulator - mepiquat chloride (Pix®) on UNR and conventionally spaced rows. There were no growth regulator applications in the other experiments, to ensure measurements were of growth responses to the row spacing treatments.

3.2 Site and climate descriptions

Six field experiments were conducted over three growing seasons and at three locations in NSW (Table 3.1).

Table 3.1 Location and year of each field experiment

Experiment	Season	Location	Latitude, Longitude
1	2001-02	Narrabri	30.31°S, 149.78°E
2	2002-03	Narrabri	30.31°S, 149.78°E
3	2002-03	Hillston	33.49°S, 145.52°E
4	2002-03	Breeza	31.25°S, 150.46°E
5	2003-04	Narrabri	30.31°S, 149.78°E
6	2003-04	Hillston	33.49°S, 145.52°E

3.2.1 Narrabri

Exps. 1, 2 and 5 were conducted at the Australian Cotton Research Institute (ACRI), near Narrabri, in a semi-arid environment of north-west New South Wales, Australia. Annual rainfall is 650 mm with a mean maximum temperature of 26.5°C and mean minimum of 11.7°C (SILO 2006b). The soil was a self-mulching Grey Vertosol (Isbell 2002) common to the area. These soils are alkaline and have a high clay fraction.

3.2.2 Breeza

Exp. 4 was conducted at "Jangaree" Camilleri Farms Pty Ltd near Breeza, in a semi-arid environment of north-west New South Wales, Australia. Annual rainfall is 520 mm with a mean maximum temperature of 25.2°C and mean minimum of 10.9°C (SILO 2006b). The soil was a self-mulching Black Vertosol (Isbell 2002) common to the area. These soils are alkaline and have a high clay fraction.

3.2.3 Hillston

Exps. 3 and 6 were conducted at "Merrowie" Twynam Pastoral Co. near Hillston, in an arid environment of south-west New South Wales, Australia. Annual rainfall is 360 mm with a mean maximum temperature of 24.2°C and mean minimum of 10.9°C (SILO 2006b). The soil was a Red Vertosol (Isbell 2002) common to the area. These soils are alkaline and have a high clay fraction.

3.3 Methods

3.3.1 General methods

Cultivar

All experiments used the cultivar Sicala V-3RRi developed by CSIRO Australia. This cultivar is a medium season cultivar with compact growth habit recommended for UNR production systems in the areas in this study (CSD 2000). It performs well in both conventionally spaced and UNR production systems. Sicala V-3RRi is a transgenic cultivar containing the *Bacillus thuringiensis* (*Bt*) insecticidal protein Ingard® gene and the Roundup Ready® gene which enables the plant to tolerate over-the-top sprays of glyphosate until the crop reaches four true leaves (Monsanto, St Louis, MO, USA). This is important for weed control in UNR systems (Fowler *et al.* 1999).

Treatments

In the **ultra-narrow row (UNR)** treatment, the row configuration was six rows spaced 0.25 m apart on a 2 m bed sown with 36 plants m^{-2} (Plate 3.1). In the **conventionally spaced** treatment, the row configuration was two rows spaced 1 m apart on a 2 m bed sown with 12 plants m^{-2} (Plate 3.2). In the **38 cm UNR** treatment the row configuration was four rows spaced 0.38 m apart on a 2 m bed sown with 24 plants m^{-2} (Plate 3.3). In the **twin row** treatment, the row configuration was 4 rows per 2 metre bed with the rows spaced 0.18 m apart either side of conventional planting line sown with 24 plants m^{-2} (Plate 3.4).

Plate 3.1 UNR treatment 67 days after sowing Exp. 4 - Breeza

Plate 3.2 Conventionally spaced treatment 67 days after sowing Exp. 4 - Breeza

Plate 3.3 38 cm UNR treatment 67 days after sowing Exp. 4 - Breeza

Plate 3.4 Twin row treatment 67 days after sowing Exp. 4 - Breeza

UNR and conventional row spacing treatments were included in all six experiments. The 38 cm UNR and twin row spacing treatments were only studied in Exp. 4. Usually conventionally spaced cotton is planted on hills spaced 1 m apart separated by a furrow. To eliminate differences in soil preparation all treatments in all experiments were planted on 2 m wide beds with a furrow either side of the bed for irrigation.

Crop management

Management for all experiments followed current commercial practices with high input management and insect control as described by Hearn and Fitt (1992). Each experiment was managed according to the crops needs with management the same across all treatments in each experiment. Appendix 1 outlines detailed crop management histories for all experiments.

Sowing dates, fertiliser application and irrigation summaries for each experiment are presented below.

3.3.2 Experiment 1: 2001-2002 Narrabri growth analysis

Exp. 1 was sown 16 November 2001 with UNR and conventionally spaced row treatments. A randomised complete block design with four replicates was used. Each plot was 15 m long and 12 m wide (6 x 2 m beds). Nitrogen was applied as anhydrous ammonia at a rate of 100 kg N ha^{-1} four months before planting. There were six irrigations over the season, scheduled according to crop requirements.

3.3.3 Experiment 2: 2002-2003 Narrabri growth analysis

Exp. 2 was sown 10 October 2002 into moisture with UNR and conventionally spaced row treatments. A randomised complete block design with four replicates was used. Each plot was 15 m long and 12 m wide (6 x 2 m beds). In one replicate, there was patchy establishment so only three were used for measurements. Nitrogen was applied as anhydrous ammonia at a rate of 120 kg N ha^{-1} two months before planting. There were six irrigations over the season, scheduled according to crop requirements.

3.3.4 Experiment 3: 2002-2003 Hillston growth analysis

Exp. 3 was dry sown on 5 October 2002 and irrigated immediately after sowing with UNR and conventionally spaced row treatments. A randomised complete block design with four replicates was used. Each plot was 15 m long and 12 m wide (6 x 2 m beds). Nitrogen was applied as anhydrous ammonia at a rate of 135 kg N ha^{-1} two months before planting. There were seven irrigations over the season, scheduled according to crop requirements.

3.3.5 Experiment 4: 2002-2003 Breeza row configuration

Exp. 4 was sown on 11 October 2002 into moisture with four treatments: UNR, conventionally spaced row, 38 cm UNR and twin row. A randomised complete block design with four replicates was used. Each plot was 15 m long and 8 m wide (4 x 2 m beds). A randomised complete block design with three replicates was used. Nitrogen was applied as anhydrous ammonia at a rate of 110 kg N ha^{-1} one month before planting. This trial received no insect sprays and only one irrigation, as water was limited due to drought conditions.

3.3.6 Experiment 5: 2003-2004 Narrabri Pix® growth analysis

Exp. 5 was sown 23 October 2003 into moisture with UNR and conventional row spacing treatments. In addition to the control (No Pix® treatment), there was also a Pix® (mepiquat chloride - an anti-gibberellin) treatment which was applied at a rate of 600 mL ha^{-1} at first square and first flower on both row spacing treatments. The aim of this experiment was to investigate if there were any interactions between Pix® and row spacing. A randomised complete block design with four replicates was used. Each plot was 15 m long and 12 m wide (6 x 2 m beds). Nitrogen was applied as anhydrous ammonia at a rate of 102 kg N ha^{-1} two months before planting. There were five irrigations over the season, scheduled according to crop requirements.

3.3.7 Experiment 6: 2003-2004 Hillston Pix®

Exp. 6 was sown 6 October 2003 with UNR and conventional row spacing treatments. In addition to the control (No Pix® treatment), there was a Pix® treatment with 600 mL ha^{-1} applied once at first square, again to see if there was an interaction between Pix® and row spacing. Two applications were originally planned; however, one week before the second application was due there was an accidental application of 300 mL Pix® over the whole trial, no third application was applied and although the control had one application of Pix® it is referred to as the "No Pix®" treatment. However, the differences in treatments between Exps. 5 and 6 meant no comparisons between the two experiments could be made. A randomised complete block design with four replicates was used. The aim of this experiment was to investigate if there were any interactions between Pix® and row spacing. Each plot was 15 m long and 12 m wide (6 x 2 m beds). Nitrogen was applied as anhydrous ammonia at a rate of 108 kg N ha^{-1} two months before planting. There were 9 irrigations over the season, scheduled according to crop requirements.

3.3.8 Measurements

In each experiment, a number of key growth parameters were determined to allow comparison between row spacings, regions and years. These were, days after sowing (DAS) to maturity (60% of bolls open), lint yield and fibre quality. To measure yield and time to maturity, all open bolls in at least 2 m^2 in each plot were hand picked weekly. This sampling began once three bolls m^{-2} had opened (open bolls defined as when two sutures on the boll dehisce), and continued until the last boll had opened. Maturity was determined by calculating the date at which 60% of the bolls had opened. The seed cotton samples were ginned in a 10-saw gin (Continental Eagle Corp, Prattville, AL, USA). Lint yields (g m^{-2}) were calculated from ginned lint sample weights. Fibre quality measurements on ginned lint samples were performed using a high-volume-instrument (HVI). The most common parameters for examining fibre quality are reported for these experiments (Ramey 1999):

- fibre length – the average length of the longest 50% of fibres in a beard of fibres reported in decimal inches ;
- micronaire – a parameter with no units which measures the combination of the fibre fineness or weight per unit length and the maturity or degree of cell wall development;
- strength – reported in g tex^{-1} as the average force to break a bundle of fibres one tex unit in size (weight in grams of 1 km of fibre);
- uniformity (%) – or the length uniformity index the ratio of the mean fibre length to the upper-half mean length (fibre length);
- short fibre index (%) - the percentage of fibre less than 13 mm long in the sample.

Final fruit distribution and plant architecture characteristics were determined through plant mapping. After all bolls were open and the crop had been defoliated, four plants were harvested from each plot. Final plant height and number of nodes were recorded. Each fruiting site was mapped and final boll position recorded to obtain number of fruiting branches, position of first fruiting branch and fruit retention. Fruit retention for the whole plant, and for first position fruit, was calculated from the final plant maps (fruit retention is expressed as the ratio of final open boll number to total fruiting site number; a first position boll is the first fruiting site developed on a sympodial branch and is the closest to the main-stem (see Fig 2.1).

Additional more detailed measurements specific to Exps. 1, 2 and 5 will be described in subsequent chapters.

Statistical analyses were conducted using Genstat® software. Unless stated otherwise significant differences were considered at 95% confidence intervals ($P < 0.05$). Most analyses performed for Exp. 1 - 4 compared row spacing treatments with a one-way ANOVA for a randomised block design. Exp. 5 and 6 compared row spacing treatments and Pix treatments with a two-way ANOVA for a randomised block design. Where designs were unbalanced (e.g. combined analysis of all experiments), generalised linear modelling (GLM) was used. In the combined analysis using GLM, the main factors were row spacing and experiment and the random factors replicate and experiment (example output in Appendix 2).

3.4 Results

A summary of results (Table 3.2) shows that there were no significant differences in DAS to maturity or lint yield between conventionally spaced and UNR spacings in any of the individual experiments. There were significant differences in boll size in all experiments except Exp. 3. Only Exp. 5 and Exp. 6 had significant differences in final boll number. Final height was significantly different between row spacings in all experiments. Final node number was significantly different in all experiments except Exp. 6. Final height to node ratio (mean internode length) was significantly different in all experiments except Exps. 2 and 5. Final retention of bolls per plant was significantly different between row spacings in Exps. 2 and 6. First position retention was significantly different in Exps. 1 and 2. The only effect on fibre quality parameters was a significant difference in fibre strength between row spacings in Exp.

5. Gin out-turn and node of first fruiting branch were not significantly different between row spacings in any of the 6 experiments.

Table 3.2 Summary of significant differences between UNR and conventionally spaced cotton on key growth parameters, maturity, lint yield and fibre quality in Exp. 1 - 7. (* = 95% confidence level; ** = 99% confidence level; - = no significant difference).

Variable	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5	Exp. 6
DAS to maturity	-	-	-	-	-	-
Lint yield (g m^{-2})	-	-	-	-	-	-
Gin out-turn (%)	-	-	-	-	-	-
Final boll number (bolls m^{-2})	-	-	-	-	**	**
Mean boll size (g $boll^{-1}$)	**	**	-	**	*	**
Fibre length (decimal inches)	-	-	-	-	-	-
Micronaire	-	-	-	-	-	-
Strength (g tex^{-1})	-	-	-	-	**	-
Uniformity (%)	-	-	-	-	-	-
Short fibre index (%)	-	-	-	-	-	-
Final height	**	*	**	**	**	**
Final node number	**	*	**	**	**	-
Height to node ratio	**	-	**	**	-	**
Node to first fruiting branch	-	-	-	-	-	-
Retention of mature bolls	-	**	-	-	-	*

3.4.1 Experiment 1: 2001-2002 Narrabri growth analysis`

In Exp. 1 there were significant differences between row spacings for some parameters, with smaller mean boll size, shorter plants with fewer nodes and shorter mean internode length (height to node ratio) in the UNR treatments compared to conventionally spaced treatments (Tables 3.3 and 3.4). While mean total boll size and mean seed weight per boll were significantly smaller in the UNR treatments, mean lint per boll was not significantly different. Maturity and yield were not significantly different although final boll number and yield were numerically higher in the UNR treatments. Node to first fruiting branch, fibre quality and overall fruit retention were not different between row spacing treatments.

Table 3.3 Means for DAS to maturity, yield components and fibre quality parameters for Exp. 1 (Significant differences indicated by * = 95% confidence level; ** = 99% confidence level)

Variable	Conventionally Spaced	UNR	LSD
DAS to maturity	148.8	144.3	7.85
Lint yield (g m^{-2})	243	338	159
Seed cotton yield (g m^{-2})	571	526	321
Gin out-turn (%)	42.47	44.81	3.53
Final boll number (bolls m^{-2})	101	146	69.2
Mean boll size (g $boll^{-1}$)	5.70	3.60	**0.216
Mean lint boll size (g $boll^{-1}$)	2.44	2.31	0.218
Mean seed boll size (g $boll^{-1}$)	3.26	2.83	**0.170
Fibre length (decimal inches)	1.14	1.13	0.067
Micronaire	3.92	3.92	0.226
Strength (g tex^{-1})	28.9	28.57	2.08
Uniformity (%)	83.9	84.45	2.13
Short fibre index (%)	5.35	5.23	2.72

Table 3.4 Means from final plant maps for Exp. 1 (Significant differences indicated by * = 95% confidence level; ** = 99% confidence level)

Variable	Conventionally Spaced	UNR	LSD
Height final (cm per plant)	88.0	60.5	**1.05
Node final (per plant)	18.7	14.8	** 5.51
Final height to node ratio	4.69	4.05	** 0.159
Node of first fruiting branch	7.25	6.94	0.649
Retention of mature bolls (%)	25.4	24.7	6.29

3.4.2 Experiment 2: 2002-2003 Narrabri growth analysis

In Exp. 2, there were significant differences between row spacings for some parameters, with smaller mean boll size, shorter plants with fewer nodes and lower fruit retention in UNR treatments compared to conventionally spaced treatments (Table 3.5 and 3.6). As with Exp. 1 mean total boll size and mean seed weight per boll was significantly smaller in the UNR treatments, but mean lint per boll was not significantly different. However, there was no difference in internode length in Exp. 2. Maturity and yield were not significantly different although final boll number and yield were slightly higher in the UNR treatments. Node to first fruiting branch and fibre quality were not different between row spacing treatments.

Table 3.5 Means for DAS to maturity, yield components and fibre quality parameters for Exp. 2 (Significant differences indicated by * = 95% confidence level)

Variable	Conventionally Spaced	UNR	LSD
DAS to maturity	148.3	146.0	7.2
Lint yield (g m^{-2})	268	289	197
Seed cotton yield g m^{-2}	624	658	407
Gin out-turn (%)	43.03	43.90	2.97
Final boll number (bolls m^{-2})	105.6	123.3	78.7
Mean boll size (g $boll^{-1}$)	5.92	5.33	*0.57
Mean lint boll size (g $boll^{-1}$)	2.55	2.34	0.32
Mean seed boll size (g $boll^{-1}$)	3.23	2.89	*0.21
Fibre length (decimal inches)	1.13	1.12	0.112
Micronaire	4.37	3.97	1.29
Strength (g tex^{-1})	31.03	30.63	2.03
Uniformity (%)	84.37	84.57	2.23
Short fibre index (%)	8.57	8.23	0.517

Table 3.6 Means from final plant maps for Exp. 2 (Significant differences indicated by * = 95% confidence level; ** = 99% confidence level)

Variable	Conventionally Spaced	UNR	LSD
Height final (cm per plant)	85.0	56.1	*19.9
Node final (per plant)	21.8	18.4	*2.98
Final height to node ratio	3.90	3.05	0.927
Node of first fruiting branch	8.17	8.25	0.612
Retention of mature bolls (%)	49.2	31.3	**8.2

3.4.3 Experiment 3: 2002-2003 Hillston growth analysis

In Exp. 3, the only significant differences were shorter plants, fewer nodes and shorter mean internode length (height to node ratio) in the UNR treatments compared to conventionally spaced treatments (Table 3.7 and 3.8). Unlike Exps. 1 and 2, boll size and retention did not differ between treatments. There was also no difference in internode length. Maturity and yield were not significantly different, although final boll number and yield were slightly higher in the UNR treatments. Node to first fruiting branch and fibre quality were not different between row spacing treatments.

Table 3.7 Means for DAS to maturity, yield components and fibre quality parameters for Exp. 3 (Significant differences indicated by * = 95% confidence level; ** = 99% confidence level)

Variable	Conventionally Spaced	UNR	LSD
DAS to maturity	174.0	172.2	8.36
Lint yield (g m^{-2})	236	257	70.7
Seed cotton yield (g m^{-2})	586	627	174
Gin out-turn (%)	40.29	41.06	1.59
Final boll number (bolls m^{-2})	174	202	70.0
Mean boll size (g $boll^{-1}$)	3.38	3.24	1.96
Mean lint boll size (g $boll^{-1}$)	1.36	1.33	0.793
Mean seed boll size (g $boll^{-1}$)	1.96	1.86	1.12
Fibre length (decimal inches)	1.16	1.14	0.034
Micronaire	4.58	4.73	0.69
Strength (g tex^{-1})	31.60	31.10	1.32
Uniformity (%)	85.08	84.58	0.87
Short fibre index (%)	7.90	7.77	0.805

Table 3.8 Means from final plant maps for Exp. 3 (Significant differences indicated by * = 95% confidence level; ** = 99% confidence level)

Variable	Conventionally Spaced	UNR	LSD
Height final (cm per plant)	70.8	53.1	**3.55
Node final (per plant)	21.3	18.1	**1.04
Final height to node ratio	3.34	2.94	**0.184
Node of first fruiting branch	8.88	8.81	0.678
Retention of mature bolls (%)	45.7	47.7	5.4

3.4.4 Experiment 4: 2002-2003 Breeza row configuration

In Exp. 4, there were significant differences between row spacings for some parameters, with smaller mean boll size, shorter plants with fewer nodes and shorter mean internode length (height to node ratio) in the UNR treatment compared to the conventionally spaced treatment (Table 3.9 and 3.10). Lint and seed weight per boll was also significantly lower in the UNR treatment. Unlike Exp. 1 and 2, retention did not differ between the UNR and conventionally spaced treatments.

Exp. 4 also had 38 cm UNR and twin row treatments. The 38 cm and twin row spaced treatments did not differ in any of the parameters measured. The plants in these treatments were shorter, had fewer nodes and shorter mean internode length than conventionally spaced treatments. Both 38 cm and twin row treatments had larger mean boll sizes than the UNR treatment. However, there were no differences in height and internode length between twin row and UNR treatments, but the 38 cm treatment had significantly taller and longer internode lengths than the UNR treatments. Maturity and yield were not significantly different between any of the row spacing treatments although final boll number and yield were numerically higher in the narrower row spacing treatments compared to the conventionally spaced treatments. Node to first fruiting branch and fibre quality were not different between row spacing treatments.

Table 3.9 Means for DAS to maturity, yield components and fibre quality parameters for Exp. 4 (Significant differences indicated by * = 95% confidence level; ** = 99% confidence level; letters indicate differences between row spacings)

Variable	Conventionally Spaced	UNR	38 cm UNR	Twin Row	LSD
DAS to maturity	154.3	155.0	153.0	153.3	5.1
Lint yield (g m^{-2})	121	146.7	150	162	33.6
Seed cotton yield (g m^{-2})	300	366	366	397	82.4
Gin out-turn (%)	40.34	40.13	40.99	40.66	0.73
Final boll number (bolls m^{-2})	64.9	98.7	83.6	92.0	23.3
Mean boll size (g $boll^{-1}$)	^{a}4.61	^{b}3.72	^{a}4.39	^{a}4.31	**0.398
Mean lint boll size (g $boll^{-1}$)	^{a}1.86	^{b}1.49	^{a}1.80	^{a}1.75	**0.163
Mean seed boll size (g $boll^{-1}$)	^{a}2.63	^{b}2.16	^{a}2.51	^{a}2.48	**0.217
Fibre length (decimal inches)	1.04	1.07	1.08	1.04	0.046
Micronaire	4.00	4.03	4.30	4.23	0.296
Strength (g tex^{-1})	30.63	30.53	30.43	30.70	2.77
Uniformity (%)	82.33	82.83	83.30	82.83	1.83
Short fibre index (%)	9.80	9.67	8.97	9.13	1.42

Table 3.10 Means from final plant maps for Exp. 4 (Significant differences indicated by * = 95% confidence level; ** = 99% confidence level; letters indicate differences between row spacings)

Variable	Conventionally Spaced	UNR	38 cm UNR	Twin Row	LSD
Height final (cm per plant)	^{a}60.3	^{c}41.7	^{b}49.7	^{bc}46.33	**4.52
Node final (per plant)	^{a}19.4	^{b}17.8	^{b}17.6	^{b}17.5	*1.25
Final height to node ratio	^{a}3.11	^{c}2.31	^{b}2.83	^{bc}2.66	**0.224
Node of first fruiting branch	9.90	10.17	9.50	10.25	1.17
Retention of mature bolls (%)	37.53	29.37	34.74	28.24	10.46

3.4.5 Experiment 5: 2003-2004 Narrabri Pix® growth analysis

In Exp. 5, there were significant differences between row spacings for some parameters, with smaller mean boll size, higher final number of bolls and shorter plants with fewer nodes in the UNR treatments compared to conventionally spaced treatments (Table 3.11 and 3.12). Like Exp. 1, mean total boll size and mean seed weight per boll were significantly smaller in the UNR treatments but mean lint per boll was not significantly different. Unlike Exps. 1 and 2, but like Exps. 3 and 4, retention did not differ between UNR and conventionally spaced treatments. Maturity and yield were not significantly different between any of the row spacing treatments, although yield was slightly higher in the UNR treatment compared to the conventionally spaced treatment. Node to first fruiting branch and fibre quality were not different between row spacing treatments.

Exp. 5 also had Pix application treatments. Plants that had Pix® applied were shorter, had fewer nodes and shorter internode lengths compared with plants in the No Pix® treatments. No other parameters measured were significantly affected by the Pix® treatment. The only significant interaction between Pix treatments and row spacing treatments was for fibre strength; with lower fibre strength in the Pix® treatment in the UNR spaced crop; but increased fibre strength in the Pix® treatment in the conventionally spaced crop.

Table 3.11 Means for DAS to maturity, yield components and fibre quality parameters for Exp. 5 (Significant differences indicated by * = row spacing 95% confidence level; ** = row spacing 99% confidence level; ‡ = interaction between row spacing and Pix® treatment 95%)

Variable	Conventionally Spaced		UNR		LSD Row spacing	LSD Pix® x Row spacing
	No Pix®	Pix®	No Pix®	Pix®		
DAS to maturity	150.0	153.8	156.1	151.0	6.2	8.8
Lint yield (g m^{-2})	239	249	252	253	15.9	22.5
Seed cotton yield (g m^{-2})	579	614	633	615	31.5	44.5
Gin out-turn (%)	40.99	40.62	40.12	41.40	1.21	1.71
Final boll number (bolls m^{-2})	107.3	116.2	126.6	124.9	**6.9	9.8
Mean boll size (g boll^{-1})	5.39	5.28	5.01	4.93	*0.27	0.38
Mean lint boll size (g boll^{-1})	2.23	2.14	1.99	2.03	**0.12	0.17
Mean seed boll size (g boll^{-1})	3.16	3.14	3.02	2.90	0.22	0.31
Fibre length (decimal inches)	1.16	1.17	1.15	1.14	0.02	0.03
Micronaire	4.38	3.62	3.90	3.87	0.27	0.38
Strength (g tex^{-1})	31.82	32.75	30.70	29.70	**1.13	‡1.60
Uniformity (%)	84.35	84.10	84.40	83.40	0.66	0.93
Short fibre index (%)	8.33	8.55	8.92	8.97	0.71	1.01

Table 3.12 Means from final plant maps for Exp. 5 (Significant differences indicated by ** = row spacing 99% confidence level; † = Pix® treatment 95 %; †† = Pix® treatment 99%; ‡ = interaction between row spacing and Pix® treatment 95%)

Variable	Conventionally Spaced		UNR		LSD Row spacing	LSD Pix® x Row spacing
	No Pix®	Pix®	No Pix®	Pix®		
Height final (cm per plant)	96.6	84.3	85.9	66.7	††**5.8	8.2
Node final (per plant)	20.8	20.4	18.3	16.5	†**0.9	1.2
Final height to node ratio	4.65	4.13	4.68	4.05	††0.24	0.34
Node of first fruiting branch	8.50	7.75	8.08	8.25	0.45	‡0.63
Retention of mature bolls (%)	48.7	48.6	40.5	43.8	7.2	10.2

3.4.6 Experiment 6: 2003-2004 Hillston Pix®

In Exp. 6, there were significant differences for some parameters between row spacing treatments, with smaller mean boll size, higher final number of bolls, shorter plants with fewer nodes and lower fibre strength in the UNR treatments compared to conventionally spaced treatments (Table 3.13 and 3.14). Lint and seed weight per boll were also significantly lower in the UNR treatments. Overall fruit retention was significantly lower in the UNR treatment. Maturity and yield were not significantly different between any of the row spacing treatments although final boll number and yield was slightly higher in the UNR treatment compared to the conventionally spaced treatment. Node to first fruiting branch and fibre quality were not different between row spacing treatments.

Exp. 6 also had Pix® application treatments. Plants that had Pix® (two Pix® applications) applied were shorter, had fewer nodes and shorter internode lengths compared with plants in the No Pix® (one Pix® application) treatments. Unlike Exp. 5, boll size was larger in the Pix® treatment and overall fruit retention was lower compared to the No Pix® treatment. No other parameters measured were significantly affected by the Pix® treatment. There were no significant interactions between Pix® treatments and row spacing treatments.

Table 3.13 Means for DAS to maturity, yield components and fibre quality parameters for Exp. 6 (Significant differences indicated by ** = row spacing 99% confidence level; † = Pix® treatment 95 %; †† = Pix® treatment 99%)

Variable	Conventionally Spaced		UNR		LSD Row spacing	LSD Pix® x Row spacing
	No Pix®	Pix®	No Pix®	Pix®		
DAS to maturity	165.7	166.4	170.5	168.3	4.7	6.6
Lint yield (g m^{-2})	208	220	241	230	25.6	36.1
Seed cotton yield (g m^{-2})	525	565	614	586	67.3	95.2
Gin out-turn (%)	39.71	39.01	39.36	39.19	0.74	1.04
Final boll number (bolls m^{-2})	116.2	116.8	148.5	134.5	**13.71	19.39
Mean boll size (g $boll^{-1}$)	4.52	4.84	4.14	4.34	†**0.18	0.26
Mean lint boll size (g $boll^{-1}$)	1.79	1.89	1.63	1.70	†**0.071	0.10
Mean seed boll size (g $boll^{-1}$)	2.72	2.95	2.51	2.64	††**0.12	0.17
Fibre length (decimal inches)	1.14	1.14	1.15	1.16	0.03	0.04
Micronaire	4.75	4.60	4.45	4.42	0.29	0.41
Strength (g tex^{-1})	32.06	31.70	31.55	32.98	1.48	2.09
Uniformity (%)	85.12	84.97	8475	86.10	0.98	1.39
Short fibre index (%)	7.55	7.9	7.75	7.7	0.80	1.13

Table 3.14 Means from final plant maps for Exp. 6 (Significant differences indicated by * = row spacing 95% confidence level; ** = row spacing 99% confidence level; †† = Pix® treatment 99%)

Variable	Conventionally Spaced		UNR		LSD	LSD Pix® x Row spacing
	No Pix®	Pix®	No Pix®	Pix®		
Height final (cm per plant)	64.5	57.9	49.6	44.0	††**3.40	4.81
Node final (per plant)	19.0	19.3	17.9	19.9	1.81	2.56
Final height to node ratio	3.40	3.01	2.76	2.38	††**0.08	0.12
Node of first fruiting branch	7.7	7.8	8.4	8.0	0.52	0.74
Retention of mature bolls (%)	67.5	61.2	65.0	51.8	††*5.47	7.73

3.4.7 Results of combined analyses across experiments

The results for the six experiments were analysed using GLM for the combined analysis to determine which parameters were significantly different across all the experiments (Tables 3.15 and 3.16). Lint yield, boll size, plant height, node number, height to node ratio, and fruit retention were significantly different between UNR and conventionally spaced cotton in the combined analysis. Final boll number and lint yield were significantly higher in the UNR crop with an increase of 33 bolls m^{-2} and 36 g lint m^{-2}. Total boll size, lint per boll and seed per boll were smaller in the UNR spacing compared to the conventionally spaced cotton. UNR plants averaged 19.9 cm shorter, had 2.7 fewer nodes and shorter internode length (difference of 0.5 cm) than conventionally spaced plants. Overall fruit retention averaged 5.4% lower in the UNR plants compared with the conventionally spaced plants. There were no significant differences in maturity or fibre quality across the experiments.

Interactions were examined between experiments and row spacing and there were differences between experiments for gin out-turn and mean boll size. Analyses of gin out-turn for each experiment individually showed no significant differences between row spacings and no consistent trend in means. Mean gin out-turn in the UNR treatments was higher in Exps. 1, 2 and 4 and lower in Exps. 3, 5 and 6 compared to the conventionally spaced treatments. Analyses of each experiment individually showed that there was significantly lower mean boll size in all experiments except for Exp. 3. Exp. 3 had much lower mean boll size than the other experiments and the UNR treatment in this experiment was only slightly lower. There were no interactions between mean lint per boll or seed per boll between experiments and row spacing treatments.

Table 3.15 Means for DAS to maturity, yield components and fibre quality parameters for all experiments (Significant differences indicated by ** = 99% confidence level; ‡ = interaction between Exp and Row Spacing)

Variable	Conventionally Spaced	UNR	LSD
DAS to maturity	157.0	156.5	3.0
Lint yield (g m^{-2})	219	254	**27.8
Seed cotton yield (g m^{-2})	530	571	62.5
Gin out-turn (%)	41.14	41.56	‡0.82
Final boll number (bolls m^{-2})	111.4	140.8	**15.5
Mean boll size (g $boll^{-1}$)	4.85	4.07	‡**0.30
Mean lint boll size (g $boll^{-1}$)	2.01	1.80	**0.14
Mean seed boll size (g $boll^{-1}$)	2.79	2.48	**0.19
Fibre length (decimal inches)	1.13	1.13	0.02
Micronaire	4.18	4.08	0.19
Strength (g tex^{-1})	31.13	30.58	0.85
Uniformity (%)	84.15	84.28	0.23
Short fibre index (%)	8.01	7.99	0.49

Table 3.16 Means from final plant maps for all experiments (Significant differences indicated by ** = 99% confidence level)

Variable	Conventionally Spaced	UNR	LSD
Height final (cm per plant)	78.2	58.3	**3.52
Node final (per plant)	20.2	17.5	**0.92
Final height to node ratio	3.88	3.35	**0.14
Node of first fruiting branch	8.32	8.39	0.33
Retention of mature bolls (%)	46.26	40.86	**0.04

3.5 Discussion

Yield and maturity were not significantly different between row spacings in any of the individual experiments. Other studies also report little difference in maturity between row spacings in cotton (Hawkins and Peacock 1973; Gerik *et al.* 1998), while some report significantly earlier maturity (Hearn and Hughes 1975; Young *et al.* 1980;

Cawley *et al.* 1998; Cawley *et al.* 1999) and others report inconsistent maturity differences between row spacings in different years of their studies (Constable 1977a; Jost and Cothren 2001).

However, yield was numerically higher in the UNR treatments in all of the individual experiments and the combined analysis showed that the mean lint yield of the UNR treatments was significantly higher (on average by 15.9% or 34.9 g m^{-2}) than the conventionally spaced treatments. Lint yield varied considerably among experiments with the highest average yield in Exp. 1 (conventionally spaced – 243 g m^{-2}; UNR – 338 g m^{-2}) and relatively low yield in Exp. 4 (conventionally spaced – 121 g m^{-2}; UNR – 147 g m^{-2}). This low yield was expected as Exp. 4 received only one irrigation due to drought conditions. These yields are all from handpicks and which tend to be approximately 10% higher than those reported for machine picked yield in Australian irrigated cotton production (Stiller 2005 pers. comm., 15 April). The yields from these experiments are consistent with the average commercial yield produced in the regions that the experiments were conducted in (Table 3.17). The variability (LSD) in lint yield in each experiment ranged from 197 g m^{-2} in Exp. 2 to 15 g m^{-2} in Exp. 5. Although in some experiments the variability was quite high, the experimental design accounted for some of this variability within the field by appropriate blocking of replicates.

While other studies also report higher yields in UNR crops (Hawkins and Peacock 1973; Koli and Morrill 1976b; Heitholt *et al.* 1992; Atwell *et al.* 1996; Gwathmey 1996; Gerik *et al.* 1998; Gwathmey 1998; Cawley *et al.* 1999; Gerik *et al.* 1999; Gwathmey *et al.* 1999; Gerik *et al.* 2000; Vories *et al.* 2001; Bader and Culpepper 2002; Nichols *et al.* 2003; Nichols *et al.* 2004), differences in yield and maturity in experiments comparing UNR and conventionally spaced cotton are not always consistent across years (Constable 1977b; Constable 1977a; Cawley *et al.* 1998; Cawley *et al.* 1999; Jost and Cothren 2001; Vories *et al.* 2001; Bader and Culpepper 2002; Nichols *et al.* 2004). Some studies report no yield benefit in UNR cotton (Baker 1976; Bednarz *et al.* 1999; Clawson and Cothren 2002; Marois *et al.* 2004; Nichols *et al.* 2004), and Boquet (2005) found that yield was lower in the UNR cotton than conventionally spaced cotton.

The combined analyses showed that seed cotton yield was not significantly different between row spacing treatments but was numerically higher. Gin out-turn was not affected by row spacing in this study indicating that there was no difference in the percentage of lint to seed cotton between row spacing treatments. Constable (1975) reported similar results with no effect of row spacing on lint percentage.

Table 3.17 Mean lint yield (g m^{-2}) estimates for irrigated cotton production each season in each region (Dowling 2002; Dowling 2003; Dowling 2004)

Season	Lower Namoi (Narrabri)	Upper Namoi (Breeza)	Southern NSW (Hillston)
2001-2002	188	N/A	N/A
2002-2003	182	184	136
2003-2004	188	N/A	141

Many of the parameters measured were not consistently different between row spacings across experiments. These differences could be due to climatic or management differences. The most consistent difference between UNR and conventionally spaced cotton was a decrease in height and nodes in the UNR crop. Most experiments also had a decrease in height to node ratio (mean internode length). The shorter and more compact UNR plants produced fewer fruiting sites and mature fruit per plant. Similar responses to higher plant populations and narrow row spacings have been found in a number of studies (Constable 1977a; Galanopoulou-Sendouka *et al.* 1980; Bednarz *et al.* 2000).

Node to first fruiting branch (FFB) was not affected by row spacing in any of the experiments. Floral initiation is primarily influenced by temperature, photoperiod and genotype (Low *et al.* 1969). While loss of early leaves or conditions that reduce photosynthesis can delay flowering and the node at which the FFB develops (Mauney 1966) row spacing does not appear to influence the node at which the FFB appears.

Retention, boll size and boll numbers were different in the UNR row spacing in one-third of the experiments but the rest showed no differences. Although fewer fruit were produced per plant, the higher plant density resulted in there being no significant change in fruit number per unit area in Exps. 1 - 4 and in Exps. 5 and 6 there was a significant increase in final boll number.

Mean boll size was significantly smaller in the UNR treatments in all experiments except Exp. 4 and the combined analysis showed that mean boll size (total, lint and seed per boll) was smaller in the UNR treatments compared to the UNR treatments. Smaller boll size is commonly reported in UNR studies (Baker 1976; Constable 1977a; Bednarz *et al.* 1999; Witten and Cothren 2000; Boquet 2005) although not always (Hawkins and Peacock 1973; Gerik *et al.* 1999). Constable (1977a) found that the smaller boll size in the narrow row (18 cm row spacing) treatments in his experiments was due to fewer seeds per boll compared to conventionally spaced rows. This indicated that conditions at flower bud formation and ovule fertilization were important in the narrower row crops as these stages determine the number of seeds per boll (Constable 1977a).

Smaller or fewer bolls in UNR cotton production would limit the potential yield of UNR cotton and may delay maturity. While there was generally no significant difference in final boll number in individual experiments, the combined analysis showed higher final boll number in the UNR treatments, which explains why yield across all the experiments was higher. An increase in boll number compensated for smaller boll size in the UNR treatments. Increase in yield ultimately occurs through either increase in the number of bolls per unit area or in the amount of lint per boll (Hearn and Constable 1984). In other studies yield increase in UNR cotton compared to conventionally spaced cotton has been associated with higher boll numbers per unit area (Heitholt *et al.* 1992; Gerik *et al.* 1998; Bednarz *et al.* 1999; Gerik *et al.* 1999; Gerik *et al.* 2000). The increase in yield in the UNR crop may be due to greater biomass production or increased partitioning to fruit (Charles-Edwards *et al.* 1986). The growth analysis in Chapter 4 will discuss these factors in more detail.

Total fruit retention per plant was lower in Exp. 2 and 6 but there were no other differences in total retention in individual experiments. However, the combined analysis showed that fruit retention per plant in the UNR crops averaged 6% less than for plants in the conventionally spaced crops. Similar results have been found by other studies on UNR cotton (Constable 1975; Baker 1976; Constable 1977b; Constable 1977a; Galanopoulou-Sendouka *et al.* 1980; Kerby *et al.* 1990a). Lower retention in the UNR plants may indicate reduced assimilate supply to support boll retention. Assimilate supply should be highest when the first position fruits develop because the main-stem leaf and subtending leaf have less shading from leaves higher in the canopy (Constable and Rawson 1980a). Boll retention and distribution will be discussed in further detail in Chapter 5.

A smaller plant with fewer bolls would be expected to set and mature bolls earlier. However, if early fruit were shed the UNR plants may compensate by producing fruit later, perhaps delaying maturity. The timing of fruit development and the relationship to assimilate supply will be discussed in Chapter 6.

The smaller boll size in the UNR crop suggests that there may have been limited assimilates for boll development, however this did not have a detrimental impact on fibre quality (micronaire and strength) as also found by Baker (1976). Other authors have reported that the effect of UNR on HVI fibre quality is inconsistent, with several studies agreeing with this study and reporting no effect on fibre quality (Hawkins and Peacock 1973; Heitholt *et al.* 1993; Gwathmey 1996; Gerik *et al.* 1998; Gerik *et al.* 2000; Jost and Cothren 2001; Nichols *et al.* 2004; Boquet 2005). However, Jost (2000) reported that fibre length was shorter in UNR cotton compared to conventionally spaced cotton. Some researchers have also reported lower micronaire in UNR production systems (Hearn and Hughes 1975; Vories *et al.* 2001).

3.6 Conclusion

The results of this set of experiments did not conform to the conceptual notion that the UNR system could produce a similar yield to the conventional system with earlier maturity. The combined analysis indicated higher yield under UNR but no difference in maturity. Although, as expected, plants under the UNR system were smaller and produced fewer and smaller bolls, the higher yield was associated with a greater number of bolls per unit area. However, the smaller plant with fewer bolls did not mature earlier than the larger plant associated with the conventional system. Although plants in the UNR crop had fewer fruiting branches and bolls per plant, these bolls did not mature earlier compared to those in the conventionally spaced crop, indicating that boll set or development was delayed in the UNR system. Lower retention in the UNR crop may be a key indicator of delayed maturity. Differences in the timing of fruit development and limitation in assimilates to support boll growth due to competition between plants in the UNR crop may also influence maturity of the UNR crop. The increase in yield in the UNR crop may be due to greater biomass production or increased partitioning to fruit.

Chapter 4

Growth analyis of UNR and conventionally spaced cotton

4.1 Aim

To compare the growth and development of UNR and conventionally spaced cotton crops under high-input conditions and identify the factors affecting biomass accumulation, partitioning and yield.

4.2 Introduction

In the U.S.A., there has been a resurgence of research into UNR systems but much of the research has focused on the agronomic level. There is little information on the growth and development of UNR cotton in high-input productions systems, particularly in Australia. Information on the growth and development of UNR cotton is required for more thorough analysis of the potential utility of UNR systems when compared with conventionally spaced cotton systems under high-input conditions. In the previous chapter, yield and maturity of UNR and conventionally spaced cotton systems were examined for a range of cotton growing regions over a number of seasons. While maturity did not differ between row spacings, there was a consistent trend towards higher yield with UNR in all the experiments. A combined analysis of the experiments found significantly higher boll numbers and a significant increase in lint yield of 15.9% in the UNR treatments compared to the conventionally spaced treatments. The increase in yield in the UNR crop may be due to greater biomass production or increased partitioning to fruit. In this chapter the differences between UNR and conventionally spaced cotton systems were examined using a framework based on the physiological determinants of crop growth (Charles-Edwards *et al.* 1986). The analysis explored growth, partitioning, leaf area development and light interception characteristics. As water and nutrients are also limiting factors for crop growth, total crop water use, nutrient uptake and leaf nitrogen were compared between row spacings as part of the growth analysis.

4.3 Growth analysis methods

UNR and conventionally spaced production systems were compared in three experiments grown in Narrabri, NSW. UNR plots consisted of six rows spaced 0.25 m apart on a 2 m bed sown with 36 plants m^{-2} and conventionally spaced plots of two rows spaced 1 m apart on a 2 m bed sown with 12 plants m^{-2}. Full experimental details are given in Chapter 3.

4.3.1 Experiment 1: 2001-2002 Narrabri growth analysis

Exp. 1 was sown 16 November 2001 into moisture with UNR and conventionally spaced row treatments.

4.3.2 Experiment 2: 2002-2003 Narrabri growth analysis

Exp. 2 was sown 10 October 2002 into moisture with UNR and conventionally spaced row treatments.

4.3.3 Experiment 5: 2003-2004 Narrabri Pix® growth analysis

Exp. 5 was sown 23 October 2003 with UNR and conventional row spacing treatments. This chapter considers only the growth analysis of the row spacing treatments, as there were no effects of Pix treatments on yield or maturity (Chapter 3).

4.3.4 Biomass accumulation and partitioning measurements

Starting just before first square, plant samples were collected from each plot approximately every 10 days. Plants were harvested from 1 m^2 (0.5 m of row and across the 2 m bed, i.e. two rows for conventionally spaced plots and six rows for

UNR plots). Total fresh biomass was measured and a sub-sample of four plants taken for partitioning and dry matter measurements. The sub-samples were partitioned into laminae, stems (including petioles), squares, green bolls (flowers and non-open bolls) and open bolls (two sutures on the boll dehisced). The number of each fruit type was recorded. Leaf area was measured using a LiCor planimeter (Model LI-3100, LiCor Inc., Lincoln, NB, USA) before drying. Samples were dried in an oven at 70°C for at least 48 hours and weighed.

To account for the high synthesis cost of cotton fruit relative to vegetative tissue, biomass components were converted into glucose equivalents for comparison (Wall *et al.* 1994), expressed as g dry matter m^{-2}, a technique successfully used by Bange and Milroy (2004). Leaf area and dry weight of squares, green bolls, open bolls, leaf and stem were determined. Glucose adjusted total dry matter and total fruit dry matter (sum of squares, green bolls and open bolls) were then derived. Peak total dry matter, peak square dry matter and peak green bolls dry matter for each row spacing treatment were noted for the harvest with the greatest average mass for that component, which differed between treatments.

In Exp. 1, fourteen harvests were cut over the season. The first biomass harvest was cut at 35 DAS when squaring started and the last at 175 DAS after all bolls in each plot had opened. In Exp. 2, eleven harvests were cut over the season. The first biomass harvest was cut at 55 DAS when squaring started and the last at 173 DAS after all bolls in each plot had opened. In Exp. 5, twelve harvests were cut over the season. The first biomass harvest was cut at 41 DAS when squaring started and the last at 161 DAS after all bolls in each plot had opened.

4.3.5 Solar radiation measurements

Total daily incoming radiation was measured using a calibrated pyranometer at the Australian Cotton Research Institute weather station less than 2 km from the experimental fields. In Exp. 1, solar radiation intercepted by the canopies was measured using tube solarimeters (Model TSL Delta-T Devices Ltd, Cambridge, UK). A single tube solarimeter was placed across one bed in each plot (in a north-south orientation) to measure transmitted radiation. One tube solarimeter was placed above the crop in the middle of the experiment to measure incident solar radiation. The solarimeters were calibrated against the solarimeter positioned above the crop before and after each experiment. The solarimeters were programmed to scan at 5-minute intervals, recording average hourly readings on a programmable datalogger (Model DL Delta-T Devices Ltd, Cambridge, UK).

In Exps. 2 and 5 solarimeter data were not collected for the full season or all plots due to problems with dataloggers. For these experiments intercepted solar radiation was calculated from weekly measurements of intercepted photosynthetically active radiation (PAR) using a sunfleck ceptometer (SF-80, Delta-T Devices Ltd, Cambridge, UK). Incident radiation was recorded between 1100 and 1300 hrs (Australian Eastern Standard Time) above each plot averaging three readings. Transmitted radiation was recorded by average readings taken at ground level in three random areas in each plot from the centre of the furrow to the centre of the bed. The proportion of PAR intercepted was calculated as:

$$LI_I = \frac{\text{(incident radiation - transmitted radiation)}}{\text{incident radiation}}$$

An exponential function was fitted to LI_I over DAS to allow interpolation between measurement dates:

$$LI_I = a(1 - e^{(-b\mathrm{DAS})}) + c$$

where *a*, *b* and c are fitted coefficients (Charles-Edwards and Lawn 1984).

To calculate the light extinction coefficient (*k*), total daily intercepted radiation (LI_D) was calculated from instantaneous measurements by adjusting the measurements using the relationship (Charles-Edwards *et al.* 1986):

$$LI_D = \frac{2LI_I}{1 + LI_I}$$

To allow interpolation between dates of measurement LI_D was also regressed over DAS using the same equation as for LI_I.

Total cumulative intercepted solar radiation (CLI_D) was calculated using total incident daily radiation (LI_D) and the measured daily proportion intercepted for the period of measurement in each experiment. For each experiment, CLI_D was calculated up to the biomass harvest with the highest average LAI, after which LAI began to drop off. In all experiments, this period covered the period of maximum growth and light interception.

4.3.6 Leaf area index

At each biomass harvest, leaf area was determined by measuring the leaf area of the sub-sample with a LiCor planimeter (Model LI-3100, LiCor Inc., Lincoln, NB, USA). This sample was dried and weighed and specific leaf area determined (m^2 g^{-1}). Leaf area index (LAI) was calculated as the product of specific leaf area and amount of leaf dry matter (g m^{-2}). Peak LAI for each row spacing treatment was determined for the harvest with the highest average LAI, which differed between treatments.

4.3.7 Leaf nitrogen

Dried leaf samples for each plot from each biomass harvest were ground, mixed, and analysed for nitrogen content using Kjeldahl digestion for leaf nitrogen concentration (% N).

4.3.8 Nutrient uptake

To identify whether nutrients were limiting factors in the growth and development of UNR spaced cotton total nutrient uptake was determined in each experiment. To determine total nutrient uptake for each experiment, the partitioned samples for each plot from the peak total dry matter harvest were combined and ground (Exp. 1 Harvest 10, 137 DAS; Exp. 2 Harvest 9, 138 DAS; Exp. 5 Harvest 10, 134 DAS). The seed cotton in green bolls and open bolls samples was removed and ginned to remove lint from the seed. The lint was discarded and the seed returned to the sample for each plot. This combined sample (i.e. total dry matter for each plot) was analysed for nitrogen, phosphorus, potassium and trace elements using Kjeldahl digestion for total nitrogen and radial inductively coupled plasma optical emission spectroscopy (ICP-OES) for K, P, S, Ca, Mg, Zn, Cu, Mn, Fe and B.

4.3.9 Total crop water use in Exps. 2 and 5

Total crop water use was calculated by monitoring water use of the crop over the season plus rainfall and irrigation inputs minus any runoff. Water use was monitored weekly using a neutron moisture meter (Model 503 Campbell Pacific Nuclear, Pacheco, CA, USA), rainfall was measured at a nearby weather station and irrigation input was calculated as the amount required to fill the soil profile at each irrigation date. Runoff was estimated to occur when a single rainfall event exceeded the amount required to refill the profile.

4.3.10 Derived variables

Ratio of fruit to total above ground dry matter

The ratio of fruit dry matter to total dry matter is often termed "harvest index" in other crops (Donald and Hamblin 1976). For these analyses the ratio of fruit to total dry matter included all fruit (i.e. squares, green bolls and open bolls) converted to glucose equivalents and including bracts of the mature bolls. Therefore, it is not truly a "harvest index" as this usually refers to the ratio of grain yield to total dry matter. The final ratio of fruit dry matter to total above ground dry matter was determined from the final biomass harvest in Exps. 1, 2 and 5 when all fruit were mature (open bolls).

Radiation use efficiency

Radiation use efficiency (RUE_g) (g MJ^{-1}) was derived from the gradient of the linear regression of accumulated total dry matter (glucose equivalent) and cumulative intercepted total solar radiation (CLI_D) (Monteith 1977).

Light extinction coefficient

The light extinction coefficient (k) is a parameter that indicates the effectiveness of a crop canopy at intercepting PAR (Charles-Edwards *et al.* 1986). The light extinction coefficient was derived for the whole season by regressing light interception (LI_D) on LAI for each plot, using a modified form of Beer's Law:

$$LI_D = a\,(1-e^{-k\mathrm{LAI}})$$

Where: LI_D is the proportion of intercepted PAR; k is the light extinction coefficient; LAI is the leaf area index; and a represents the maximum value of light interception that can be attained by the crop canopy. This analysis, however, assumes that light interception characteristics are constant throughout crop development, thereby ignoring changes in leaf angle, the condition of leaf surface, and the overall canopy structure (Charles-Edwards *et al.* 1986).

Day degrees

Thermal time can be used to account for temperature effects on crop development. For cotton the thermal time derivative is termed Day Degrees (DD) (Constable and Shaw 1988). For cotton in Australia day degrees is calculated using 12°C as a base temperature via the function:

$$\text{Day Degrees} = [(T_{max} - 12) + (T_{min} - 12)] / 2$$

where T_{max} is the maximum temperature and T_{min} is the minimum temperature. If T_{min} is less than 12°C, it is set to 12.

Specific leaf nitrogen

Specific leaf nitrogen (SLN (g N m^{-2})) was calculated as the quotient of leaf nitrogen content and specific leaf area as it is the amount of nitrogen (g) per unit area of leaf (m^2) (Muchow 1988). SLN for UNR treatments was then plotted against SLN for conventionally spaced treatments using data from all experiments.

Crop growth rate

To compare crop growth rates (dry matter g m^{-2} day^{-1}) over the season between row spacing treatments, logistic curves were fitted to total dry matter and fruit dry matter data (squares, green bolls and open bolls) and the derivative of these functions was plotted against days after sowing.

Partitioning

Where dry matter analyses showed significant differences in timing of production of either fruit dry matter or total dry matter, allometric ratios were used to test whether there was a significant trend for one row spacing to partition more dry matter to fruit. Allometric ratios do not account for differences in partitioning through time and are used to determine differences in partitioning where ontogenetic drift has occurred (Coleman *et al.* 1994). Reproductive partitioning was examined using the allometric approach by plotting *ln* fruit dry matter against *ln* total dry matter for each row spacing treatment for each experiment. The slope of this plot is equivalent to the ratio between the relative growth rate (RGR) of the fruit and the whole plant.

Where fruit and total dry matter production where not markedly different between row spacings, distribution ratios (DR) were used to test whether there were differences between row spacing treatments in partitioning of dry matter to fruit over time (Bange and Milroy 2000). DR was calculated for the interval between each biomass harvest. This was derived as the ratio of the change in fruit dry matter_g to the change in total dry matter_g. The distribution ratio for UNR treatments was then plotted against the distribution ratio for conventionally spaced treatments using data from all experiments.

Statistical analyses

Analysis of covariance was used to test for differences between row spacings in the regressions for *k*, RUE_g and distribution ratios. One-way analysis of variance (ANOVA) for a randomised block design was used for comparing row spacings for dry matter components. Combined analyses for dry matter components were performed using generalised linear modelling (GLM). In the combined analysis using

GLM, the main factors were row spacing and experiment and the random factors replicate and experiment.

All statistical analyses were conducted using Genstat® software. Unless stated otherwise significant differences were considered at 95% confidence intervals ($P < 0.05$). Where shown graphically the standard errors are two x one standard error of the treatment means from the associated ANOVA. In some data sets, the means of all harvests are presented, whereas an ANOVA was performed for each harvest date.

4.4 Results

4.4.1 Climatic conditions

Exps. 1, 2 and 5 had similar weather patterns resulting in similar cumulative day degrees and cumulative rainfall at the end of the growing season (Table 4.1). The later sowing of Exp. 1 meant that day degree and solar radiation accumulation was slightly slower at the end of the season (Figure 4.1). In-crop rainfall was lower in Exps. 1 and 2 compared with Exp. 5; however, 155 mm of the rainfall during Exp. 5 was precipitated in a 5-day period (Figure 4.2).

Table 4.1 Cumulative day degrees, cumulative solar radiation and total rainfall from sowing in Exps. 1, 2 and 5

Variable	Exp. 1	Exp. 2	Exp. 5
Cumulative day degrees	2123	2298	2127
Cumulative solar radiation (MJ m^{-2})	4111	4567	4182
Total rainfall (mm)	256	173	433

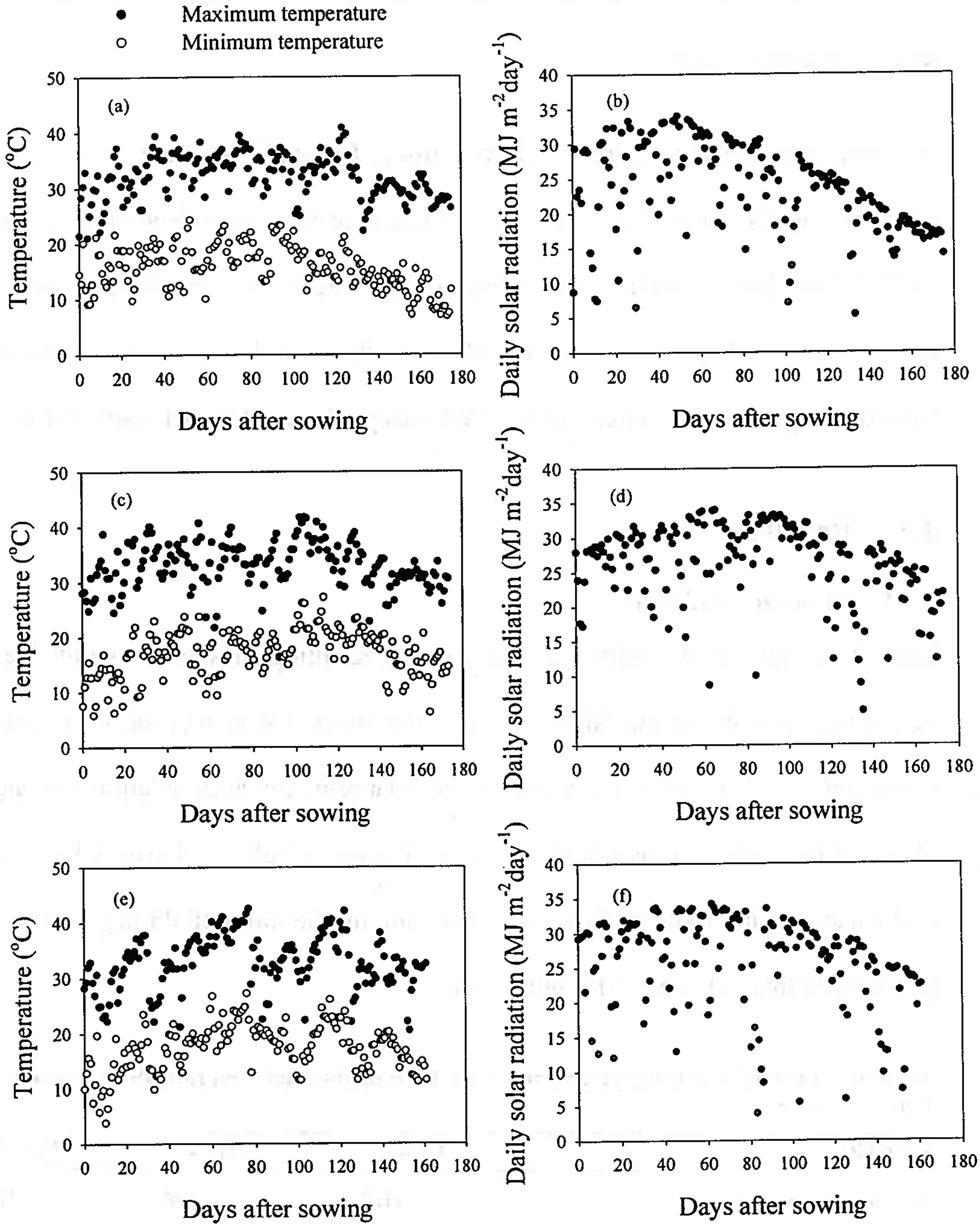

Figure 4.1 Daily temperature (a;c;e) and daily incident solar radiation (b;d;f) for Exps. 1 (a;b), 2 (c;d) and 5 (e;f).

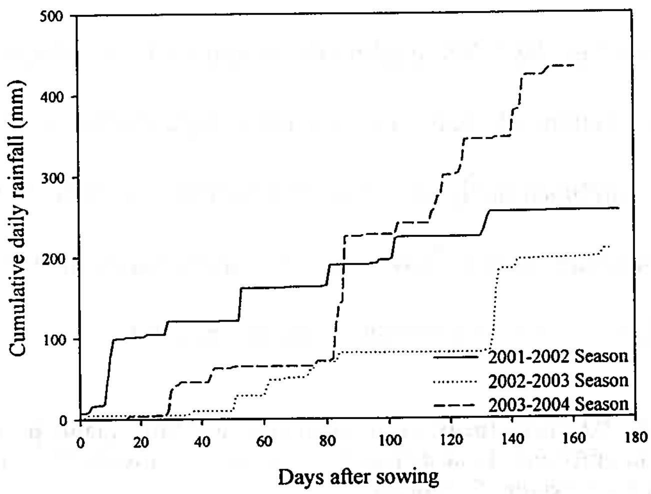

Figure 4.2 Cumulative daily rainfall from sowing to final biomass harvest for Exps. 1, 2 and 5.

4.4.2 Yield components for Exps. 1, 2 and 5

Analyses in Chapter 3 found no differences in yield and maturity between row spacing treatments in Exp. 1, 2 or 5. Combined analyses in Chapter 3 showed significant differences in lint yield, boll size, final, boll number, plant height, node number, height to node ratio and overall retention between row spacings across the six experiments. Combined analyses of these components including only Exps. 1, 2 and 5 gave similar results to the combined analyses for all experiments (Table 4.2 and 4.3).

Lint yield, boll size, plant height, node number, height to node ratio and overall retention were significantly different between UNR and conventionally spaced cotton in the combined analysis. Final boll number and lint yield were significantly higher in the UNR crop with an increase of 28 bolls m^{-2} and 43 g lint m^{-2} or 17.2 % increase in lint yield.

Total boll size, lint per boll and seed per boll were smaller in the UNR spacing compared to the conventionally spaced cotton. UNR plants averaged 22.1 cm shorter, had 3.4 fewer nodes and shorter internode length (difference of 0.47 cm) than conventionally spaced plants. Overall fruit retention per plant averaged 8.8% lower in the UNR plants compared with the conventionally spaced plants. Micronaire was also significantly lower in the UNR treatments compared to the conventionally spaced treatments in the combined analysis of the three experiments, although this was not different in the combined analysis of the six experiments. There were no significant differences in seed cotton (g m^{-2}) (P = 0.176), time to crop maturity (P = 0.890) or other fibre quality parameters across the three experiments.

Table 4.2 Means for DAS to maturity, yield components and fibre quality parameters for Exps. 1, 2 and 5 (Significant differences indicated by * = 95% confidence level; ** = 99% confidence level). SE is the standard error of the mean.

Variable	Conventionally Spaced	UNR	SE
DAS to maturity	149.0	148.8	1.45
Lint (g m^{-2})	250	293	**13.6
Seed cotton (g m^{-2})	591	606	28.9
Gin out-turn (%)	42.16	42.94	0.41
Final boll number (bolls m^{-2})	104.5	132.0	**5.7
Mean boll size (g $boll^{-1}$)	5.52	4.43	**0.10
Mean lint boll size (g $boll^{-1}$)	2.34	2.12	**0.06
Mean seed boll size (g $boll^{-1}$)	3.13	2.79	**0.06
Fibre length (decimal inches)	1.14	1.13	0.01
Micronaire	4.22	3.92	*0.09
Strength (g tex^{-1})	30.59	29.97	0.45
Uniformity (%)	84.21	84.46	0.20
Short fibre index (%)	7.41	7.45	0.20

Table 4.3 Means from final plant maps for Exps. 1, 2 and 5 (Significant differences indicated by * = 95% confidence level; ** = 99% confidence level). SE is the standard error of the mean.

Variable	Conventionally Spaced	UNR	SE
Height final	89.84	66.48	**3.08
Node final	20.49	17.03	**0.48
Final height to node ratio	4.41	3.92	**0.057
Node of first fruiting branch	7.95	7.80	0.15
Retention of mature bolls	41.65	32.75	**0.016

4.4.3 Summary of key results from the growth analysis

A summary of results from the growth analysis of key parameters shows that there were few significant differences between row spacings in any of the experiments (Table 4.4). The most consistent difference was light extinction coefficient (k), which was significantly higher in UNR treatments compared to conventionally spaced treatments in Exps. 1 and 2. Total dry matter, peak total dry matter, and peak LAI were not significantly different between row spacings in any of the experiments.

Some parameters measured were not consistently different across all three experiments. The only significant difference in peak total dry matter of fruit components was a significant difference in peak square dry matter between row spacings in Exp. 5. Radiation use efficiency was significantly different in Exp. 1 but not in Exps. 2 and 5. Total cumulative intercepted solar radiation was significantly different in Exp. 5 but not in Exps. 1 and 2. Fruit to dry matter ratio at final harvest differed significantly in Exp. 1 but not in Exp. 2. There were significant differences between row spacings in specific leaf nitrogen (SLN) at peak LAI in Exps. 2 and 5, but not in Exp. 1.

Combined analyses using GLM were performed on final total dry matter and the components that had either significant differences in one or more of the three experiments or a consistent numerical trend (Table 4.4). There was no significant difference in total cumulative intercepted solar radiation or the ratio of fruit to dry matter between the two row spacings. Light extinction coefficient and radiation use efficiency were significantly different between row spacings over the three experiments.

Table 4.4 Summary of significant differences between UNR and conventionally spaced cotton on key growth parameters, maturity, yield and fibre quality in Exps. 1, 2 and 5. (* = 95% confidence level; ** = 99% confidence level; n.s.d. = no significant difference; N/A = no analysis performed).

Variable	Exp. 1	Exp. 2	Exp. 5	Combined Analysis
Final total dry matter	n.s.d.	n.s.d.	n.s.d.	n.s.d
Peak total dry matter	n.s.d.	n.s.d.	n.s.d.	N/A
Peak LAI	n.s.d.	n.s.d.	n.s.d.	N/A
K	**	**	n.s.d.	**
Radiation use efficiency (RUE)	**	n.s.d.	n.s.d.	**
Total cumulative intercepted solar radiation	n.s.d.	n.s.d	*	n.s.d
Final ratio of fruit to dry matter	*	n.s.d.	n.s.d.	n.s.d
Final fruit distribution ratio	n.s.d.	n.s.d.	n.s.d.	N/A
Peak square dry matter	n.s.d.	n.s.d.	*	N/A
Peak green boll dry matter	n.s.d.	n.s.d.	n.s.d.	N/A
Final open boll dry matter (seed cotton plus bracts)	n.s.d.	n.s.d.	n.s.d.	N/A

4.4.4 Biomass accumulation and partitioning measurements

Total, stem and leaf dry matter

There were some differences between treatments in total dry matter accumulation over the season, but no differences in final or peak dry matter in Exps. 1, 2 or 5 (Figure 4.3). In Exp. 1 the UNR treatments had significantly higher total dry matter than the conventionally spaced treatments at 47 and 69 DAS ($P = 0.012$; $P = 0.004$) and significantly lower total dry matter at 167 DAS ($P = 0.003$) (Figure 4.3a). The UNR treatments in Exp. 2 had significantly higher total dry matter than the conventionally spaced treatments at 55, 74 and 92 DAS ($P = 0.040$; $P = 0.025$; $P = 0.039$ respectively) (Figure 4.3b). In Exp. 5 UNR total dry matter was significantly higher than conventionally spaced treatments at 41, 54, 60 and 148 DAS ($P = 0.008$; $P = 0.018$; $P = 0.008$; $P = 0.005$ respectively) (Figure 4.3c). A combined analysis of total dry matter at the last harvest in Exps. 1, 2 and 5 also showed no significant difference between row spacings ($P = 0.507$) (Table 4.5). There was, however, an interaction between experiment and row spacing effects on total dry matter (P = 0.012). In Exp. 1 and 2, the conventionally spaced treatments had higher average final total dry matter compared to the UNR treatments, whereas in Exp. 5 final total dry matter was lower in the conventionally spaced treatment (Table 4.5).

Table 4.5 Mean final total dry matter in UNR and conventionally spaced treatments for Exps. 1, 2 and 5 (Significant differences indicated by * = 95% confidence level)

Exp.	Conventionally Spaced	UNR	SE from combined analysis
1	2771	2110	
2	2197	1879	266.8
5	2079	2648	

Stem and leaf dry matter showed similar responses to total dry matter. In Exp. 1 the UNR treatments had significantly higher leaf and stem dry matter than the conventionally spaced treatments at 47 and 69 DAS (leaf: P = 0.006; P = 0.013 respectively; stem: P = 0.024; P = 0.002 respectively) and significantly lower stem dry matter at 167 DAS (P = 0.017) (Figure 4.4). Leaf dry matter of the UNR treatment was not significantly different at 167 DAS (P = 0.089) but was significantly lower at 137 DAS (P = 0.014) when neither stem (P = 0.059) nor total dry matter (0.061) were significantly different to the conventionally spaced treatment.

The UNR treatments in Exp. 2 had significantly higher leaf dry matter than the conventionally spaced treatments at 55 and 74 DAS (P = 0.028; P = 0.003 respectively) but not at 92 DAS (P = 0.060) (Figure 4.5). Stem dry matter was not significantly different between row spacings at any of the biomass harvests (55 DAS P = 0.051; 74 DAS P = 0.076; 92 DAS P = 0.091).

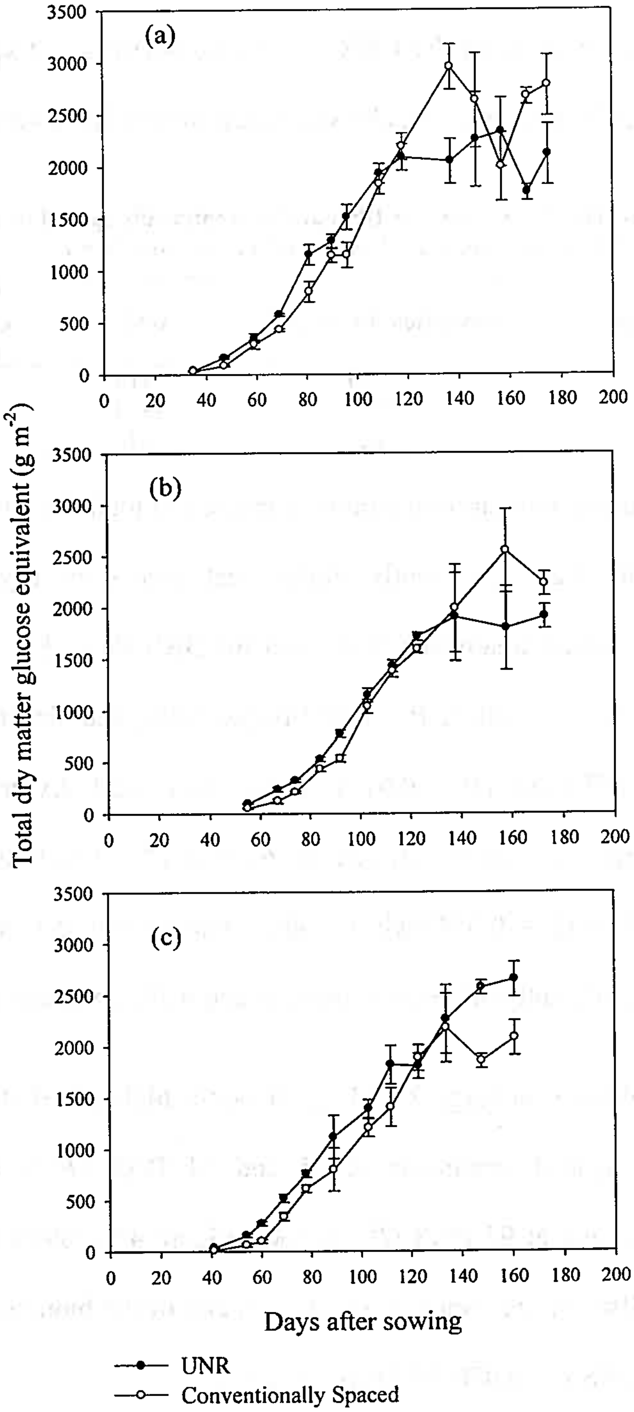

Figure 4.3 Mean total dry matter versus days after sowing for UNR and conventionally spaced treatments in Exps. 1 (a), 2 (b) and 5 (c). Error bars are two standard errors of the mean.

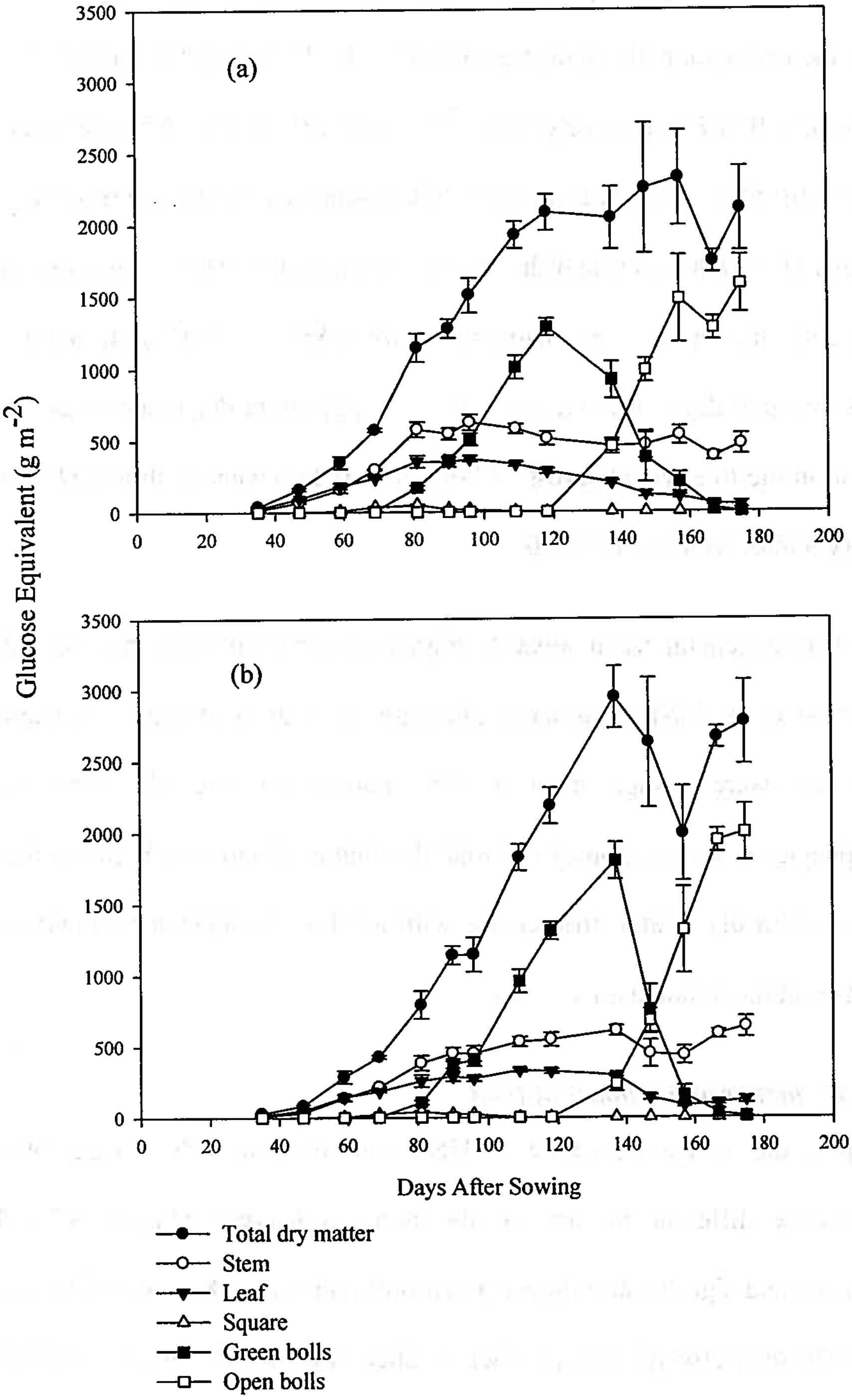

Figure 4.4 Mean dry matter of stem, leaf, squares, green bolls and open bolls versus days after sowing for UNR (a) and conventionally spaced (b) treatments for Exp. 1. Error bars are two standard errors of the mean.

In Exp. 5 leaf and stem dry matter in the UNR treatment were significantly higher than in the conventionally spaced treatment at 41, 54 and 60 DAS (leaf: $P = 0.007$; $P = 0.020$; $P = 0.007$ respectively; stem: $P = 0.009$; $P = 0.034$; $P = 0.009$ respectively) (Figure 4.6). Stem dry matter in the UNR treatment was also significantly higher at 148 DAS ($P = 0.004$) but leaf dry matter was not ($P = 0.055$). Leaf dry matter was significantly higher in UNR treatments at 69 DAS ($P = 0.049$) although stem ($P = 0.058$) and total dry matter were not ($P = 0.053$). Stem dry matter was significantly different in the following harvest 78 DAS ($P = 0.043$) when both leaf ($P = 0.075$) and total dry matter were not ($P = 0.064$).

There was a general trend towards higher earlier total, stem and leaf dry matter production in the UNR treatments, although this was not totally consistent. If these differences were compared at a 10% confidence interval, there were fewer discrepancies in the relationship of total dry matter differences between treatments to leaf and stem dry matter differences, with all three components showing consistent responses at most biomass harvests.

Fruit dry matter and number of fruit

In Exp. 1, the number of squares in UNR and conventionally spaced cotton was not significantly different for any of the biomass harvests (Figure 4.7). The UNR treatments had significantly higher green boll numbers at 81 and 90 DAS ($P = 0.034$; $P = 0.026$ respectively) and a higher number of open bolls at 147 DAS ($P = 0.025$) compared with the conventionally spaced treatments. These differences in fruit number were not translated into significant differences in green boll or open boll dry matter. The only significant difference in fruit dry matter was that the UNR treatment had a lower green boll dry matter at 137 DAS ($P = 0.017$) and a lower open boll dry matter at 167 DAS ($P = 0.010$) than the conventionally spaced treatment (Figure 4.4).

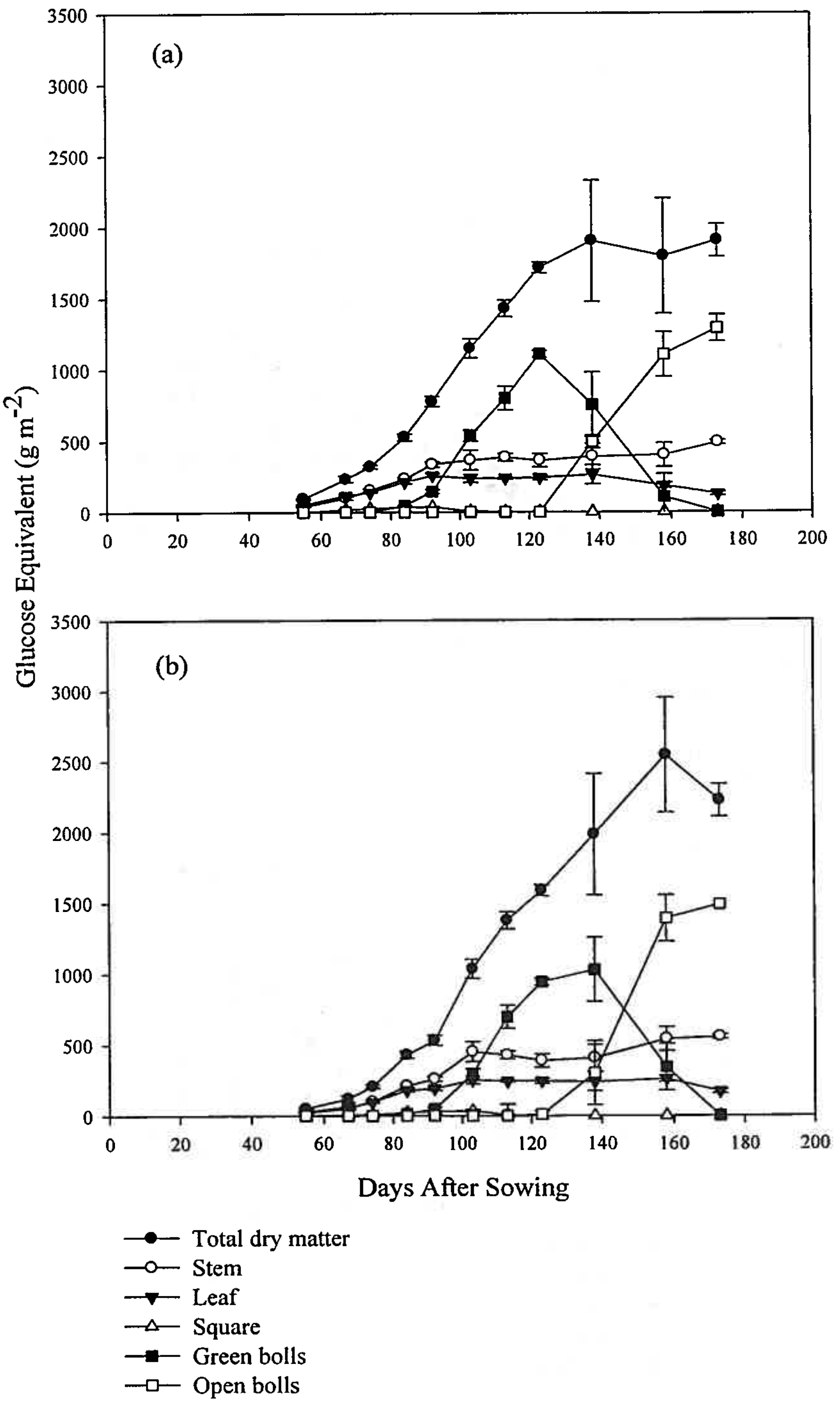

Figure 4.5 Mean dry matter of stem, leaf, squares, green bolls and open bolls versus days after sowing for UNR (a) and conventionally spaced (b) treatments for Exp. 2. Error bars are two standard errors of the mean.

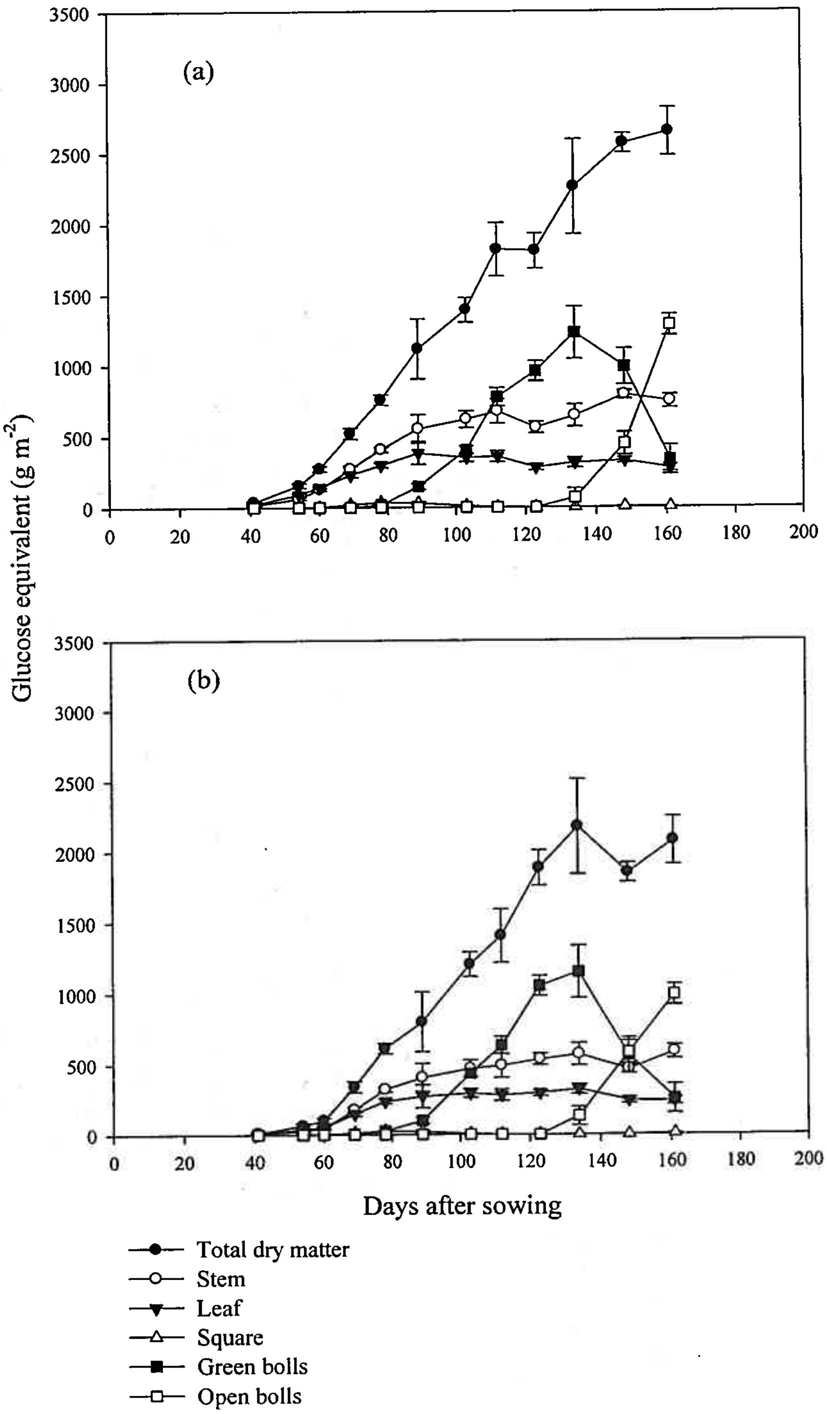

Figure 4.6 Mean dry matter of stem, leaf, squares, green bolls and open bolls versus days after sowing for UNR (a) and conventionally spaced (b) treatments for Exp. 5. Error bars are two standard errors of the mean.

Exp. 2 had a greater number of significant differences in fruit number and dry matter over the season than Exp. 1. The UNR treatment in Exp. 2 had significantly higher square number at 67 DAS and 92 DAS ($P = 0.030$; $P = 0.046$ respectively) (Figure 4.8), with square dry matter approaching significance at 67 DAS ($P = 0.051$). It also had significantly higher square dry matter at 84 DAS but not at 92 DAS ($P = 0.049$; $P = 0.324$ respectively) (Figure 4.5). Green boll numbers were significantly higher in the UNR treatment compared to the conventionally spaced treatment at 84 and 92 DAS ($P = 0.041$; $P = 0.030$ respectively) (Figure 4.8), with green boll dry matter significantly higher at 84, 92, 103 and 123 DAS ($P = 0.008$; $P = 0.033$; $P = 0.047$; $P = 0.044$ respectively) (Figure 4.5). The number of open bolls was significantly higher in the UNR treatment compared with the conventionally spaced treatment at 138 and 158 DAS ($P = 0.006$; $P = 0.015$ respectively) (Figure 4.8), but there were no differences in open boll dry matter (Figure 4.5).

Exp. 5 had few differences in fruit number and dry matter between row spacing treatments. Square number was significantly higher in the UNR treatment compared to the conventionally spaced treatment at 69 DAS ($P = 0.047$) (Figure 4.9) as was square dry matter ($P = 0.035$) (Figure 4.6). Square dry matter was also higher at 78 DAS ($P = 0.035$). Green boll number in the UNR treatment was significantly higher than in the conventionally spaced treatment at 112 and 148 DAS ($P = 0.019$; $P = 0.003$ respectively) (Figure 4.9), but there were no significant differences in green boll dry matter, open boll number or open boll dry matter (Figure 4.6).

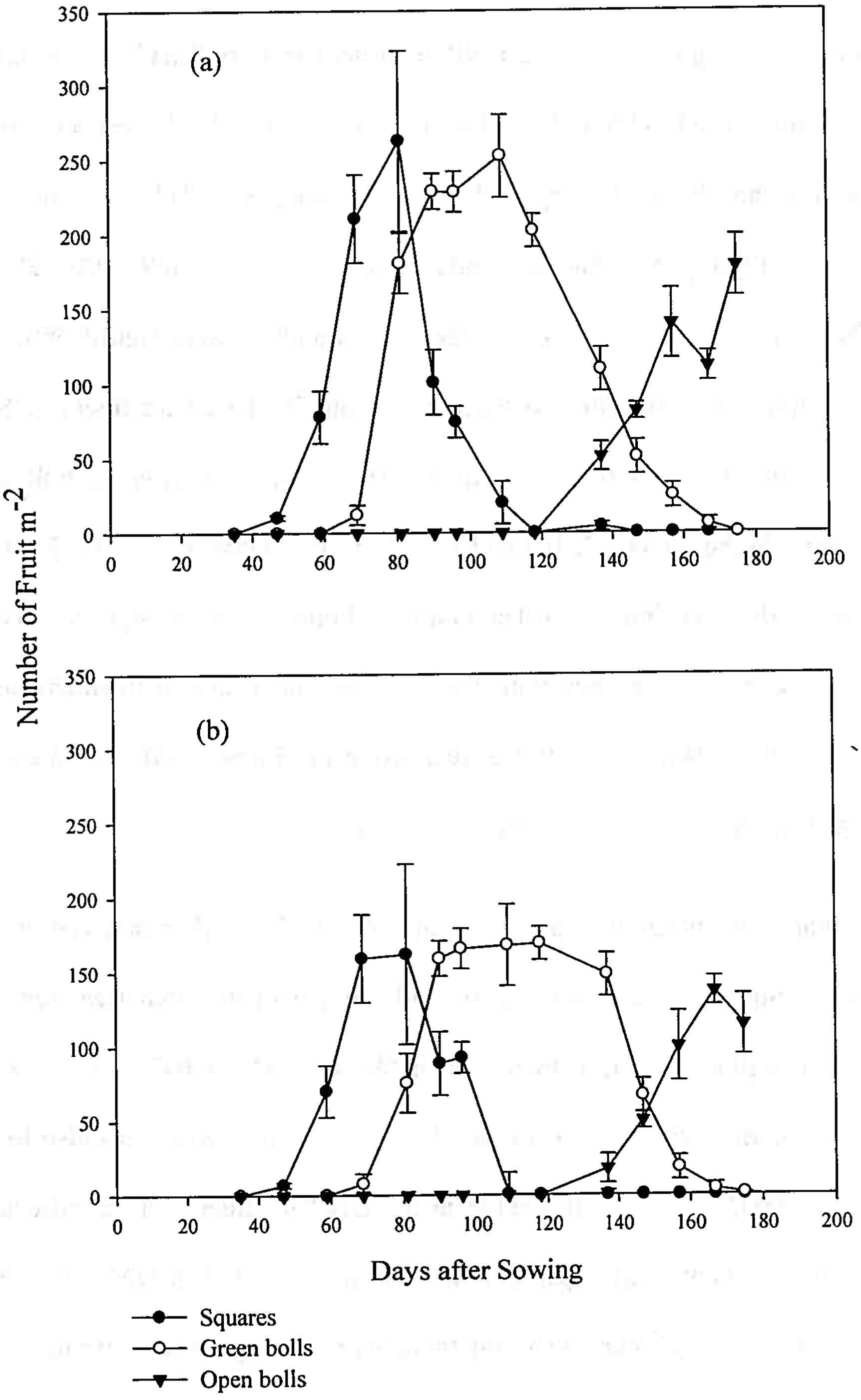

Figure 4.7 Mean numbers of squares, green bolls and open bolls versus days after sowing for UNR (a) and conventionally spaced (b) treatments in Exp. 1. Error bars are two standard errors of the mean.

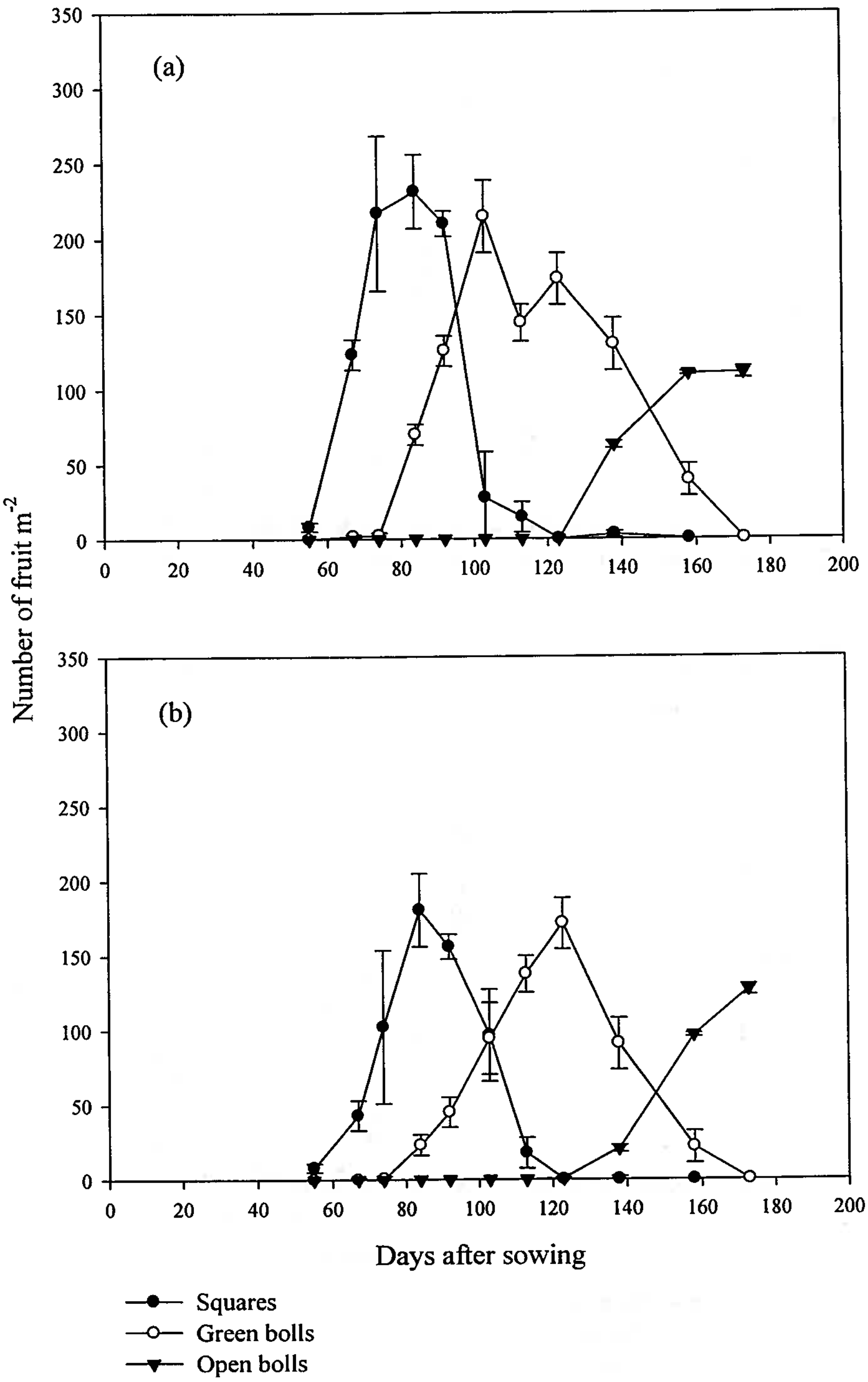

Figure 4.8 Mean numbers of squares, green bolls and open bolls versus days after sowing for UNR (a) and conventionally spaced (b) treatments in Exp. 2. Error bars are two standard errors of the mean.

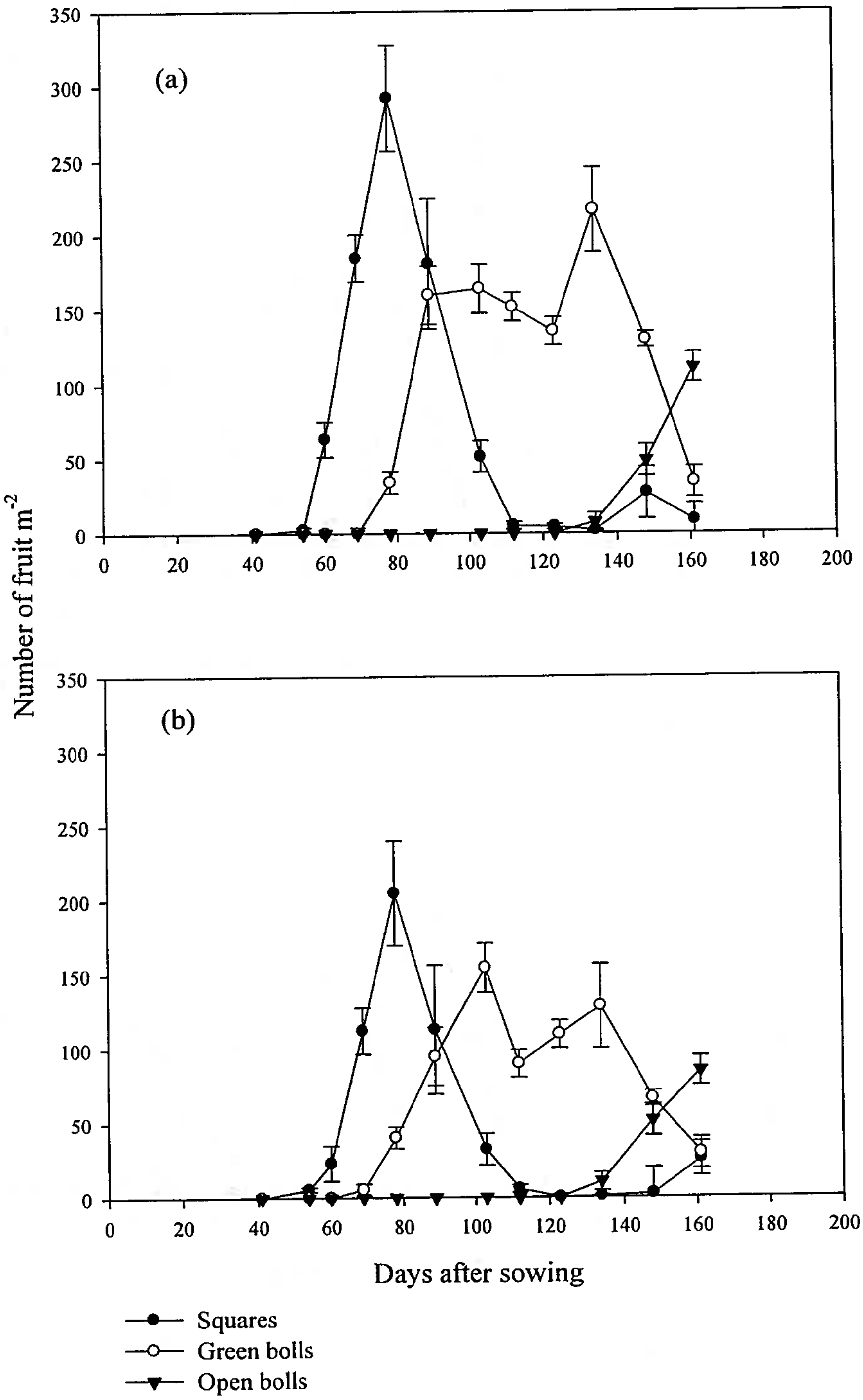

Figure 4.9 Mean numbers of squares, green bolls and open bolls versus days after sowing for UNR (a) and conventionally spaced (b) treatments in Exp. 5. Error bars are two standard errors of the mean.

Ratio of fruit to total above ground dry matter

The ratio of final fruit dry matter to total above ground dry matter was higher in the UNR treatments in Exp. 1, but there were no significant differences between row spacings in Exps. 2 and 5 (Table 4.6). A combined analysis for the ratio across the three experiments also showed no significant difference between row spacing treatments at the 5% confidence level, but the UNR treatment had a higher ratio than the conventionally spaced treatment at the 10% confidence interval ($P = 0.068$).

Table 4.6 Final fruit dry matter to total above ground dry matter ratio in UNR and conventionally spaced treatments for Exps. 1, 2 and 5 (Significant differences indicated by * = 95% confidence level)

Exp.	Conventionally Spaced	UNR	LSD
1	0.7282	0.7531	*0.0241
2	0.6711	0.6761	0.0676
5	0.5920	0.6170	0.0813

4.4.5 Crop growth rates

Average crop growth rate was higher early in the season in the UNR treatments compared to the conventionally spaced treatments in all three experiments (Figure 4.10). However, the increase in growth rate (gradient) was not very different between row spacings except for a slightly more rapid increase in crop growth rate in Exp. 5 for the conventionally spaced treatment (Fig 4.10c). Peak crop growth rate was slightly higher in the conventionally spaced treatments in each experiment although only marginally; however, peak fruit growth rate was higher in conventionally spaced treatments in Exps. 1 and 5.

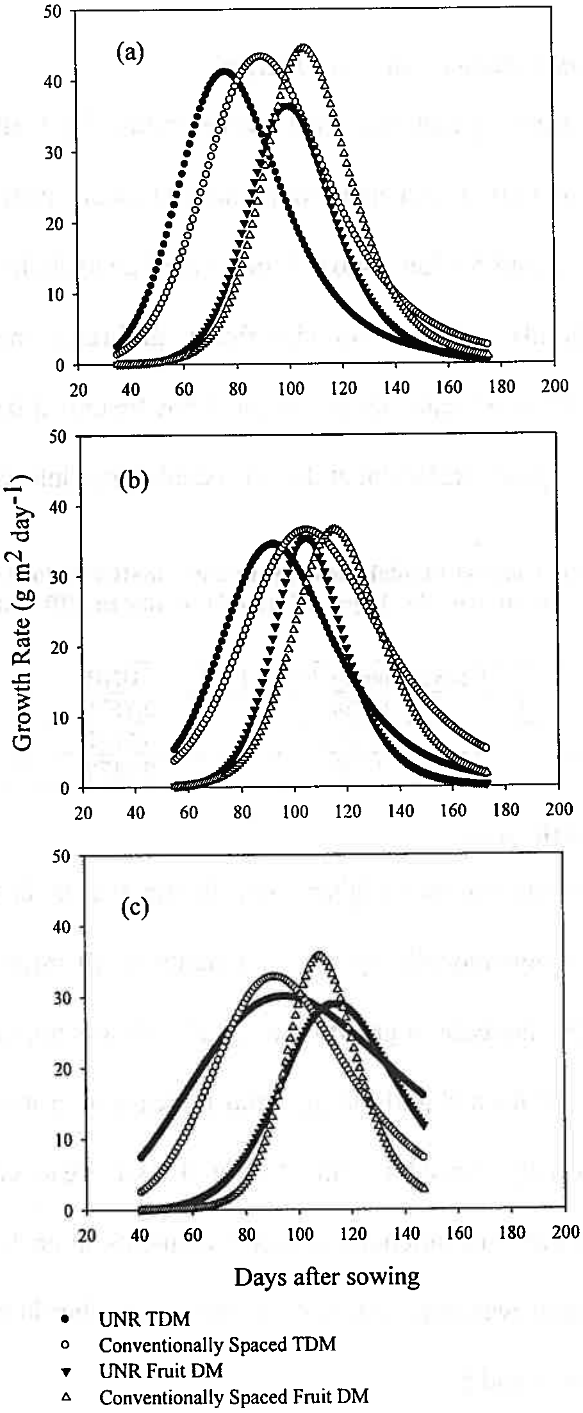

Figure 4.10 Estimated mean crop growth rates versus days after sowing for UNR and conventionally spaced treatments in Exps. 1 (a), 2 (b) and 5 (c).

4.4.6 Partitioning

As no differences were found in timing of production of either fruit dry matter or total dry matter, distribution ratios were used to examine differences in partitioning between row spacings for all three experiments.

There were some significant differences in fruit distribution ratios (DR) between row spacing treatments in the three experiments (Figure 4.11). In Exp. 1 the UNR treatments partitioned significantly more of the current increment of dry matter to fruit than the conventionally spaced treatments at early squaring 47 DAS ($P = 0.005$). In Exp. 2 the UNR treatments partitioned significantly more of the current increment of dry matter to fruit than the conventionally spaced treatments at early squaring 67 DAS ($P = 0.042$) and early boll set 84 DAS ($P = 0.001$). In Exp. 5 the conventionally spaced treatments partitioned significantly more of the current increment of dry matter to fruit than the UNR treatments at peak green boll numbers 103 DAS ($P = 0.021$).

When DR for UNR treatments was compared to DR for conventionally spaced treatments, the regression of the slope for Exps, 1 and 5 was significantly different from unity ($P < 0.001$; $P < 0.05$ respectively) but not for Exp. 2 (Figure 4.12). An analysis of covariance showed no significant differences between the three experiments so a regression of the data from all three experiments was performed. This had a slope of 0.66, which was significantly different from unity ($P < 0.001$).

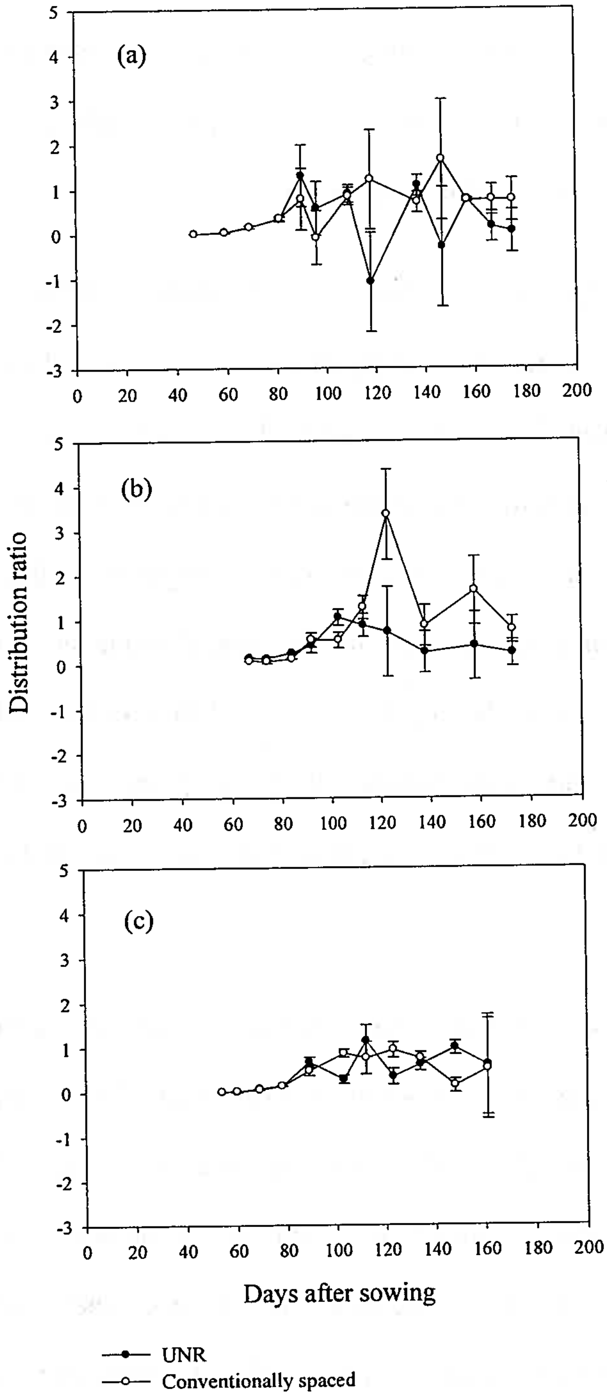

Figure 4.11 Mean distribution ratios versus days after sowing for UNR and conventionally spaced treatments in Exps. 1 (a), 2 (b) and 5 (c). Error bars are two standard errors of the mean.

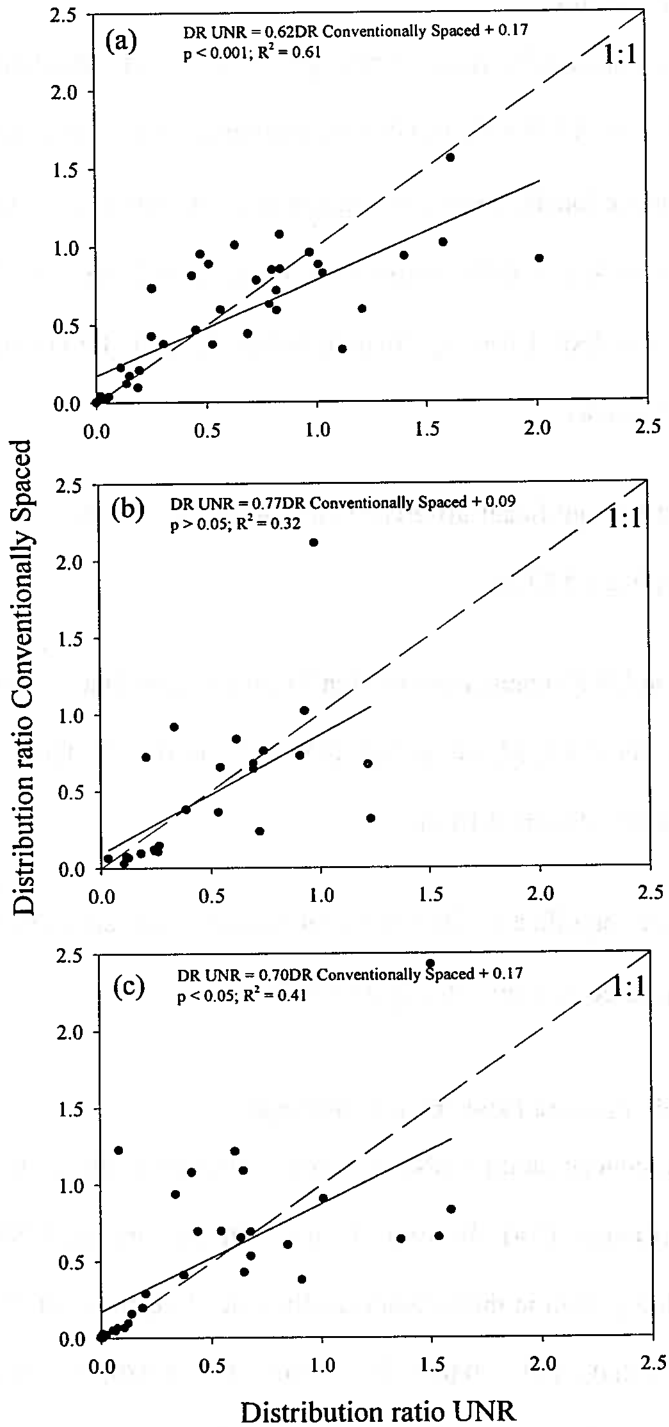

Figure 4.12 Comparison of distribution ratios (DR) between UNR and conventionally spaced treatments in Exps. 1 (a), 2 (b) and 5 (c).

4.4.7 Leaf area index

Responses of leaf area index (LAI) to row spacing were not consistent across the three experiments (Figure 4.13). LAI in UNR treatments in Exp. 1 was significantly higher than LAI in conventionally spaced treatments at 35, 47, 69 and 96 DAS ($P = 0.035$; $P = 0.018$; $P = 0.013$; $P = 0.001$ respectively) (Figure 4.13 a). At 137 DAS LAI for UNR treatments in Exp. 1 was significantly lower than LAI for conventionally spaced treatments ($P = 0.038$).

Exp. 2 showed no significant differences in LAI between row spacings at any of the harvest dates (Figure 4.13 b).

In Exp 5 LAI in UNR treatments was significantly higher than LAI in conventionally spaced treatments at 41, 54, 60 and 69 DAS ($P = 0.013$; $P = 0.016$; $P = 0.014$; $P = 0.039$ respectively) (Figure 4.13 c).

There were few significant differences in specific leaf area (SLA) between row spacings in the three experiments (Appendix 3).

4.4.8 Leaf nitrogen and specific leaf nitrogen

Leaf nitrogen concentration (%N) was not consistently different across the three experiments (Figure 4.14). In Exp. 1, leaf nitrogen in the UNR treatment was significantly lower than in the conventionally spaced treatment at 35, 59, 69, 118 and 137 DAS ($P = 0.024$; $P = 0.011$; $P = 0.001$; $P = 0.030$; $P = 0.008$ respectively) (Figure 4.14a). In Exp. 2, leaf nitrogen in the UNR treatment was significantly lower than in the conventionally spaced treatment at all harvests except 84, 103, 113 and 138 DAS (Figure 4.14b). The only difference in leaf nitrogen concentration in Exp. 5 was significantly lower leaf nitrogen in the UNR treatment at 89 DAS ($P = 0.023$) (Figure 4.14c).

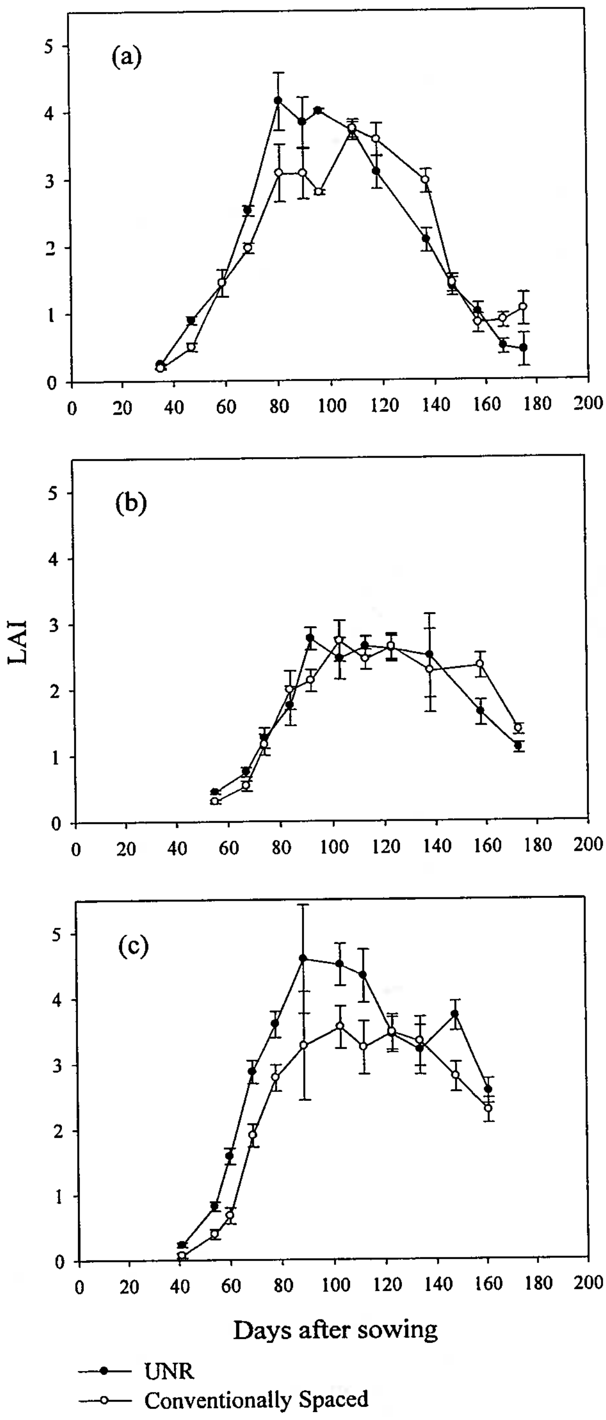

Figure 4.13 Mean LAI versus days after sowing for UNR and conventionally spaced treatments in Exps. 1 (a), 2 (b) and 5 (c). Error bars are two standard errors of the mean.

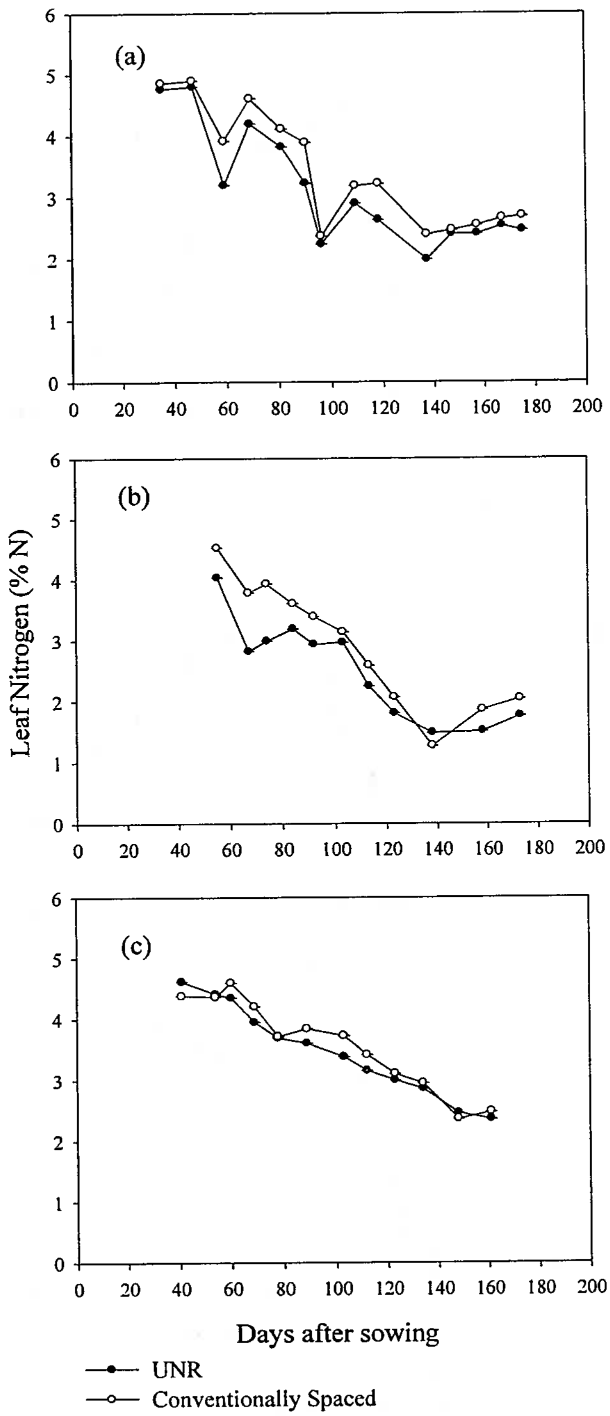

Figure 4.14 Mean leaf nitrogen versus days after sowing for UNR and conventionally spaced treatments in Exps. 1 (a), 2 (b) and 5 (c). Error bars are two standard errors of the mean.

Differences in specific leaf nitrogen (SLN) between row spacings were not consistent across the three experiments (Figure 4.15). Although SLN was consistently numerically higher in the conventionally spaced treatments, there were few significant differences in SLN. This may have been influenced by high variability in leaf area. A regression analysis comparing SLN in conventionally spaced treatments with SLN in UNR treatments showed a tendency for SLN in UNR treatments to reach lower values than the conventionally spaced treatments in Exps. 1 and 5 ($P < 0.001$) (Figure 4.16). In Exp. 2, however, there was no difference between treatments. No combined analysis was performed as an analysis of covariance showed that the SLN relationship differed significantly across experiments.

4.4.9 Nutrient uptake

Differences in nutrient uptake between row spacing were not consistent, however, all levels of nutrient uptake measured were all non-limiting for a high yielding cotton crop in Australia (Appendix 4).

4.4.10 Total crop water use for Exps. 2 and 5

Crop water use was not measured in Exp. 1 and there were no significant differences in total crop water use in Exps. 2 or 5. Average total crop water use in Exp. 2 was 696 mm for the UNR treatment and 603 mm for the conventionally spaced treatment (S.E. = 17.5 mm; $P = 0.063$). Average total crop water use in Exp. 5 was 678 mm for the UNR treatment and 674 mm for the conventionally spaced treatment (S.E. = 47.5 mm; $P = 0.960$).

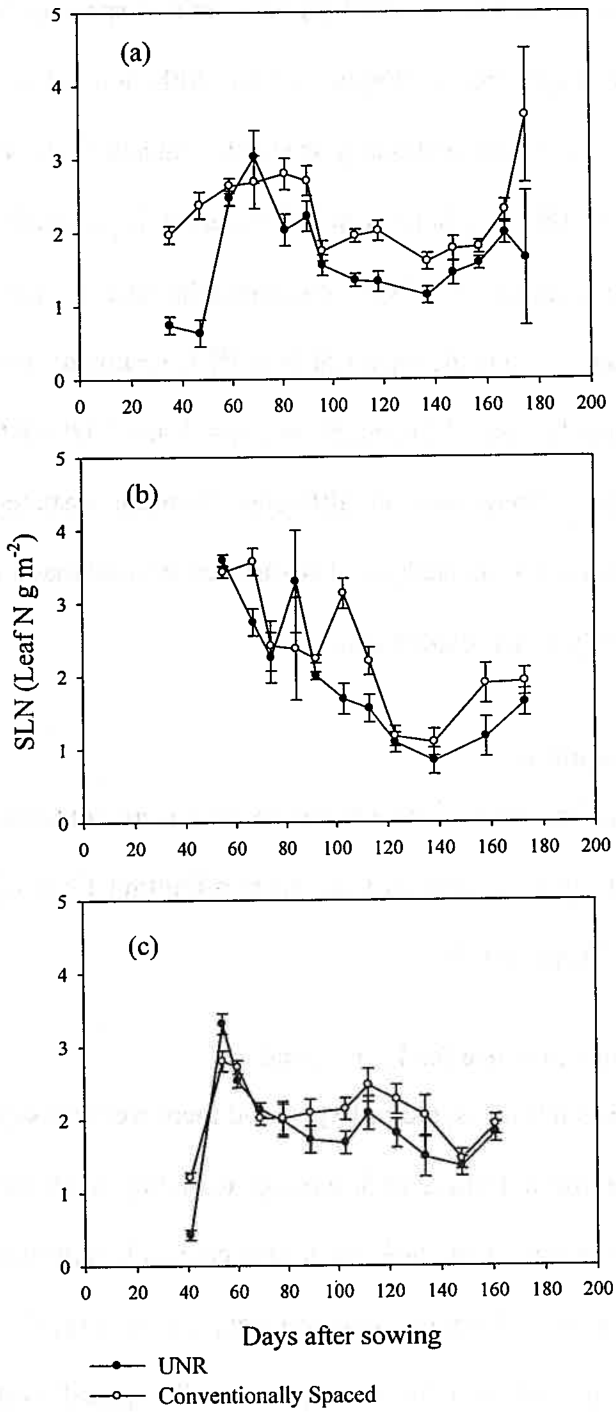

Figure 4.15 Mean specific leaf nitrogen versus days after sowing for UNR and conventionally spaced treatments in Exps. 1 (a), 2 (b) and 5 (c). Error bars are two standard errors of the mean.

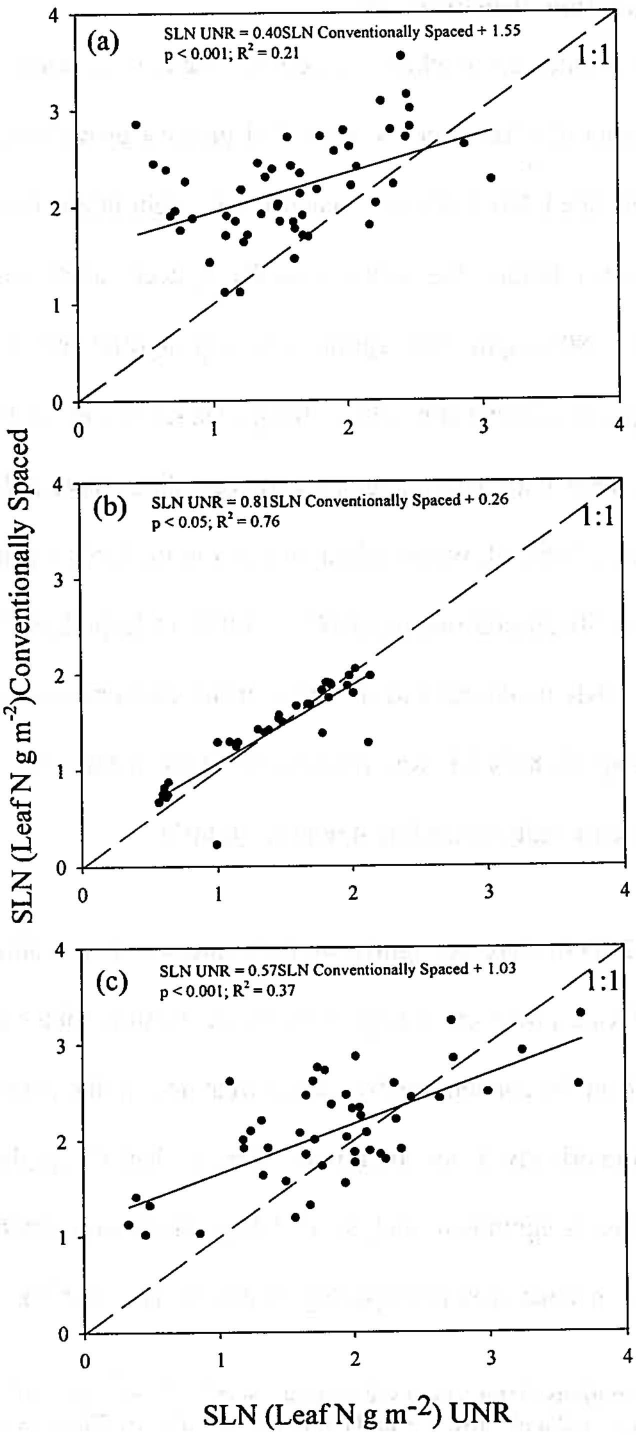

Figure 4.16 Comparison of specific leaf nitrogen between UNR and conventionally spaced treatments in Exps. 1 (a), 2 (b) and 5 (c).

4.4.11 Solar radiation measurements

The proportion of intercepted photosynthetically active radiation (LI_I) was derived from measurements of PAR over the period of greatest growth (Figure 4.17). In all three experiments, the UNR treatments reached 80% light interception (approximation of canopy closure) before the conventionally spaced treatments (Figure 4.17). However, DAS to 80% light interception was only significantly earlier in the UNR treatments compared with the conventionally spaced treatments in Exps. 1 and 5. Due to technical problems with data loggers, solarimeter data converted to PAR was used in Exp 1. In Exp. 1, 80% LI_I was reached 54 DAS in the UNR treatment and 89 DAS in the conventionally spaced treatment ($P = 0.007$). In Exp. 2, 80% LI_I was reached 77 DAS in the UNR treatment and 82 DAS in the conventionally spaced treatment ($P=0.138$). In Exp. 5, 80% LI_I was reached 62 DAS in the UNR treatment and 73 DAS in the conventionally spaced treatment ($P=0.001$).

In Exps. 1 and 2 there were no significant differences in total cumulative intercepted solar radiation CLI_D, however, in Exp. 5 the UNR treatment intercepted significantly more radiation than the conventionally spaced treatment in the period of measurement (Table 4.7). Numerically UNR treatments had higher CLI_D than conventionally spaced treatments. A combined analysis of CLI_D across experiments did not show a significant difference between row spacing treatments ($P = 0.298$).

Table 4.7 Total cumulative intercepted solar radiation in UNR and conventionally spaced treatments for Exps. 1, 2 and 5 (SE = Standard Error Significant differences indicated by * = 95% confidence level) (period covered in this analysis indicated by DAS for each Exp.)

Exp.	Conventionally Spaced	UNR	SE
1 (118 DAS)	1376	1847	235.7
2 (123 DAS)	1583	1695	35.4
5 (112 DAS)	2346	2576	*42.4

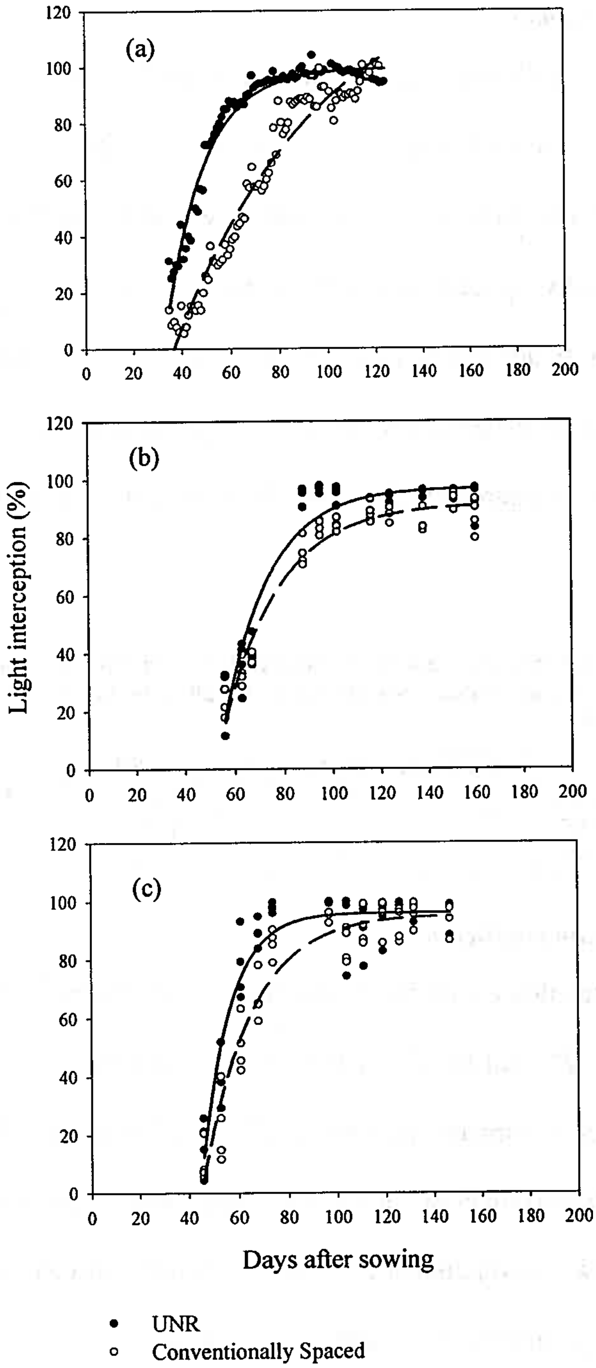

Figure 4.17 Proportion of intercepted photosynthetically active radiation (LI_I) versus days after sowing for UNR (solid line) and conventionally spaced (broken line) treatments in Exps. 1 (a), 2 (b) and 5 (c).

4.4.12 Radiation use efficiency and light extinction coefficient

Radiation Use Efficiency

Crop radiation use efficiency (RUE) was derived from the slope of the linear regression of cumulative total dry matter versus cumulative intercepted total solar radiation (Figure 4.18). RUE was significantly lower in the UNR treatment compared to the conventionally spaced treatment in Exp. 1, but there was no significant difference between treatments in Exps. 2 and 5 (Table 4.8). A combined analysis of RUE across the three experiments showed a significantly lower RUE in the UNR treatments (1.030) compared to the conventionally spaced treatments (1.231) ($P < 0.001$).

Table 4.8 Radiation use efficiency (g total dry matter MJ^{-1}) in UNR and conventionally spaced treatments for Exps. 1, 2 and 5 (SE = Standard Error Significant differences indicated by * = 95% confidence level)

Exp.	Conventionally Spaced	UNR	SE
1 (118 DAS)	1.586	1.193	*0.077
2 (123 DAS)	1.132	1.053	0.028
5 (112 DAS)	0.975	0.845	0.095

Crop light extinction coefficient

The crop light extinction coefficient k was significantly higher in the UNR treatments in Exps. 1 and 2 ($P = 0.016$; $P = 0.001$ respectively) but there was no significant difference between treatments in Exp. 5 ($P = 0.577$) (Figure 4.19). A combined analysis of the relationship between LI_I and LAI showed a significantly higher k in the UNR treatments ($k = 0.81$) compared to conventionally spaced treatments ($k = 0.69$) across all three experiments ($P = 0.009$) (Figure 4.20).

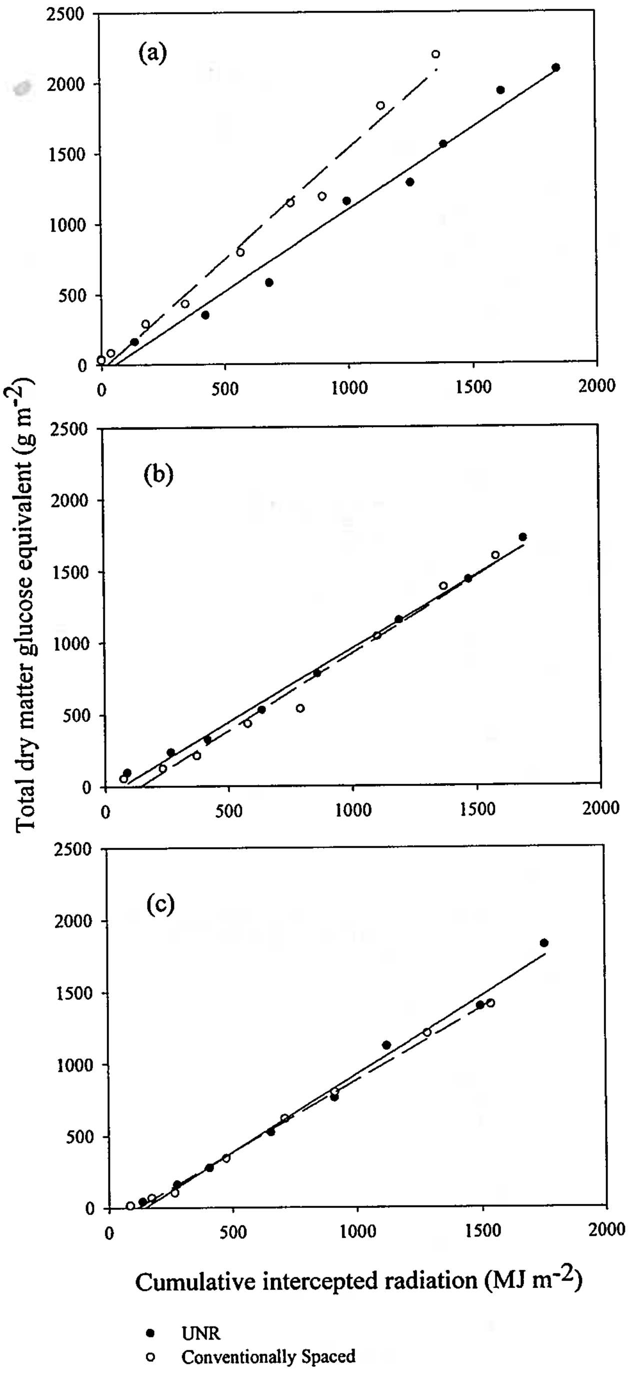

Figure 4.18 Relationship between total dry matter and cumulative intercepted solar radiation for UNR (solid line) and conventionally spaced (broken line) treatments in Exps. 1 (a), 2 (b) and 5 (c).

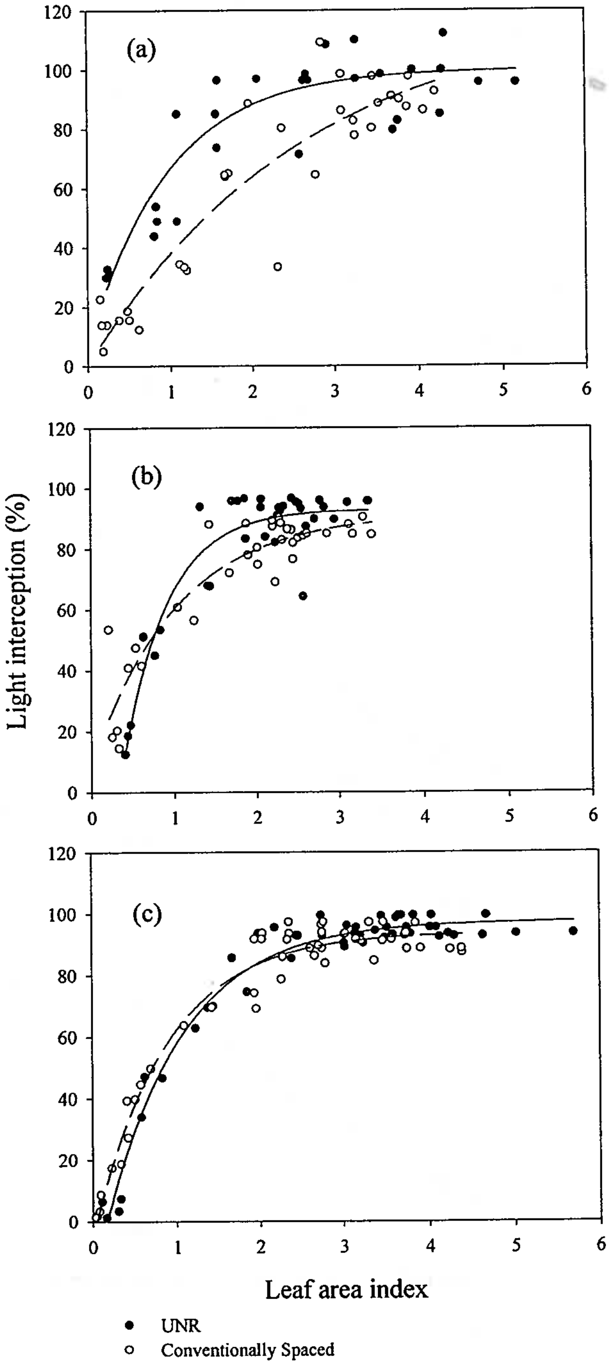

Figure 4.19 Relationship between light interception and leaf area index for UNR (solid line) and conventionally spaced (broken line) treatments in Exps. 1 (a), 2 (b) and 5 (c).

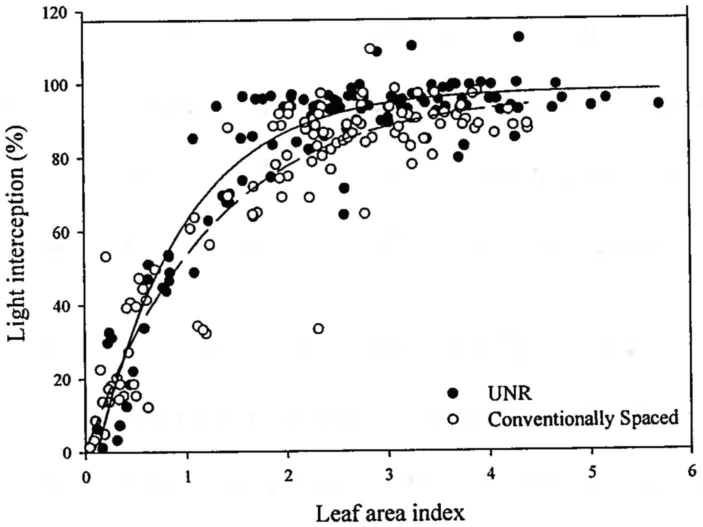

Figure 4.20 Relationship between light interception and leaf area index for UNR (solid line) and conventionally spaced (broken line) treatments all data from Exps. 1, 2 and 5.

4.5 Discussion

The growth analyses of the three experiments presented in this chapter, showed few significant differences in crop biomass production in UNR and conventionally spaced cotton. The combined analysis of the three experiments showed the same trend to higher yields in UNR cotton compared to conventional row spacings as presented in Chapter 3. While there were no significant differences at a crop level in final and peak total dry matter between the two row spacings, the three-fold increase in plant numbers in the UNR treatments meant that dry matter production per plant was significantly reduced in the UNR treatments compared with the conventionally spaced treatments. Similar responses to high plant populations has been found in many other crops (Yoda *et al.* 1963) and is supported by other studies which have found that plant size decreases with increased plant populations in UNR spaced cotton crops (Jost and Cothren 2001; Vories *et al.* 2001; Marois *et al.* 2004; Nichols *et al.* 2004).

While generally there were few differences in the growth of different components, there was a trend in the UNR crop to higher early biomass production and fruit number at a crop level compared with the conventionally spaced crop. Later in the growth of the crop, there were few differences in biomass production of individual growth components, with no difference in final dry matter between the two row spacings. Leaf area development was also higher during early crop growth in two of the experiments, but there were few differences in LAI later in the season.

There was also a trend to higher number of squares and green bolls in the UNR crop early in fruit production; however, by the end of the season these differences were not as large. The decline in the number of fruit may indicate fruit loss or earlier "cut-out" of the UNR crop. This is supported by lower total plant fruit retention in the UNR treatments compared with the conventionally spaced treatments in the combined analysis of all the experiments in this study (Chapter 3). Other studies have also found that fruit retention is often lower in UNR crops compared with conventionally spaced crops (Constable 1975; Baker 1976). A smaller plant would be expected to stop producing new fruiting sites or "cut-out" earlier than a larger more vegetative plant (Lewis 1971).

Due to the increased number of plants, the UNR crop had a higher crop growth rate early, but this also stopped earlier than the conventionally spaced crop with little differences in peak growth rate. The growth rate curves for the two row spacings were essentially similar with the UNR crop being 10-20 days advanced in peak crop growth rate and fruit growth rate compared to the conventionally spaced crop.

This trend to differences between the two row spacings early in the season but not later in the season was most likely due to more rapid canopy closure and increased competition between plants for resources limiting the growth of plants in the UNR crop earlier than in the conventionally spaced crop. However, these differences were often within the error level of the experimental measurements.

Although increased biomass production was not significantly different between row spacings, there were some differences in partitioning of dry matter to fruit and vegetative parts of the crop between row spacings. While the ratio of final fruit dry matter to total above ground dry matter was higher in the UNR treatments in Exp. 1 and there were no significant differences between row spacings in Exps. 2 and 5, the combined analysis showed increased partitioning of final fruit dry matter to total above ground dry matter at the 10% confidence limit. It is difficult to determine a "true" indicator of partitioning of fruit to dry matter as this study did not collect senesced leaves or distinguish between the lint, seed or bract components of boll in biomass harvests. When the two treatments were compared on a common time basis (DR), UNR had greater distribution of dry matter to fruit compared to conventionally spaced cotton.

Increased partitioning to reproductive growth in UNR cotton has been reported by a number of researchers (Best *et al.* 1997; Jost and Cothren 2001). Best *et al.* (1997) found that as row spacing decreased partitioning to fruit increased but the lowest plant population (10 plants m^{-2}) had the highest harvest index. These results are not always consistent year to year as Jost and Cothren (2001) found increased partitioning in one year but not the following year. LAI exceeded 8 in the UNR crop that year, whereas in the previous year there were no differences in LAI between row spacings. Jost and Cothren (2001) concluded that soil type differences between the experiments led to excessive vegetative growth in UNR in the second year of their study. The three experiments in this study were on similar soils within 1 km of each other, so differences in soil type would not have been a factor in the differences in responses among the three experiments.

Yield components, particularly boll number and boll size, are an important part of partitioning. Although there were some differences in boll number over the growing season in the three experiments, there were no significant differences in final boll number (Chapter 3). There was a trend to higher boll number in the UNR treatments in each experiment and a combined analysis in showed that final total boll number was greater across the three experiments. It is important to note that these differences were not reflected in total fruit dry matter, indicating reductions in boll size. Final average boll size was reduced across experiments (Chapter 3). The increase in plant density in the UNR crop compensated for fewer bolls per plant with a slight increase in boll number, which was accompanied by a decrease in boll size. Smaller boll size in the UNR crop suggested that carbohydrate supply may not have been adequate to meet boll demand. This trend to higher boll number and greater partitioning to fruit in the UNR crop led to higher yield across the experiments. However, many of these differences were within the error of measurement in individual experiments.

The UNR plants were smaller, with less biomass was produced per plant indicating limitations in assimilates for growth due to the increased number of plants competing for resources in the UNR crop. Light, water and nutrients are limiting factors for crop growth and if competition between plants in the UNR treatments reduced the availability of these to individual plants, this would have limited their biomass production and growth. The amount of light available to the leaves is a key factor influencing assimilate production and hence growth of the crop (Mason 1922; Eaton and Ergle 1954; Guinn 1974; Guinn 1982). Along with light stress, water stress is one of the key reasons for delayed growth and early shedding of fruit. Adequate nitrogen is also critical for assimilate production and hence fruit retention and boll development (Hearn 1975a; Hearn 1975b; Longstreth and Nobel 1980; Jackson and Gerik 1990; Gerik *et al.* 1994). Analyses of total crop water use and nutrient uptake indicated that these were not limiting during the period of measurement in any of the experiments.

While water and nutrient status did not differ between the two row spacing treatments, the light environment did. The UNR treatments had higher early light interception and reached 80% light interception 35 days earlier than the conventionally spaced treatments in Exp. 1 and 11 days earlier than the conventionally spaced treatments in Exp. 5. There was no significant difference in early light interception in Exp. 2, however 80% light interception had to be estimated as there was missing data for this period in Exp. 2. Later in the season, however, there were few differences in total canopy LAI. This may explain why total intercepted solar radiation was not significantly different. Total cumulative intercepted solar radiation only differed significantly between row spacings in Exp. 5. However, there was a trend to higher total cumulative intercepted solar radiation in the UNR treatments compared with the conventionally spaced treatments.

Earlier canopy closure in UNR cotton crop means that light interception is higher earlier in the season compared to a conventionally spaced crop (Kerby *et al.* 1996b). Closer plant spacing means that plants do not need to be as large for the canopy to achieve maximum light interception. This means that the crop is potentially making greater use of the light available earlier in the season. Generally, this earlier canopy closure is due to the increased number of plants, not an increase in the growth of an individual plant in a UNR production system. However, greater yield is achievable through increased light interception only if additional growth is partitioned into reproductive structures.

While light interception was higher early in the season and there was numerically higher total cumulative intercepted solar radiation, the radiation use efficiency (RUE) of the UNR crop was lower in Exp. 1 and significantly lower in the combined analysis of RUE across the three experiments. However, the canopy light extinction coefficient (k) was higher in the UNR treatments. While a lower RUE indicated that the UNR treatment was less efficient in converting intercepted solar radiation into biomass production, the UNR crop intercepted more light at the same LAI levels compared to conventionally spaced treatments. Kreig (1996) found that UNR cotton had greater light interception per unit ground for the same LAI compared with conventionally spaced cotton.

It is most likely that increased k in UNR is associated with changes in canopy architecture due to change in plant structure with increased plant population. UNR plants tend to be shorter, with fewer nodes and fewer vegetative branches than conventionally spaced cotton (Jost and Cothren 2001; Vories *et al.* 2001; Marois *et al.* 2004; Nichols *et al.* 2004). UNR plants have a higher number of mature bolls on first positions, with few second or third position fruiting sites being initiated (Cawley *et al.* 1998). Although not measured in this study, fewer vegetative branches and columnar shaped plants indicate that a greater proportion of the canopy would be made up of main-stem leaves, which are larger and more planophile. A dense canopy with overlapping leaves may mean that although there was more light intercepted per unit LAI in the UNR treatments, the distribution of light in the canopy is poorer. As the

UNR and conventionally spaced treatments have different spatial arrangements and plant structure, difference in the light extinction coefficient (k) is likely due to differences in canopy architecture.

A higher k in the UNR crop, and hence, greater light capture at low LAI, did not increase final total biomass production most likely because of a compensating reduction in RUE. Higher k generates less uniform light distribution in the canopy so that overall conversion efficiency is reduced, especially at high LAI (Duncan *et al.* 1967).

Although peak LAI was not significantly different in the three experiments, LAI continued to develop after maximum LI_I had been reached, whereas in the conventionally spaced treatments peak LAI was more aligned with maximum LI_I. This means that the UNR crop was continuing to develop leaves that were not increasing light interception. Therefore, the higher k would have only been of benefit to the UNR crop before canopy closure, while light interception was still increasing. This might explain the tendency for greater fruit number in UNR, which in turn generates greater demand for assimilates from the fruit and higher partitioning to fruit. Elevated LAIs can be detrimental if the lower canopy causes excessive shading reducing assimilate production to support boll development (Hake *et al.* 1996).

The results of this study suggest that light interception and conversion may be the primary factors responsible for differences found between UNR and conventionally spaced crops. The higher k in UNR crops would be advantageous to light capture in early canopy development, generate greater earlier crop growth, and thus allow initiation of a greater number of fruit. However, the associated reduction in RUE would generate reduced crop growth at the higher LAI found after canopy closure.

Hence, the similar total final biomass of the two systems is a consequence of two compensating factors. Limitations in assimilates to individual plants in the UNR crop due to lower RUE and increased shading of the lower part of the canopy may also explain why boll size was smaller in the UNR treatments as boll size is related closely to carbohydrate supply, especially from nearby leaves. At a crop level, even though boll size was reduced in the UNR crop, the setting of more fruit may have stimulated enhanced partitioning to fruit. The ability of individual plants in the UNR and conventionally spaced crops to produce and retain fruit will be examined in Chapters 5 and 6.

4.6 Conclusion

The three experiments in 2001-02, 2002-03 and 2003-04 showed a trend to higher yields in UNR cotton compared to conventional row spacings and a combined analysis showed an average 13.1% increase across the three experiments. While early season growth, fruit production and light interception tended to be higher in the UNR crop this did not translate into greater final crop biomass production. However, there was a trend to greater partitioning of carbohydrates to fruit in the UNR crop. Biomass production per plant was lower in the UNR crop compared with the conventionally spaced crop indicating competition for resources between plants was limiting crop growth. Water and nutrients did not appear limiting for the period measured in these experiments. Differences in the light interception and conversion efficiency and their consequences on carbohydrate availability to individual plants at differing developmental stages were implicated as major factors affecting growth, fruit set, and yield differences between row spacing systems.