

A comparison of 1.0 m and 1.5 m row irrigated cotton water use efficiency, gross margins, yield and quality in Warren, NSW, Australia

Timothy M. Bartimote

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Abstract

Water is the most limiting input in irrigated cotton production. Compaction reduces access to the soil water resource and reduces soil health. Incorporating Controlled Traffic Farming (CTF) in 1.5 m row irrigated cotton improves water use efficiency (WUE). This investigation compared 1.0 m and 1.5 m row-spacing on cotton yield, fibre quality and WUE. The 1.5 m row-spacing cotton was hypothesised to have a similar gross margin and fibre characteristics but greater WUE and yield per plant through access to a larger soil water resource. This replicated study was conducted over two years (2013-14 and 2014-15) and had an RCB design with a field scale whole block experiment which contained nine replicates of 1.0 m and 1.5 m row treatments. The field scale whole block contained two large field blocks of 1.0 m and 1.5 m treatments. The 1.5 m cotton had a greater WUE by producing 0.09 more bales per ML. This reduced the irrigation requirement in the 1.5 m resulting in a higher gross margin than 1.0 m cotton (\$2658/ha and \$2466/ha, respectively). The 1m cotton out yielded the 1.5 m in both seasons by 1.8 bales/ha (16%) and 1.09 bales/ha (6%) respectively. Yield differences in the 1.0 m cotton were only achieved through an increase in inputs. Fibre quality was slightly better in 1.5 m cotton. The 1.5 m row-spacing, based on its capacity to improve WUE, is more suitable for water limited environments. Furthermore, CTF provides greater water use efficiency by minimising soil compaction.

Introduction

Water is essential for producing high yielding and high quality cotton and cotton is demanding in its water consumption requiring, on average, 5.2 ML/ha for peak production in Australia (Cotton Australia 2015). With the majority of the Australian cotton industry being water limited and changing climatic conditions indicating continued water scarcity, increased research into producing more cotton per unit of water has resulted. This approach is termed Water Use Efficiency (WUE) and is described by Howell (2000) as crop yield per unit of water use. Cotton crop yields would benefit from evaluation on bales produced per megalitre of water used, rather than on a per hectare basis (Roth *et al.* 2013).

In Australia water resource availability is highly variable due to the range of climates found across the country. The majority of Australia's runoff (65%) is positioned in three drainage partitions located towards the far-north of the country, associated with tropical/sub-tropical climates. However, the majority of irrigated cotton (96%) is situated within the Murray Darling Basin (southern Queensland and New South Wales) which accounts for a mere 6.1% of national runoff (Murray Darling Basin Authority 2015). Hence, the majority of Australia's irrigated cotton is concentrated where water resources are the most restricted (Chartres and Williams 2006; Roth *et al.* 2013).

Currently 16,660 GL of the 70,000 GL extracted in Australia is used in agriculture (Chartres and Williams 2006). In the 2011-12 season 14% (2231 GL) of this 16,660 GL was required to produce 4,240,000 bales (227 kg of lint per bale) of Australian cotton (Cotton Australia 2015). In general, the trend for Australian irrigated agricultural industries as a whole is increased water demand, highlighting that water availability is now the most limiting factor for not just cotton production (Chartres and Williams 2006; Roth *et al.* 2013), but agriculture in general.

Furthermore, irrigated agriculture will be integral to meeting demand if food production is to be doubled by 2050 (FAO 2009), as the challenge is to essentially produce more with less (Fraiture *et al.* 2007). The opportunity to grow crops close to their yield potential in areas which would otherwise be unable to, under rain fed conditions, is allowed for via irrigation. Hence, these crops primarily rely on irrigation water supply for optimal production (Howell 2000; Roth *et al.* 2013), meaning that in uncertain, or marginal, climatic conditions, minimising water losses is inextricably linked to production and profitability.

WUE involves the management of inputs and losses water. Inputs impact the volume of soil water contained within the profile (Roth *et al.* 2013). Characteristics such as porosity, bulk density and hydraulic conductivity affect a soils ability to hold water and a plant's ability to access it (Radford *et al.* 2000). Inputs consist of irrigation and rainfall. Utilising rainfall reduces the irrigation requirement and improves irrigation efficiency (Cull *et al.* 1981). The effectiveness of these events is a function of soil infiltration and evaporative demand. Each cotton plant in a linear row has access to a certain volume of soil water in the row and inter-row space. The volume available is dependent on the row-spacing configuration. Wider row-spacings allow for greater access of soil moisture per plant (Roche *et al.* 2006). However, plant available soil moisture is limited by destructive management practices such as uncontrolled traffic (Chan *et al.* 2006).

The Australian cotton industry is currently considering a transition to 1.5 m row-spacing. The 1.5 m row benefits WUE, soil health and enterprise integration. Plants have access to larger volumes of soil water which increases utilisation of rainfall while reducing irrigations. Low plant densities per hectare would assist in reducing water input requirements (Enciso-Medina *et al.* 2002; Brodrick *et al.* 2012b). Current practice involves uncontrolled traffic in fields.

This increases compaction and negatively impacts bulk density, mechanical impedance, porosity and hydraulic conductivity (Radford *et al.* 2000; Chan *et al.* 2006). The 1.5 m row-spacing enables Controlled Traffic Farming (CTF) where all machinery is driven on the same 3 m wheel tracks. Compaction is minimised to 15 – 20% of the total land area and allows for the soil structure to recover. Over time, water infiltration and root penetration will expand, demonstrated by an increase in yield (Tullberg 2000; Tullberg *et al.* 2007; Hamza and Anderson 2005; Antille *et al.* in press). The 1.5 m row-spacing enables enterprise integration through crop rotations with grains. Currently, 3 m is the factory standard wheel track width of a combine harvester. It is simpler for other machinery (e.g. pickers and spray rigs) to be adjusted to this track width than to adjust the combine. The combine is required during wheat harvest, the other major crop in a cotton rotation (Chan *et al.* 2006). Hence compaction is minimised on the entire farm all year round. The benefits of CTF are then experienced by all crops.

Conventional row-spacing in Australia is on 1.0 m rows (CRDC 2013). The reason being, that this was the width required for a mule to pass between crop rows with minimal trampling. Since then, multi-row cotton pickers have been arranged to fit this 1.0 m standard. Progressively plant breeding and cotton genetics followed suit and were evaluated on their ability to yield successfully in this configuration. CTF cannot be implemented in these systems as machinery would have wheels on a hill and a furrow in a 1.0 m row-spacing configuration (Masek *et al.* 2010) (Figure 1). Machinery implements would have to be offset to compensate for the three rows that would need to be picked in one run as opposed to the normal two. The centre for gravity would be quite high creating an engineering issue. Logistically this would become unnecessarily difficult (Tullberg *et al.* 2007), especially since 1.5 m wide row spacing accommodates for 3 m tracks comfortably.

In recent times other configurations have become increasingly more common (Clark and Carpenter 1992). These include Ultra Narrow Row (UNR) (< 0.4 m) and Narrow Row (0.75 m) (Roche *et al.* 2006). Row configurations influence yield, plant vigour as well as WUE (Figure 2). To determine the most suitable row spacing farm managers must consider a variety of factors. These include water availability, local climate, soil type and machinery logistics (Roth *et al.* 2013). Increasing or decreasing row spacing from the conventional 1.0 m can provide various advantages and disadvantages (Clark and Carpenter 1992). UNR and narrow row spacing reduces time to crop maturity (i.e. when the plant stops producing new fruit) and increases in yield per hectare (Brodrick and Bange 2010). This is important in regions where cotton seasons are particularly short (e.g. Riverina in NSW) (Jost and Cothren 2001; Brodrick *et al.* 2013). CTF can be implemented into a narrow row system but WUE is found to decrease with decreasing row-spacing, therefore it is not a suitable configuration for the water limited regions of northern NSW (Stone and Nofziger 1993). A substantial amount of research has been conducted on UNR and narrow row spacing in cotton (Clark and Carpenter 1992; Jost and Cothren 2001; Brodrick and Bange 2010; Brodrick *et al.* 2013). However little is known about the effect of 1.5 m row configurations on WUE, yield and fibre quality compared with conventional row spacing.

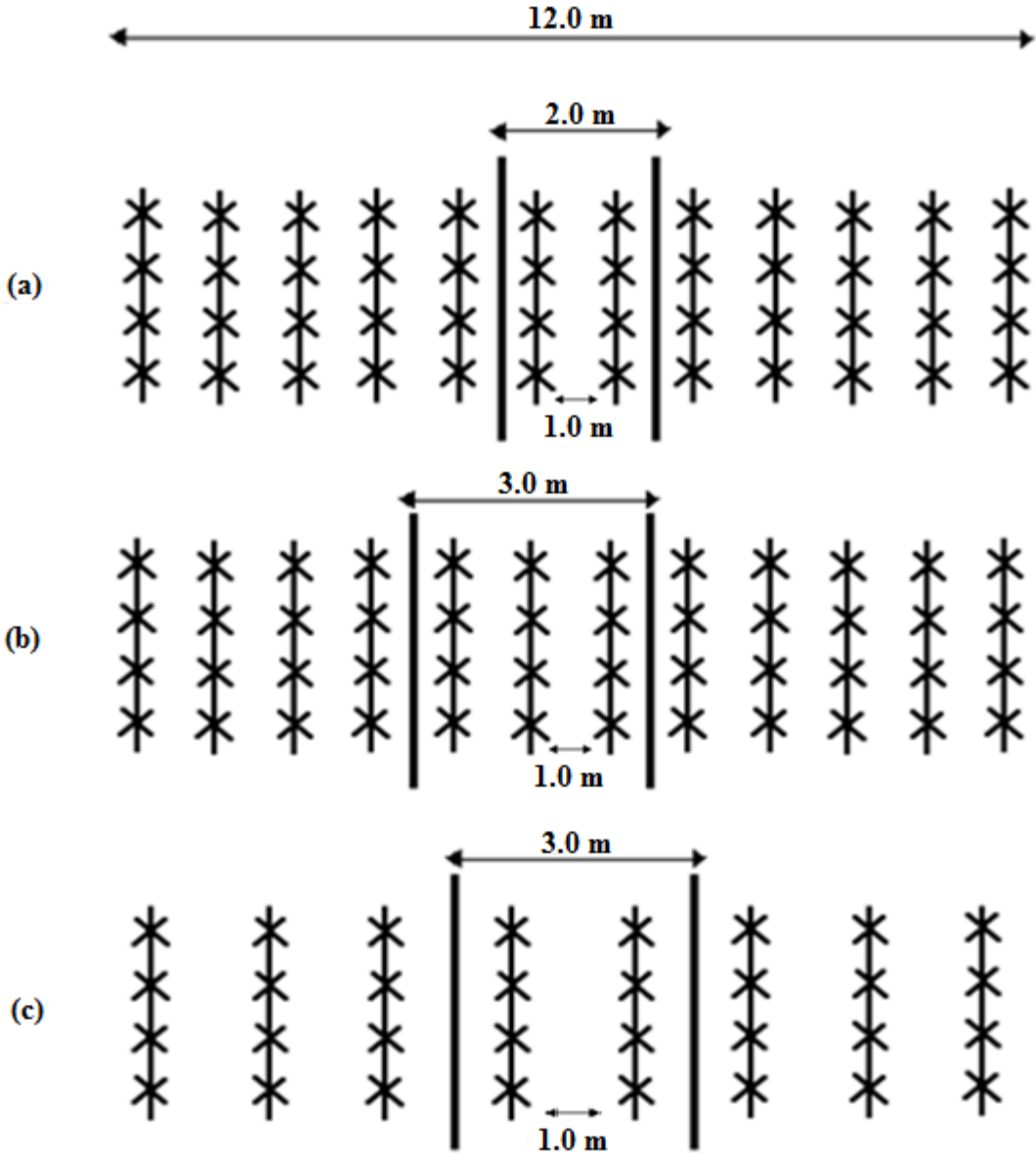


Figure 1. Cotton with 1.0 m row spacing and 2 m wheel tracks (a). 1.0 m row spacing with 3 m wheel tracks (b). Wide row (1.5 m) cotton with 3 m wheel tracks for CTF (c). Plant lines are expressed with x line.



Figure 2. Example of the difference in plant vigour and boll count of two cotton plants with different row spacings (50 cm rule). Left: 1.5 m, Right: 1.0 m

Hence, this investigation aims to assess the effects of 1.5 m row-spacing on cotton yield, fibre quality and WUE in comparison to the traditional 1.0 m row-spacing system. The primary hypothesis is: A 1.5 m row-spacing cotton system has a similar gross margin to 1.0 m row spacing cotton due to increased WUE, similar fibre quality and increased yield per plant in response to greater soil water resource access. In order to interrogate the aim, the following objectives must be met:

1. Compare water inputs and losses for 1.5 m and 1.0 m row-spacing cotton systems, including soil water balance resulting from infiltration differences
2. Assess cotton yield and fibre quality characteristics for the two systems
3. Economically compare the two systems with respect to production and profitability
4. Evaluate the potential differences in the systems due to changes in machine traffic footprint

Materials and Methods

The experiment was located at Auscott Warren (31.78° S 147.77° E, 195 m above sea level). Auscott Warren is situated 11 km south-west of Warren, NSW, Australia. This semi-arid region receives 513 mm of annual rainfall. Summers are characteristically hot (mean maximum temperature is 32.5°C) while winters exhibit slightly cooler conditions (mean maximum temperature is 16.3°C) (BOM 2015).

This replicated plot experiment comprised of a randomised complete block design (RCBD) which contained nine blocks (one replicate from each treatment in each block). An RBCD design reduces experimental error in field research by minimising variability by known sources. Randomisation occurs separately, each treatment has the same probability of being assigned to a particular block. This design included nine replicates each of 1.0 m and 1.5 m row treatments (Figure 3; Table 1) (Jayaraman 2015). The cultivar Sicot 74BRF was used and treatments ran the full length of the field. This experiment was conducted over two cotton growing seasons, 2013-14 and 2014-15.

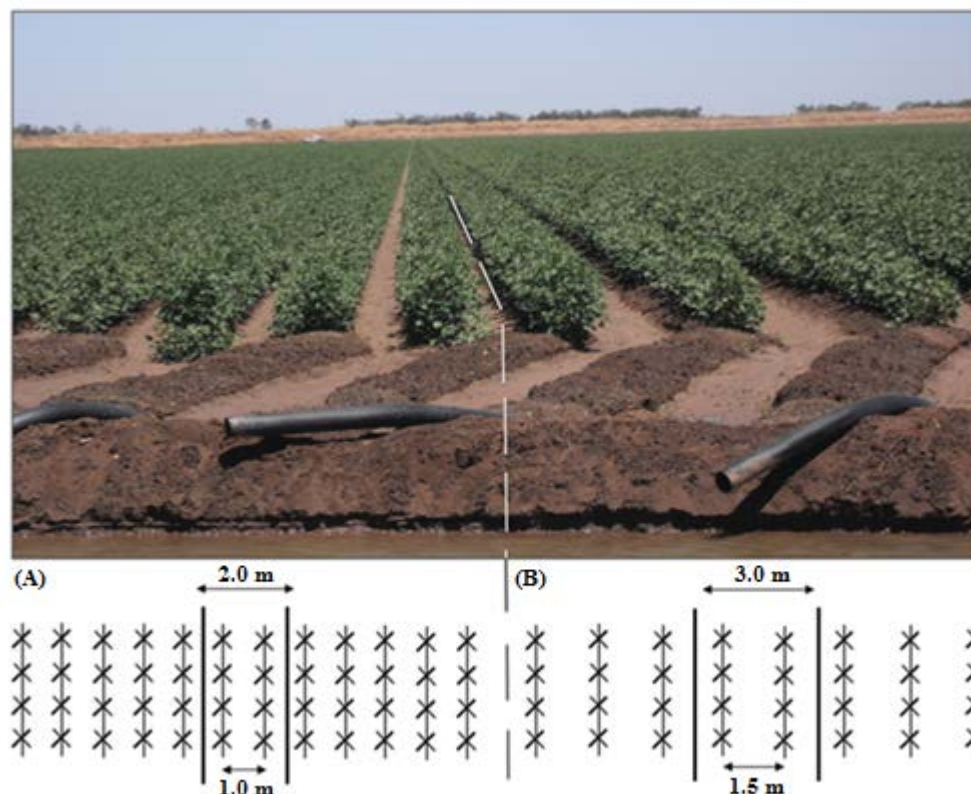


Figure 3. Cotton growing by system (top) and diagram representing these systems (bottom) by (A) 1.0 m row spacing and (B) 1.5 m row spacing. Lines with x represent plant line; vertical solid lines represent machinery wheel tracks.

Table 1. Experimental design and row configuration for row spacing experiment in 2014-15. (A) treatment represents 1.0 m row spacing. (B) treatment represents 1.5 m row spacing. (X) represent wheel tracks for spraying rigs. Blocks are 12 m in width with a 24 m buffer of wide row cotton on the southern border (top of Table).

Treatment	Replicate	AB line	Description	Swath width (m)	Cumulative (m)
B		0	Buffer	12	12
B		1	X Buffer	12	24
A	1	2	1.0 m	12	36
A	2	3	1.0 m	12	48
B	1	4	X 1.5 m	12	60
A	3	5	1.0 m	12	72
A	4	6	1.0 m	12	84
B	2	7	X 1.5 m	12	96
B	3	8	1.5 m	12	108
A	5	9	1.0 m	12	120
B	4	10	X 1.5 m	12	132
A	6	11	1.0 m	12	144
B	5	12	1.5 m	12	156
B	6	13	X 1.5 m	12	168
A	7	14	1.0 m	12	180
A	8	15	1.0 m	12	192
B	7	16	X 1.5 m	12	204
A	9	17	1.0 m	12	216
B	8	19	1.5 m	12	228
B	9	20	X 1.5 m	12	240

Soil gravimetric analysis

A gravimetric analysis was conducted in the 2014/15 season from three sites in each treatment to determine the initial volumetric soil water at the beginning of the season. Volumetric soil water was determined to a depth of 0.9 m at intervals of 0.1.0 m. Rows subjected to this practice were chosen at random in the top, middle and bottom sections of the field. Samples were oven-dried to determine soil dry weight. Bulk densities were obtained from Dr Patrick Holmes and in-field, Volumetric Soil Water (VSW) was calculated using the following formulae:

$$\text{Dry soil volume} = \frac{\text{Dry soil (g)}}{\text{Bulk density}}$$

$$\text{VSW} = \frac{\text{Water weight (g)}}{\text{Dry soil volume}}$$

The average accumulation of these values were used to determine the initial volumetric soil water in ML/ha for each treatment. This method assisted in confirming whether each treatment started with similar amounts of soil moisture.

Water balance

To determine the WUE of each treatment, net water was calculated in the 2014/15 season through measurement of water inputs and outputs (Figure 4). Water inputs included: irrigation applications and rainfall. Water outputs included: field evapotranspiration, deep drainage and run-off captured in the tail drain. The change in volumetric soil water throughout the season was also monitored in-field with a capacitance probe to make this method more rigorous. A single probe was installed to monitor this change for each treatment in a random row.

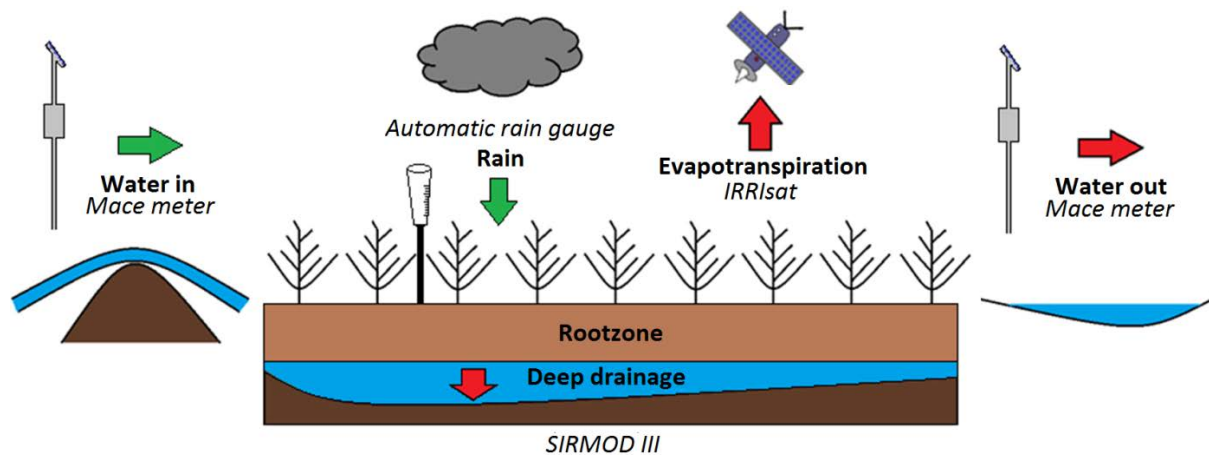


Figure 4. Diagram demonstrating the inputs and outputs of water in a cotton field as well as the methods which were used to measure them.

Irrigation occurred separately for each treatment. The amount of water added into the head ditch was measured using a flow meter on the inlet pipe (see ANCID 2015 for more information). Likewise there was another flow meter attached to the outlet pipe at the end of the head ditch which measured water which left the field.

An automatic rain gauge measured seasonal rainfall (October – April). Knowing that 1.0 mm of rainfall is equal to 0.01 ML/ha and the total area each treatment covered, the amount of water which entered the system was able to be calculated.

Evapotranspiration for cotton was determined through the formula:

$$ET_C = ET_O \times K_C$$

Where ET_C is the crop water requirement, K_C is the crop coefficient and ET_O is the standard value based on the ET of fully green alfalfa. IRRIsat (Figure 5) (see Montgomery *et al.* 2015 for more information), a program which utilises Normalised Difference Vegetation Index (NDVI) and Landsat 8, was used to determine K_C values. Evapotranspiration was determined for each treatment block. ET_O values were sourced from the nearby Trangie Research Station.

This information was available from the Bureau of Meteorology (BOM) who use the adapted Penman-Monteith equation recommended by the United Nations Food and Agriculture Organisation (FAO56-PM equation) (Webb 2010). In IRRIsat, ET_c values were determined for each replicate and an average was calculated for each treatment plot.

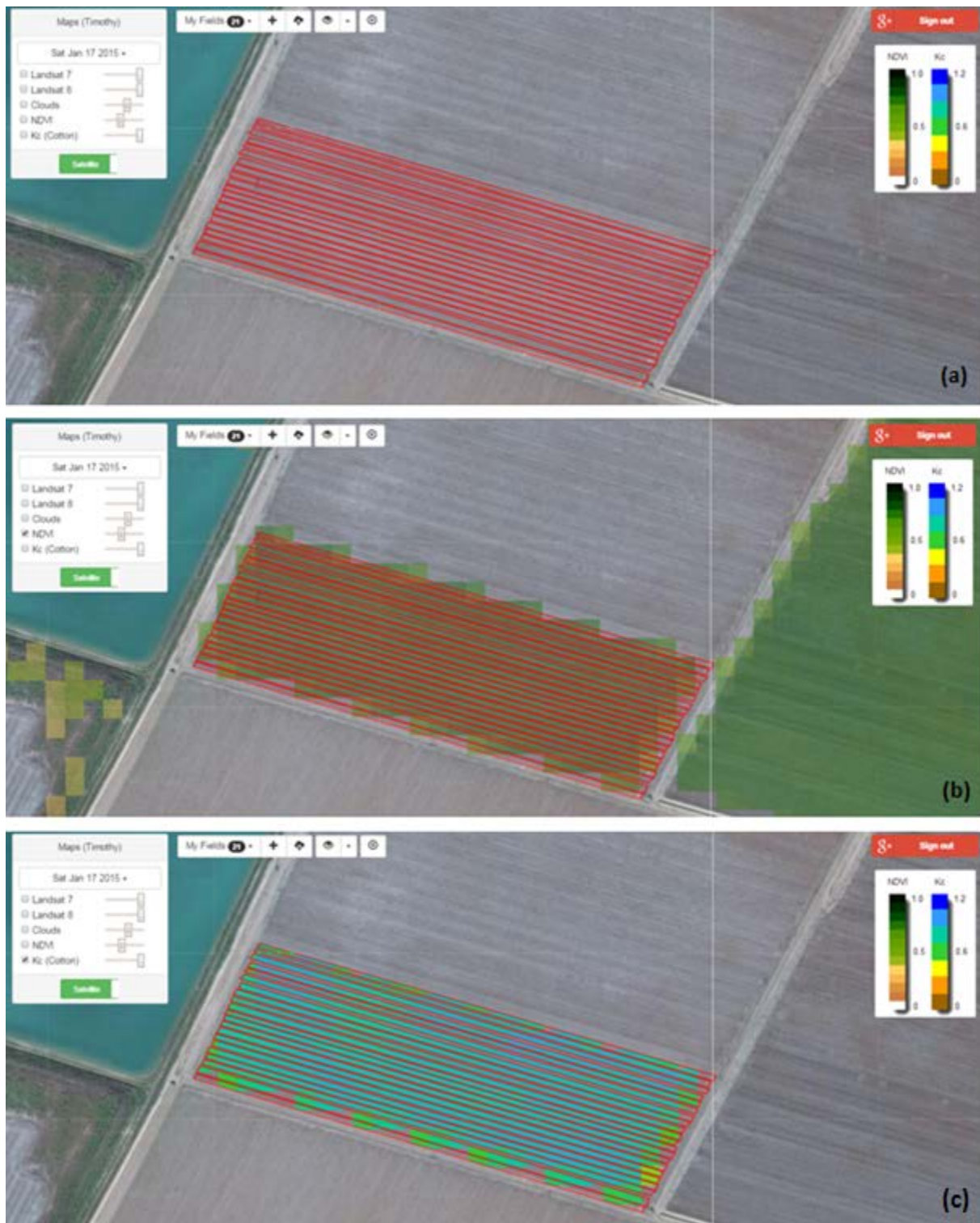


Figure 5. IRRIsat interface displaying Field 12 at Auscott Warren. (a) Evapotranspiration was measured separately for each treatment block. (b) IRRIsat provided NDVI for each treatment block. (c) Crop coefficient (K_c) was determined for each treatment block.

Deep drainage was estimated using a computer program called SIRMOD III (Walker 2003) on a single irrigation. The estimated deep drainage from the program was compared against

peer-reviewed studies conducted under similar conditions to determine the reliability of the data.

Hand segment picked cotton

Six individual linear metre rows were randomly selected from plots in each treatment to be handpicked. These samples were further separated into eight plant fruiting segments (Figure 6). Plant numbers were noted per linear metre while boll numbers were recorded per segment. These samples were processed in experimental gins at Cotton Seed Distributors (CSD), Wee Waa, where sample yield and quality characteristics were identified using the High Volume Instrument (HVI) (see Suh and Sasser 1996). Treatments were compared on a brown hectare rather than green hectare basis. Brown ha refers to the total area required to grow the 1.5 m cotton in hectares. Green ha refers only to the area occupied by plant rows and does not account for the additional inter-row space. This ensured a fair comparison considering the 1.5 m row spacing treatment had access to a larger area (1.5 m²) which would present data from this treatment more favourably. Handpicked yield data was obtained from Quigley (2014) which provided two years of data for analysis.

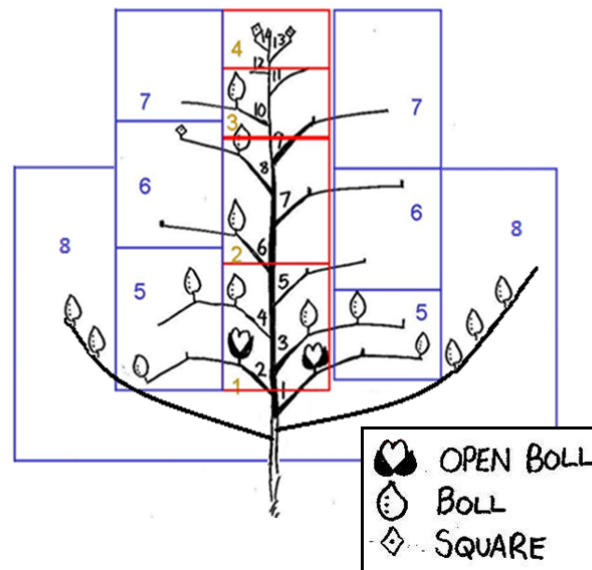


Figure 6. Segment picking diagram outlining cotton fruiting segments 1-8. (1) Mainstem fruiting nodes 1-4 position 1. (2) Mainstem fruiting nodes 5-8 position 1 (3) Mainstem fruiting nodes 9-12 position 1. (4) Mainstem fruiting nodes 13+ position 1. (5) Mainstem fruiting nodes 1-4 position 2+. (6) Mainstem fruiting nodes 5-8 position 2+. (7) Mainstem fruiting nodes 9+ position 2+. (8) Vegetative branches (identified by smooth stem on the other side of where a boll is formed)

Machine picked cotton

This in-field experiment occurred in an 18.42 ha paddock over two seasons. Each replicate was 12 m wide. The 1.0 m row configurations contained 12 rows of cotton while 1.5 m row configurations only contained 8 rows. A 24 m buffer zone occupied the southern border to reduce field edge effects on the results of the experiment. Cotton was planted at the opposite edge of the field for the 2013/14, but this was not present for the 2014/15 season. The 1.5 m cotton occupied 9.68 ha while the 1.0 m treatment occupied 8.74 ha. Each treatment was machine harvested separately and were ginned independently to provide an in-field broad scale comparison between 1.0 m and 1.5 m row spacing (Table 1). Data was utilised from Quigley (2014) which provided two years of yield data for Field 12.

Determining WUE

WUE was defined as the number of bales (227 kg) of cotton produced per megalitre of water (bales/ML). Once yield data per ha was acquired WUE could be determined using the total amount of ML/ha available for use by plants in each treatment.

Economic analysis

To compare the economic sustainability of the two cotton row configurations, a comprehensive gross margin (GM) analysis was created, which incorporated industry standard values for the Macquarie Valley. The response of each treatment's GM to increasing and decreasing water pricing was determined with a sensitivity analysis. This provided a theoretical response to increased variability in future water availability, which is the greatest influence on the price of water. Besides water, all other input costs and the price received for cotton seed was determined using the NSW DPI cotton gross margin template for furrow irrigated cotton in central and northern NSW (NSW DPI 2015).

Data analysis

Data from 2013-14 was analysed using a one-way analysis of variance (ANOVA) in Genstat V16 (see VSN International Ltd. 2015) for machine picked (227 kg bales/ha), handpicked yield, bolls/m², lint per boll, fibre strength and fibre length. Data from 2014-15 was analysed using a t-test to compare the difference between means in JMP 12 (see SAS Institute Inc. 2015) for handpicked yield, machine picked yield, bolls/m², lint per boll, fibre strength and fibre length. Linear regressions were fitted for lint yield, lint per boll (g), and number of bolls per m² for both 2013-14 and 2014-15.

Results

Water balance

The 1.0 m treatment experienced a deficit of 1.66 ML in net available water compared with the 1.5 m row spacing. The difference in water outputs (deep drainage and evapotranspiration) between the two treatments was minimal. The 1.5 m row spacing had greater initial soil water (by 1.0 ML) and captured more rainfall per unit of cotton, as it covered a large area than the 1.0 m row spacing. One linear metre of 1.5 m cotton occupied a 1.5 m² area while a linear metre of 1.0 m cotton only occupied a 1.0 m². However, the 1.0 m row spacing had a slight increase in applied irrigation. The 1.5 m row-spacing requirement was less per hectare to maintain crop productivity (Table 2).

Table 2. Total treatment inputs and outputs of the 2015 water balance in ML. Accounting for initial soil moisture and displaying total available water for each treatment in ML/ha.

Row spacing	1.0 m	1.5 m
Initial soil moisture (ML)	14.25	15.29
Rainfall (ML)	13.90	15.40
Irrigation input (ML)	184.89	202.40
Irrigation runoff (ML)	113.62	131.53
Deep drainage (ML)	1.31	1.45
Evapotranspiration (ML)	7.23	7.57
Net water (ML)	90.88	92.54
ML/ha	10.40	9.56

Water use efficiency

More water was available per hectare for the 1.0 m treatment (0.84 ML/ha) which resulted in a greater yield compared with the 1.5 m system. The 1.5 m row-spacing achieved a greater yield per ML. This equated to a slight difference in WUE (bales/ML) in favour of the 1.5 m row spacing (Figure 7).

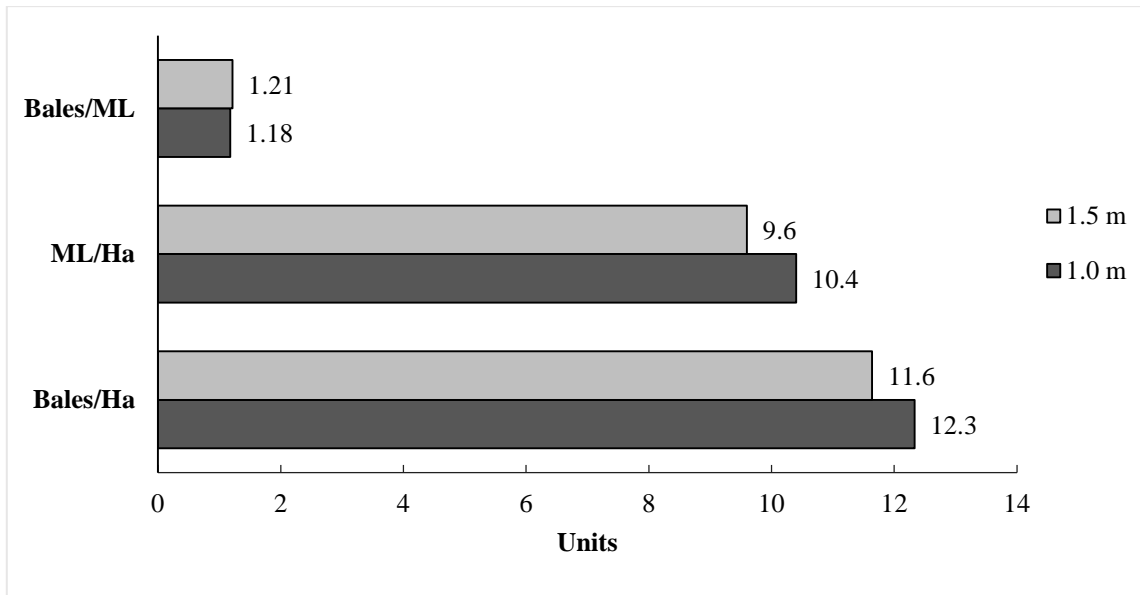


Figure 7. Difference between 1.5 m (light grey) and 1.0 m (dark grey) row spacing in cotton in bales/ML, total ML/ha and bales/ha (227 kg bales) when incorporating a full water balance (inputs and outputs).

When irrigation efficiency was compared based only on applied irrigation water there was a greater difference between 1.5 m and 1.0 m row spacing than in Figure 7 (Figure 8).

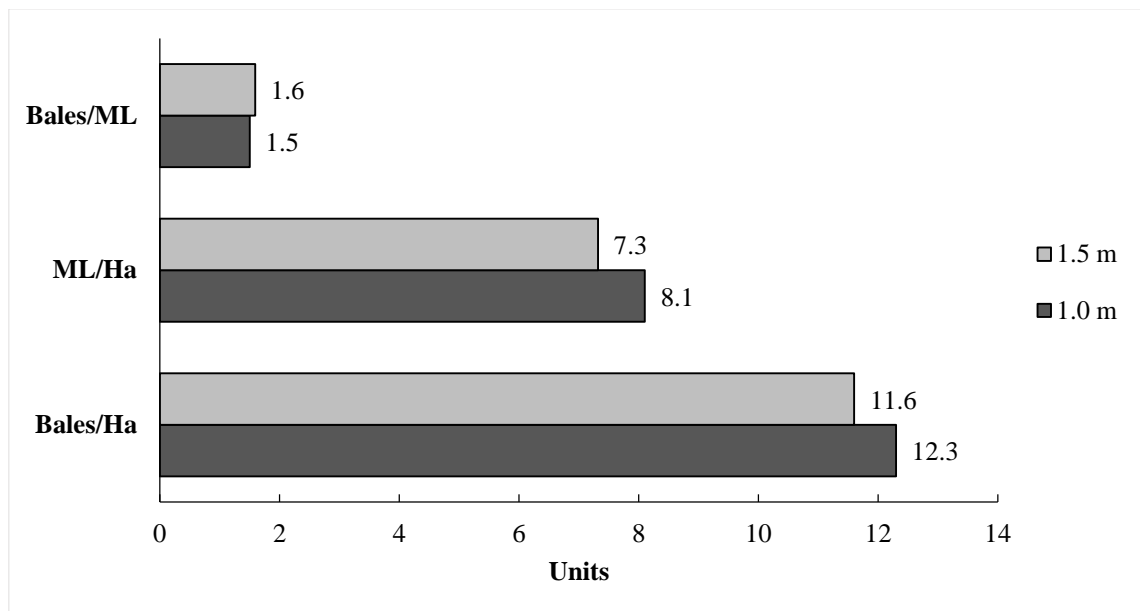


Figure 8. Difference between 1.5 m and 1.0 m row spacing in Bales/ML, ML/ha and bales/ha considering only applied irrigation water.

Machine picked and handpicked yields in the 2013-14 and 2014-15 seasons (in 227 kg bales)

In both the 2013-14 and 2013-14 seasons, 1.0 m row out yielded 1.5 m row cotton in both the machine picked ($P<0.001$) and handpicked field experiments ($P<0.001$) when compared on a brown ha basis (Figure 9). A 16% (2013-14) and 6% (2014-15) yield difference was observed in the machine picked fields. This equated to a reduced yield/ha for the 1.5 m row-spacing of almost 2 and 1 bale/ha, respectively compared with 1.0 m row. A similar trend was witnessed in the handpicked cotton with a 23% (2013-14) and 9% (2014-15) lower yield in the 1.5 m row compared with 1.0 m row. Both seasons (2013-14 and 2014-15) experienced below average (283 mm) in-season rainfall at 206 mm and 160 mm, respectively. Accumulative day degrees for the cotton growing season were 1814 °Cd (degree days) for 2013-14 and 1897°Cd for the 2014-15 season.

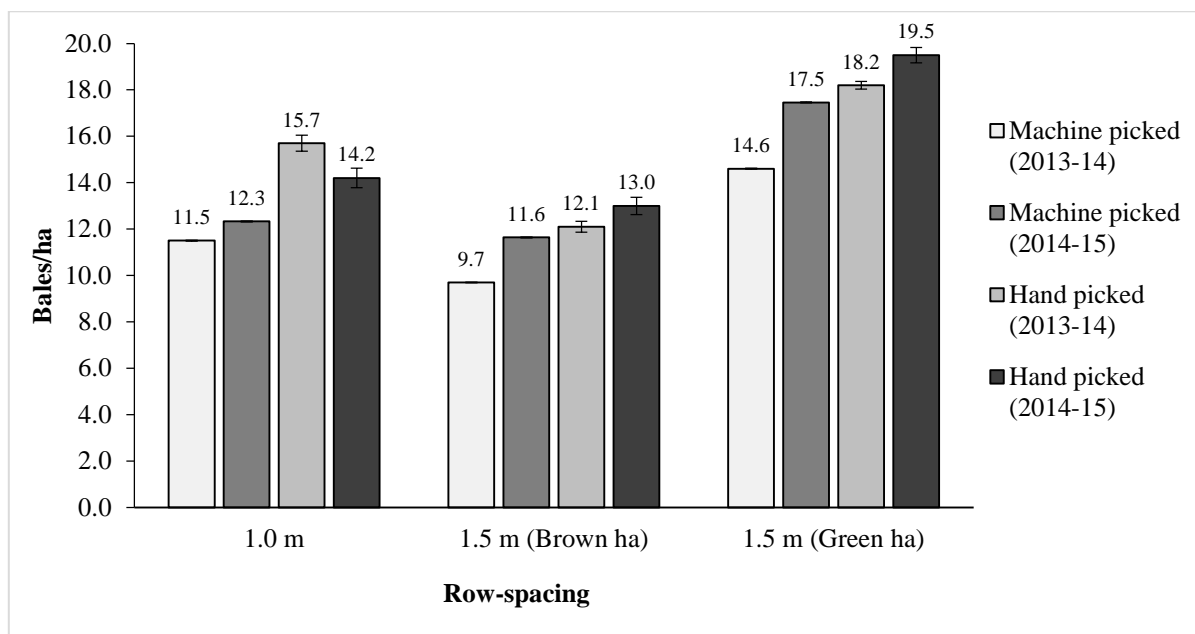


Figure 9. Cotton lint yields (227 kg bales) by machine and by hand from cotton grown on 1.5 m and 1.0 m row spacing in the 2013/14 and 2014/15 seasons. Brown ha refers to the total area required to grow the 1.5 m cotton in hectares. Green ha refers only to the area occupied by plant rows and does not account for the additional interrow space. Error bars represent standard errors of the mean. Some error bars are not visible due to low standard errors (below 0.02).

Figure 10 demonstrates the distribution of yield (2014-15) (bales/ha) across Field 12. Yield was affected by overflow from the tail drain during irrigations, which may have caused waterlogging. Hence the lighter colour at the bottom of the field.

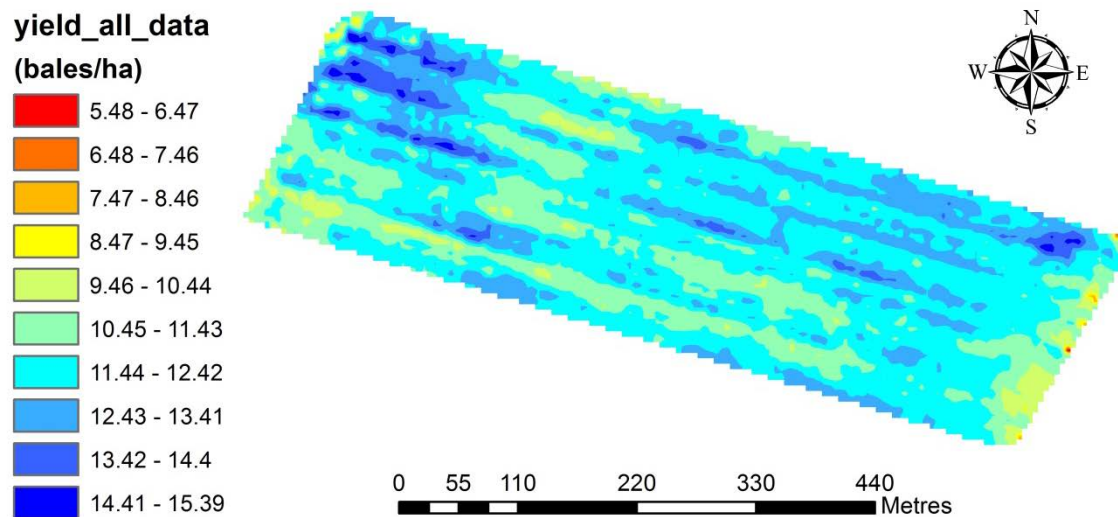


Figure 10. Yield map containing data from 2014-15 which includes both 1.0 m and 1.5 m row-spacings to demonstrate the distribution of yield amongst Field 12.

Economic analysis

The 1.5 m row cotton had a \$191.30/ha higher gross margin (GM) than 1.0 m row (\$2657.50/ha and \$2466.20/ha, respectively) at a cotton price of \$500/bale and water price of \$200/ML (industry average prices for the 2014-15 cotton season) (Figure 11). Water inputs were the most significant cost. The town of Warren, being located in the Macquarie Valley, Central West NSW, is a region with low water availability and inconsistent water allocations. A sensitivity analysis of each GM to variable water prices revealed that the 1.5 m cotton production system always had a greater GM than the 1.0 m cotton. The difference between the GMs increased with increasing water price.

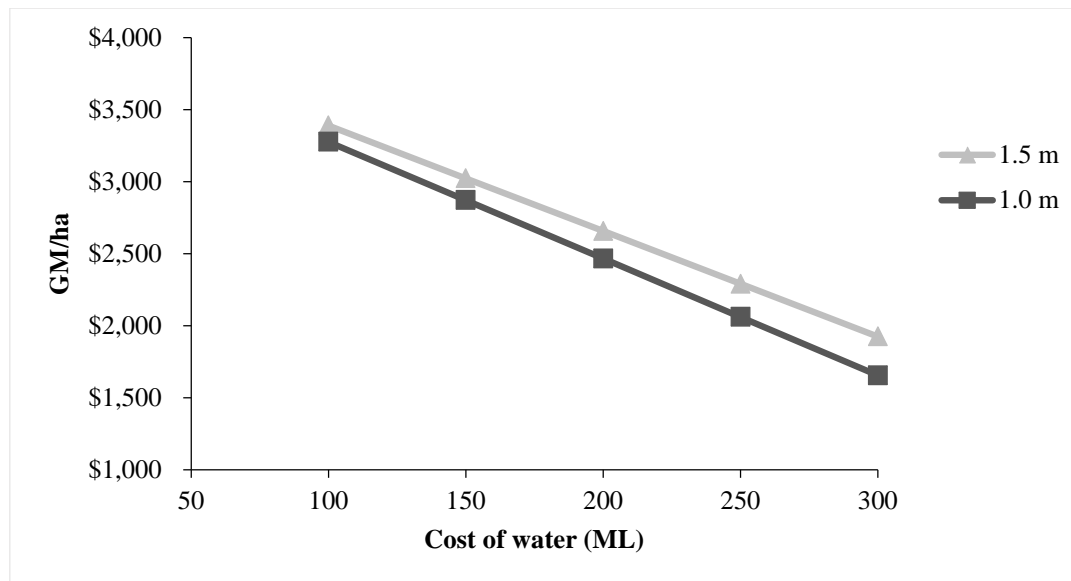


Figure 11. A sensitivity analysis demonstrating the sensitivity of gross margins to variable water prices in 1.5 m and 1.0 m cotton production systems. All other input and output prices remained constant (e.g. \$500/bale).

Segment picking (2013-14 and 2014-15)

The majority of the lint yield on the 1.0 m row spacing was found on fruiting positions 1-8 with some fruit on the lower vegetative branches. Yield on the 1.5 m row spacing was primarily established on the vegetative branches (Figure 12). The number of bolls per square meter for each fruiting segments follows this trend (Figure 13). There was an increased amount of vegetative fruit on the 1.5 m cotton in 2014-15. More cotton was found on 2nd pos+ in the 2013-14 season compared with the 2014-15 season.

The average weight of bolls in the first position from each fruiting segment was spread fairly evenly amongst both the 1.5 m and 1.0 m row spacing treatments. However, 1.5 m row spacing had slightly more lint in second position fruit in fruiting branches 1-12 (Figure 14). Boll numbers in 1.0 m row cotton were reduced in 2014-15 compared with 2013-14.

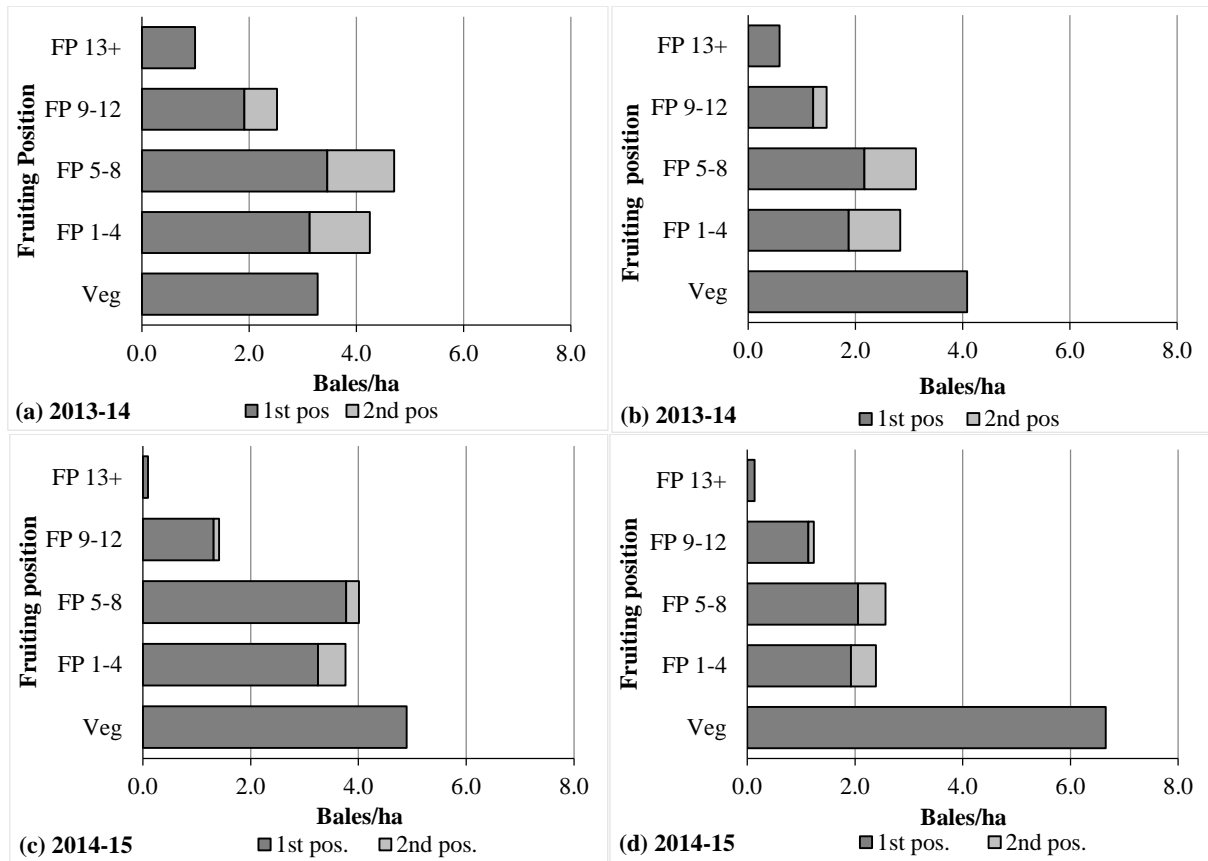


Figure 12. The 2013-14 and 2014-15 yields of handpicked cotton separated into each fruiting segment (227 kg bales) in (a) 1.0 m from Quigley (2014), (b) 1.5 m from Quigley (2014), (c) 1.0 m from Bartimote (2015) and (d) 1.5 m row-spacing from Bartimote (2015) in bales/brown ha.

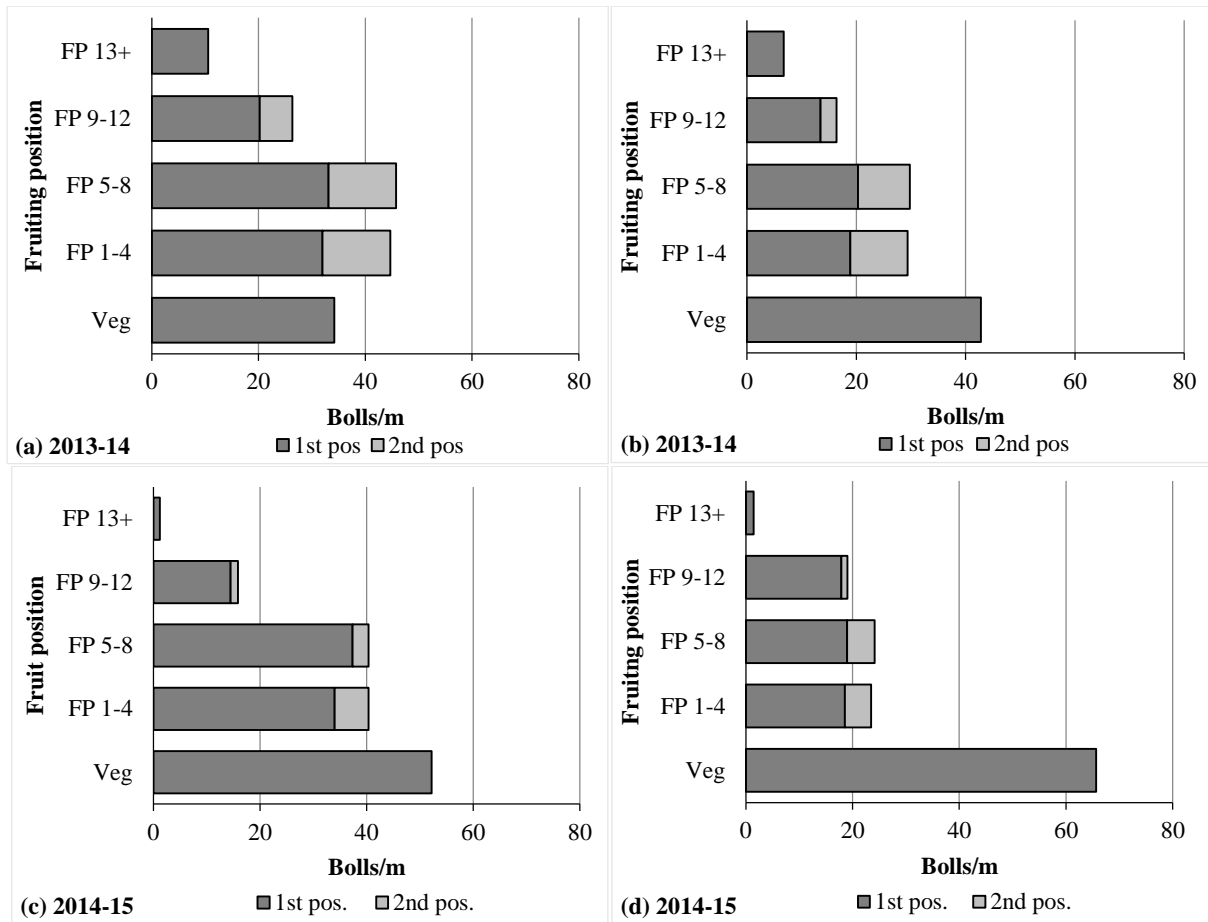


Figure 13. The number of bolls per metre of handpicked cotton (2013-14 and 2014-15) separated into various fruiting positions (bolls/m²) in (a) 1.0 m from Quigley (2014), (b) 1.5 m from Quigley (2014), (c) 1.0 m from Bartimote (2015) and (d) 1.5 m row-spacing from Bartimote (2015) in bales/brown ha.

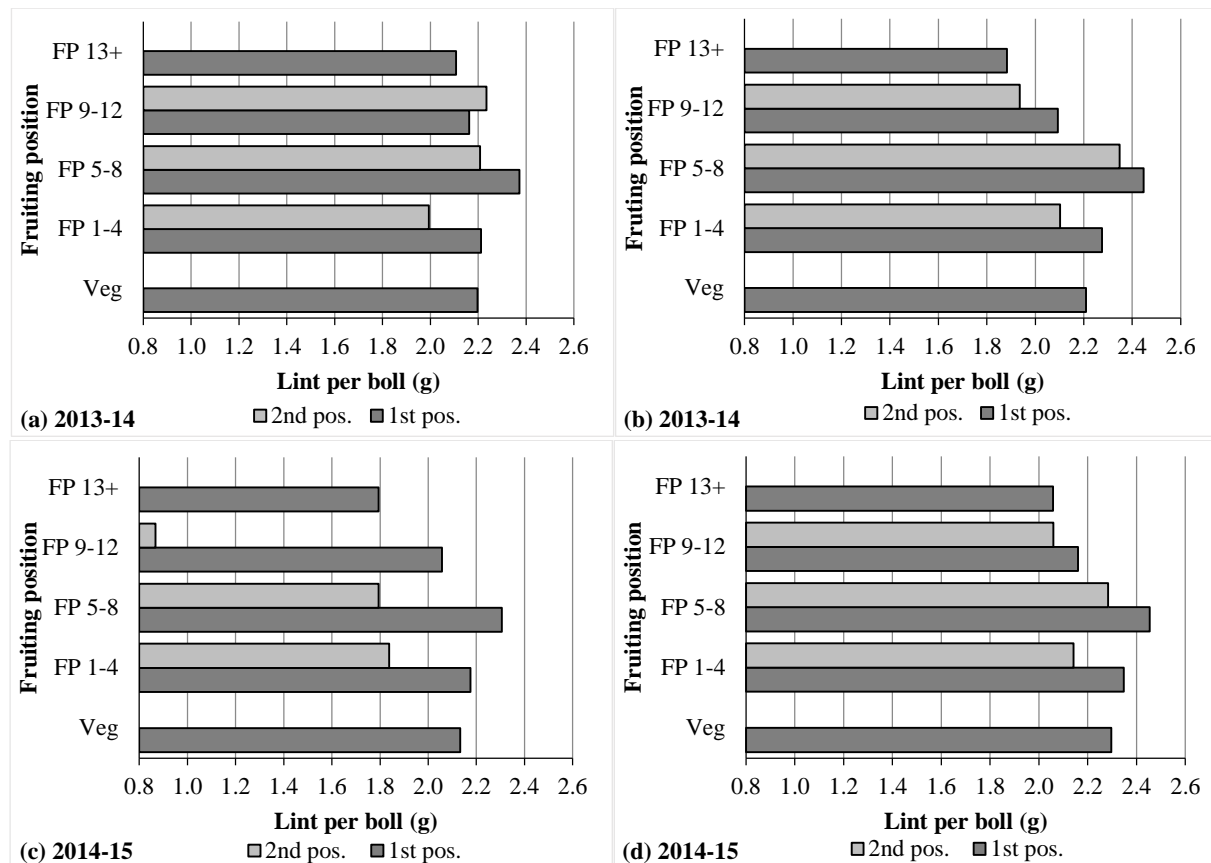


Figure 14. The average weight of lint per boll in grams for each fruiting segment for each season (2013-14 and 2014-15) in (a) 1.0 m from Quigley (2014), (b) 1.5 m from Quigley (2014), (c) 1.0 m from Bartimote (2015) and (d) 1.5 m row-spacing from Bartimote (2015).

A strong correlation was observed between the number of bolls per fruiting segment and the lint yield per fruiting segment ($R^2 = 0.99$) (Figure 15). There were similar relationships for 1.5 m row and 1.0 m row cotton between lint per boll and lint yield per fruiting segment (Figure 16) as well as between the number of bolls and lint per boll (Figure 17).

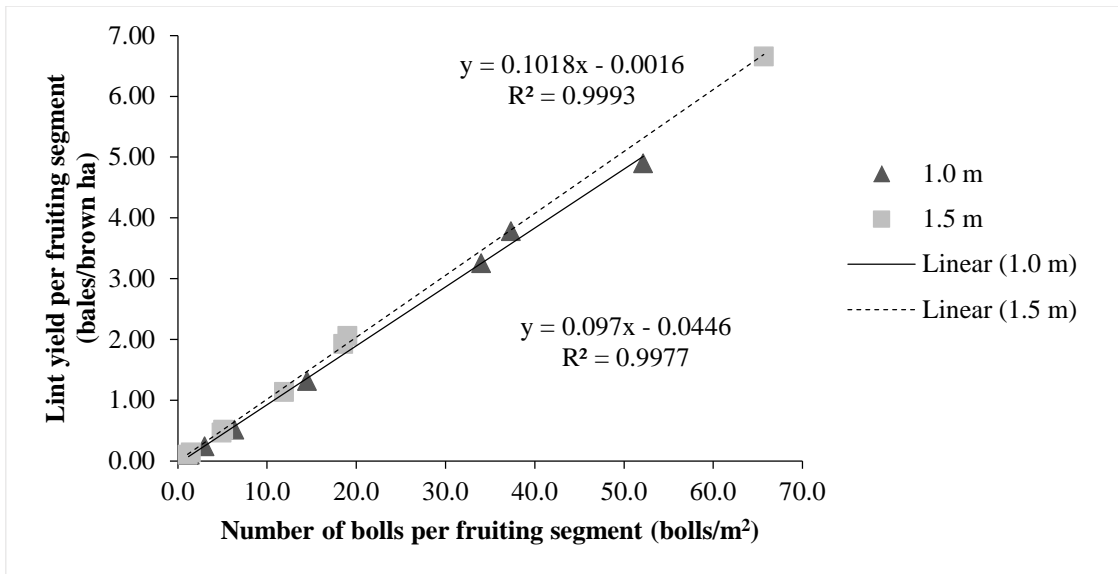


Figure 15. The relationship between the number of bolls (bolls/m²) and yield (227 kg bales/ha) across all fruiting segments.

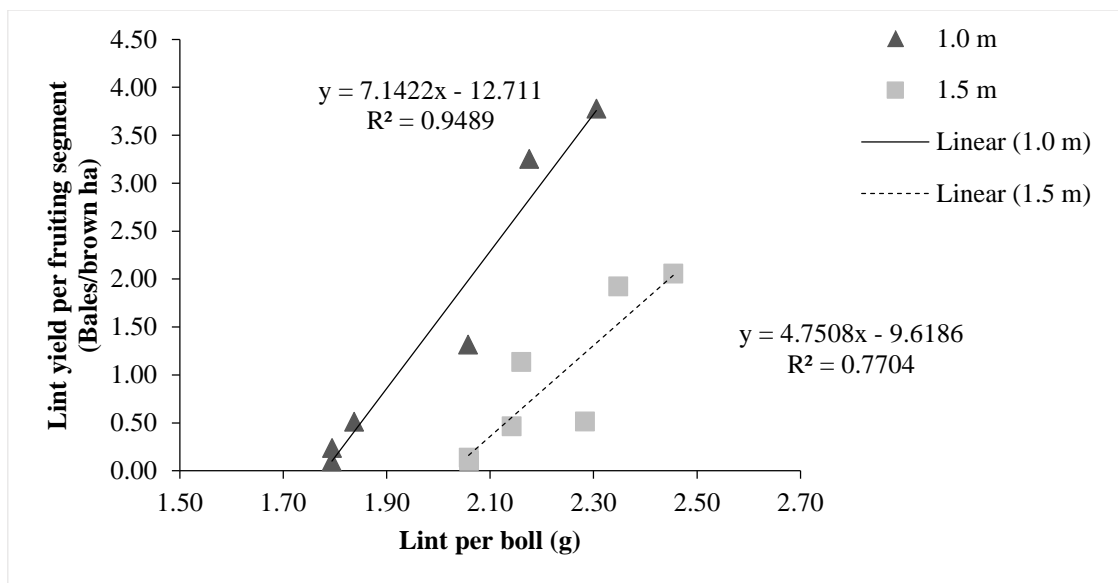


Figure 16. The relationship between the average lint weight (g) per boll and the yield (227 kg bales/ha) across all fruiting segments.

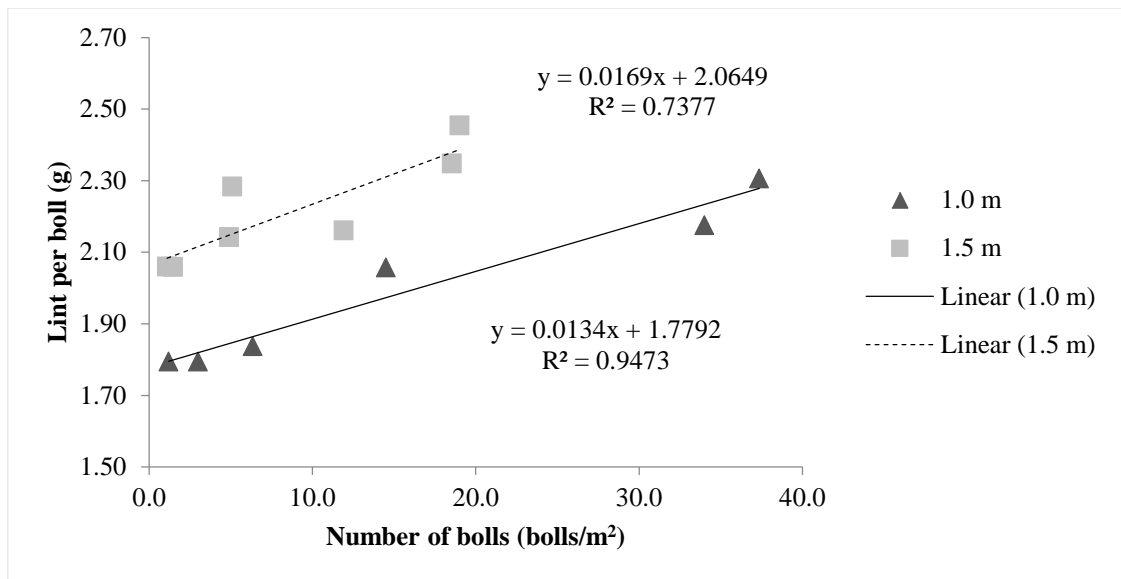


Figure 17. The relationship between the average lint weight (g) per boll and the number of bolls per m² across all fruiting segments.

Fibre quality of the handpicked cotton from 2014-15

Fibre length in the first and second position fruit was longer in all fruiting segments below fruiting position 13 in the 1.5 m row compared with the 1.0 m row spacing (Figure 18). In 2013-14 1.5 m cotton fibres were longer than 1.0 m cotton fibre ($P < 0.031$). This occurred again in 2014-15 ($P < 0.022$).

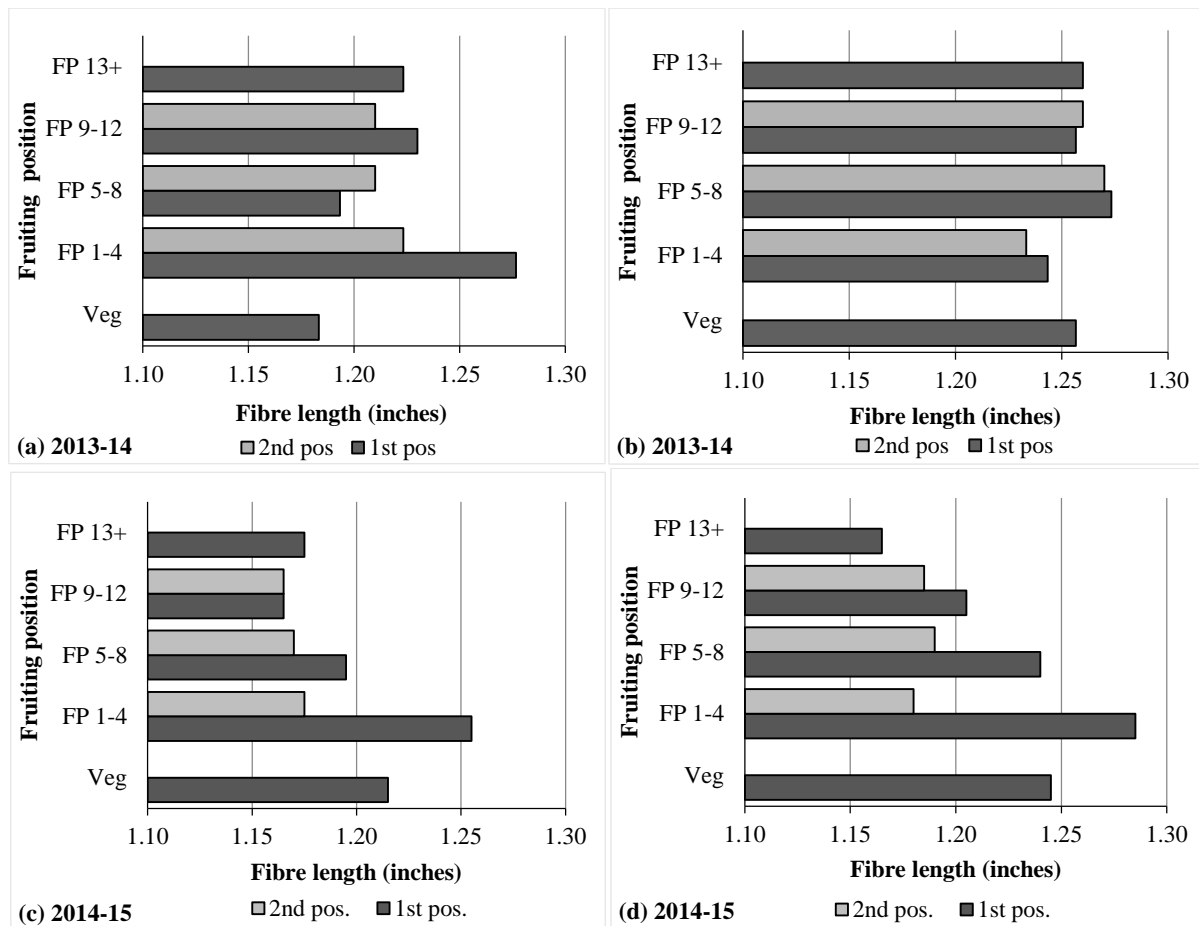


Figure 18. Fibre length (1 inch = 25.4 mm) of the handpicked cotton from 2013-14 and 2014-15 presented in separate fruiting positions; (a) 1.0 m from Quigley (2014), (b) 1.5 m from Quigley (2014), (c) 1.0 m from Bartimote (2015) and (d) 1.5 m row-spacing from Bartimote (2015).

Marginally stronger fibres were observed in each fruiting segment aside from fruiting positions 1-4 in the 1.5 m compared with the 1.0 m cotton. Bolls on the vegetative branches of 1.5 m cotton had significantly stronger fibres than the 1.0 m cotton (33 g/tex and 30 g/tex, respectively) (Figure 19). In 2013-14, 1.5 m fibre was stronger than 1.0 m fibre ($P < 0.020$). This occurred again in 2014-15 ($P < 0.037$).

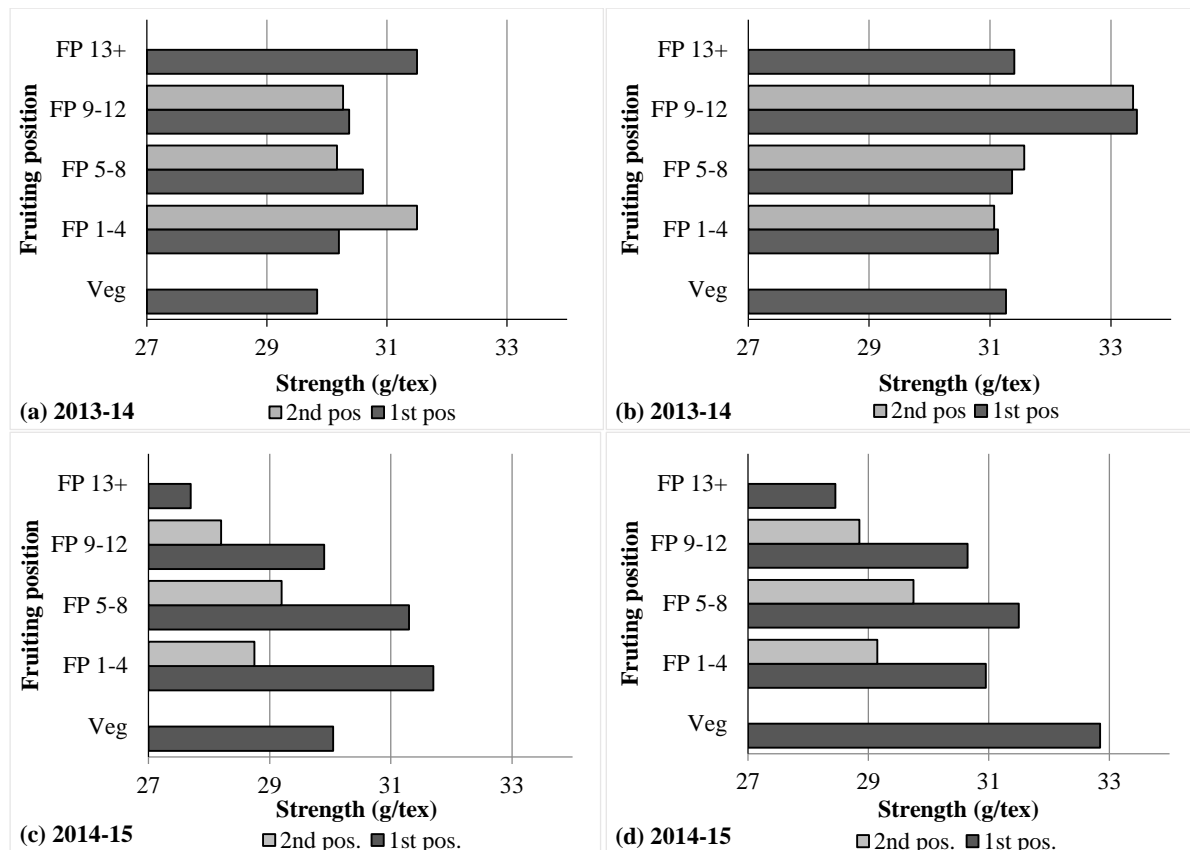


Figure 19. Fibre strength (g/tex) of the handpicked cotton from 2013-14 and 2014-15 presented in separate fruiting positions; (a) 1.0 m from Quigley (2014), (b) 1.5 m from Quigley (2014), (c) 1.0 m from Bartimote (2015) and (d) 1.5 m row-spacing from Bartimote (2015).

Discussion

Water use efficiency

Water has been identified as the most limiting factor to production in the many Australian cotton producing regions (Roth *et al.* 2013). Hence irrigators must employ strategies to improve their WUE even if it involves a slight yield loss per ha as the increase in gross margins (\$/ha) will compensate for this initial loss.

The 1.5 m row-spacing required less water per hectare to produce a similar yield to that of the 1.0 m row-spacing (1.21 bales/ML and 1.18 bales/ML, respectively). Overall, 1.0 m cotton received more water than the 1.5 m cotton per ha. The biggest differences in inputs were

rainfall and initial soil moisture. The 1.5 m cotton experienced higher amounts of these inputs compared with the 1.0 m cotton. An expected outcome since the 1.5 m cotton had a greater catchment area per plant than the 1.0 m cotton (33% more area per row). The largest water input was irrigation water. WUE increased when only applied irrigation water alone was considered (1.59 bales/ML and 1.50 bales/ML, respectively). An important outcome since irrigation efficiency has a direct impact on the gross margin of irrigated cotton production.

WUE increased with reduced traffic. In the two years this experiment was conducted, IWUI was found to increase in 2014-15. As traffic was controlled, soil compaction was reduced, the soil given time to recover, and water infiltration increased (McGarry and Chan 1984; McGarry 1990; Braunack *et al.* 1995; Chan *et al.* 2006). The size of the infiltration boundary increased improving the soils water holding capacity. This contributed to an increase in water content in the volume of soil available to each plant and improvement of soil health (e.g. porosity, bulk density hydraulic conductivity). This reduction in compaction would not have been evident in the data of 2013-14 as there had not been any traffic on Field 12. Hence, the reduced infiltration boundary conditions in the 1.0 m system after traffic, which affected the 2014-15 yield, would not have been seen prior to the 2013-14 harvest where an effect on yield and WUE would not be expected (Figure 20) (Barley 1963; Braunack *et al.* 1995; Bennett *et al.* 2015a).

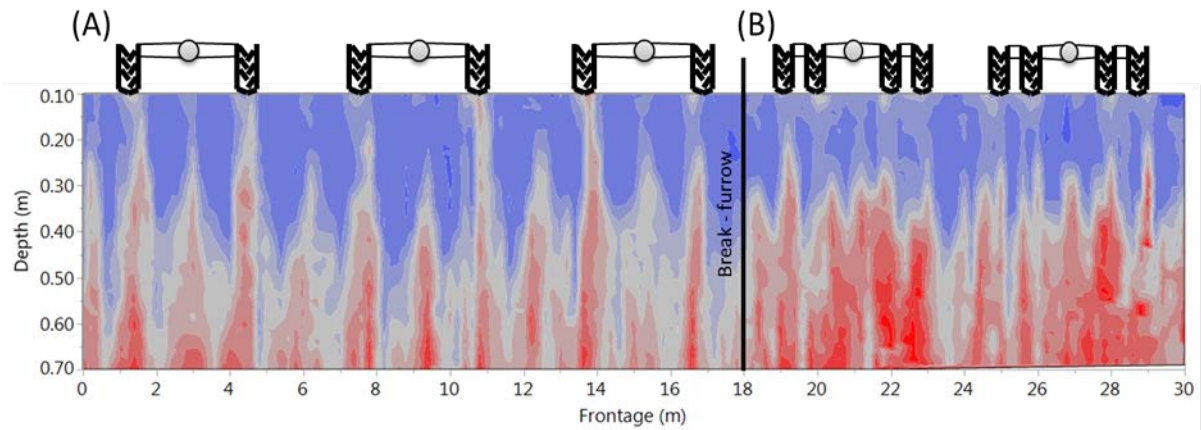


Figure 20. A cross-section of the soil profile which displays the average soil strength for the (A) 1.0 m and (B) 1.5 m cotton row treatments in Field 12 at Auscott Warren after two years (2013-14 and 2014-15) of controlled (1.5 m) and uncontrolled (1.0 m) traffic. High soil strength is depicted by light grey and the darker grey sections towards the bottom. This data corresponds with the bulk density of the soil. The higher soil strength in the non-traffic rows under the 1.5 m system are a function of evaporation from the furrows and the weight of water increasing soil density (sourced from Bennett *et al.* 2015a).

The Australian cotton industry is placing more importance on the cotton yield produced per unit of water. This is expressed in the form of defining appropriate benchmarks growers should aim to achieve (Montgomery and Bray 2014). Benchmarks are determined every few years as technology and management practices improve. They involve two performance indicators: (1) Gross Water Use Index (GPWUI), which compares yield against all water inputs on farm; and (2) Irrigation Water Use Index (IWUI), which measures the amount of cotton produced per volume of irrigation water applied (Montgomery and Bray 2014). These benchmarks were the result of increasing scrutiny by the public towards WUE in the Australian cotton industry and encouraged more research to be conducted to determine its current state (Cameron and Hearn 1997; Tennakoon and Milroy 2003; Tennakoon *et al.* 2004; Payero and Harris 2007; Williams and Montgomery 2008; Wigginton 2011). These benchmarks provide an average industry WUE. Comparisons can be made to data from this experiment, identifying their importance for other growers in rain-limited cotton growing regions.

WUE has increased over time (Figure 21). In the space of 10 years there has been an increase of 40% in GPWUI and IWUI (Montgomery and Bray 2014). The GPWUI in both the 1.0 m and 1.5 m treatments in this experiment is greater than industry averages observed in other studies, with 1.5 m cotton obtaining the highest GPWUI. IWUI of the two treatments (1.0 m and 1.5 m) in the current study was similar to the industry average over the last six years. In addition, 1.5 m cotton was the only treatment above the industry IWUI average of 1.5 bales/ML obtained from Tennakoon *et al.* (2004) data.

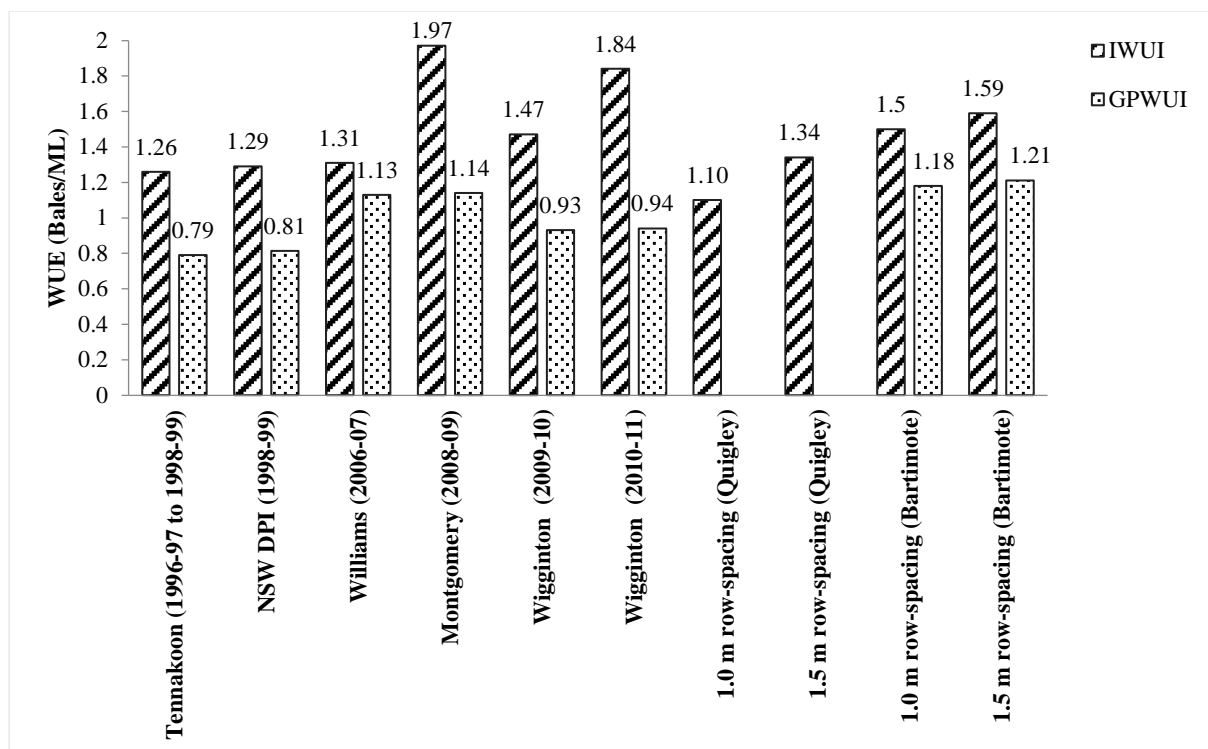


Figure 21. A combination of experimental data from Cameron and Hearn (1997), Tennakoon *et al.* (2004), Payero and Harris (2007), Williams and Montgomery (2008), Wigginton (2011), Quigley (2014) and this experiment (Bartimote 2015). This figure demonstrates the change in WUE (bales/ML) (227 kg bales/ha) in the last fifteen years. WUE was compared by means of Irrigation Water Use Index (IWUI) and Gross Water Use Index (GPWUI).

The WUE (IWUI) increased in this experiment (2014-15) compared with the data obtained in the 2013-14 cotton season (Quigley 2014). Yield was higher in 2014-15 than in 2013-14 for both treatments and the difference in yield between treatments was reduced (Table 3). The

yield increase observed in the 1.5 m cotton between 2013-14 and 2014-15 is due to an increase in the size of the effective infiltration boundary, a result of reduced traffic. High soil strength is limited to the profile beneath the wheel tracks. The impact on 1.0 m cotton yield would only be observed in the 2014-15 season as that field had not experienced any compaction prior to the 2013-14 season (Bennett *et al.* 2015a).

Table 3. Comparison in water inputs and IWUI between two years of data (2013-14 and 2014-15) which compared 1.0 m and 1.5 m row-spacing irrigated cotton in north-west NSW. Utilised data from Quigley (2014).

Season	Quigley (2013-14)		Bartimote (2014-15)	
	1.0 m	1.5 m	1.0 m	1.5 m
Yield (bales/ha)	11.52	9.73	12.33	11.64
Applied water (ML/ha)	10.43	7.27	8.20	7.30
In crop rainfall (ML/ha)	1.24	1.86	1.59	1.59
IWUI (bales/ML)	1.10	1.34	1.50	1.59

The 1.5 m row-spacing had a greater WUE (GPWUI and IWUI) than the 1.0 m row-spacing. The greatest water saving was in the applied irrigation water. In both seasons (2013-14 and 2014-15), the difference in applied irrigation water between the two treatments (1.0 m and 1.5 m) was 1 to 3 ML/ha. The significance of this being that cotton crops grown on 1.5 m row-spacing require smaller irrigations or employ longer water cycles. Water savings improve the sustainability of irrigated cotton production in regions where water is most-limiting (Tennakoon 2004). Incorporating new technologies and practices to improve WUE will provide long-term stability in a volatile industry. The shift in public opinion towards diverting water resources to maintain environmental flows will heighten the requirement for increased WUE amongst cotton growers (Meyer 2000).

Wide row configurations aim to conserve soil water alongside each planted row. During periods of rain this will extend plant growth, especially in regions where soils (e.g. Vertosols)

have a high water holding capacity. Each plant has access to a larger volume of soil water (larger bucket) and requires less irrigation to maintain optimal plant growth and development (Bange *et al.* 2005). Coupling this with a controlled traffic program, such as that employed in the 1.5 m system, serves to enhance this benefit (Bennett *et al.* 2015a, 2015b).

Gillies (2012) conducted an extensive analysis of irrigation practices on clay soils (e.g. Vertosols) to determine the optimum water velocity and run-time. Running water above 4.5 L/s and irrigating for less than 12 h was found to reduce deep drainage from the industry average of 28.4 mm to 15 mm (0.15 ML/ha). Deep drainage in this experiment was determined by conducting an analysis on a single irrigation with SIRMOD III (Walker 2003). No deep drainage was observed in that irrigation due to a high water velocity (7 L/s) and reduced run-time of 11.5 h. Hence the optimised average (0.15 ML/ha) was adopted and used as the deep drainage measurements for this experiment.

Yield

Crop yields (bales/ha) have a direct impact on the gross income of cotton producers. Incorporating new technologies and better management practices into production assists in improving the economic sustainability. Crop yields are influenced by different factors, including: cultivar selection, climate, pests, diseases, management decisions and timing of operations (Bakhsh *et al.* 2005; Antille *et al.* in press). Row-spacing has a large impact on yield performance as it influences the number of plants per hectare which can provide various advantages or disadvantages. One meter row-spacing has become standard practice for cotton, due to harvesting implement frontage and the size of tyres (Lal 2006), hence numerous cultivars and machinery has been designed to suit this system (Clark and Carpenter 1992). A greater yield was observed in the 1.0 m cotton compared with 1.5 m cotton in both seasons

(2013-14, 2014-15) this experiment was conducted. This equated to an 18% in the first year (2013-14) and reduced to a 6% difference in yield in the second (2014-15). Soil compaction was reduced in the second year (2014-15) contributing to an increase in yield (Bennett *et al.* 2015a).

Generally yield potential decreases with increasing row-spacing. In water deficient environments, wide row systems can minimise yield penalties due to: reduced risk of crop failure; allowing for the extension of water cycles; maintaining, fibre quality; better use of in-crop rainfall; and, reduction of other on-farm costs e.g. seed/ha; factors which were observed in the 1.5 m cotton. In particular, fibre quality was significantly improved in the 1.5 m cotton fibres compared to 1.0 m cotton fibres.

Single skip and 1.5 m row-spacing are two popular wide row options (CRDC 2012). Single skip involves skipping one plant row in every four and is typically utilised in rain-fed cotton production as it maximises rainfall use efficiency (Figure 22). Irrigated single skip yields are comparable to solid 1.5 m row spacing yields as both options occupy 67% of the available land per ha (Pyke 1991; Bange *et al.* 2005). Single skip cannot employ CTF, unlike 1.5 m row-spacing. Hence compaction will occur.

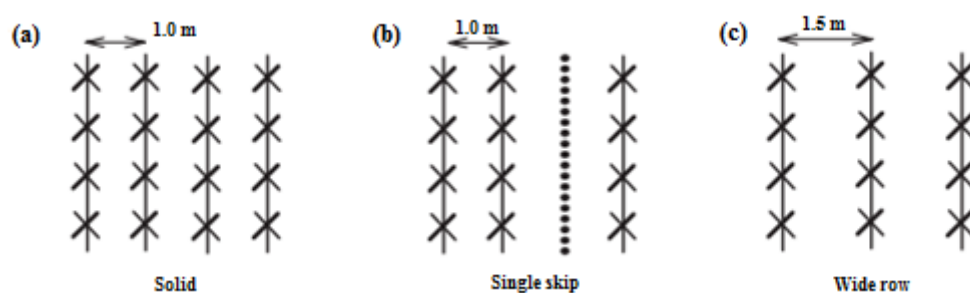


Figure 22. Diagram demonstrating the difference between (a) solid 1.0 m row-spacing, (b) single skip row-spacing and (c) wide row 1.5 m row-spacing.

Narrow row cotton (0.75 m) and Ultra Narrow Row (UNR) (< 0.4 m) are row-spacing configurations which aim to maximise yields when water is non-limiting. These are typically grown in the southern cotton growing regions of Australia where water is highly available and seasons are shorter (Brodrick *et al.* 2012a). Yields are maximised by increasing the plant density per ha. On average yields are 14.4% ($P < 0.05$) greater in UNR configurations compared with 1.0 m row-spacing. However, they tend to have a greater irrigation requirement (Brodrick *et al.* 2010). The 1.5 m cotton had a greater WUE than the 1.0 m cotton. Hence it is more suitable than UNR and narrow row for regions with limited water e.g. Macquarie Valley.

Data from this experiment is consistent with those from other studies which span across multiple seasons and in various climatic zones (Figure 23) (Brodrick *et al.* 2010; CSD 2010; Brodrick 2012; Quigley 2014; CSD 2015). Comparisons indicate that the 1.5 m and 1.0 m row-spacing data is slightly above average indicating a more suitable season for achieving higher yielding cotton. Data from Quigley (2014) is slightly below average for 1.5 m cotton and slightly above for 1.0 m cotton. On average yield increased with decreasing row spacing. Brodrick *et al.* (2010) conducted an experiment to determine the yield difference between 1.0 m and UNR (0.25 m) row-spacing in cotton. This experiment occurred in three different locations over three growing seasons. Yield was greater in UNR cotton but uptake of this configuration was theorised to be low due to associated logistical difficulties (Brodrick *et al.* 2010; Brodrick *et al.* 2012a). Cotton Seed Distributors (CSD) have conducted multiple field experiments comparing 1.0 m row spacing with single skip cotton in fully and semi-irrigated production systems. Single skip cotton produced a lower yield compared to conventional spacing but in each experiment single skip was found to have a greater WUE, essential for the

water limited environments of north-west NSW (Bourke) and south-east QLD (Goondiwindi) where these experiments were conducted (CSD 2010; CSD 2015).

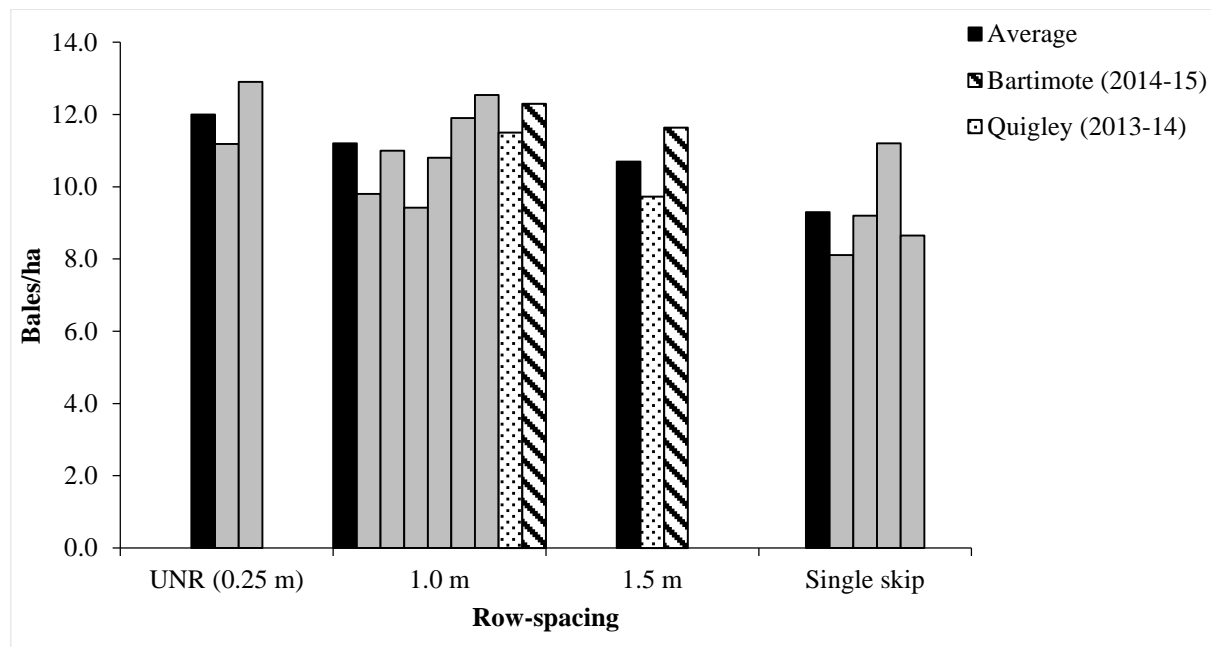


Figure 23. Data comparison of CSD field experiments (CSD 2010; CSD 2015), Brodrick's UNR field experiments (Brodrick *et al.* 2010; Brodrick *et al.* 2012a), Quigley's field experiment (Quigley 2014) and using machine picked data from this experiment (Bartimote 2014-15). It compares yields from multiple row configurations (UNR, 1.0 m, 1.5 m and single skip) from these experiments and against a calculated average of all the available data. Grey bars represent yields from various other studies.

Yield in each fruiting segment (bales/brown ha) in both the 1.0 m and 1.5 m row-spacing treatments was directly correlated ($R^2 = 0.99$ and $R^2 = 0.99$ respectively) with the number of bolls per fruiting segment (bolls/m²) (Figure 15). Increasing the number of bolls/m² has a positive impact on yield (Constable *et al.* 2001). Hence the introduction of narrow row and UNR row configurations under optimal irrigated conditions (Brodrick *et al.* 2012a), which may suggest that yield in a 1.5 m row-spacing system could be hampered.

The lower yield per ha for both years of the experiment (2013-14 and 2014-15) was in the 1.5 m cotton compared with 1.0 m cotton could be attributed to those plants reaching their

seasonal yield potential (as light interception may be limiting due to reduced early season canopy cover). Where the performance of a crop in particular conditions is determined by their genetic potential. Inputs were not limiting as the experiment was fully irrigated with nitrogen being applied as required. This suggests that each plant reached fruiting capacity, hence restricting yield, as demonstrated in Gibbs (1995). Lower plant densities, such as those in the 1.5 m row-spacing system, are known to inhibit yield (Bednarz et al. 2000), although cotton plants are capable of compensating yield, as was observed in the current project. Where the 1.5 m cotton had reduced plant density in comparison to the 1.0 m cotton, it also produced more bolls per plant, particularly in the vegetative branches. In the Spring 2015 Spotlight Magazine, it was suggested yield potential will increase each season as new genetics and better management practices are introduced by cotton breeders and utilised by growers (CRDC 2015). Hence seasonal yield potential may have been one factor among others which influenced yield, e.g. insect damage and disease.

There was a large difference between handpicked and machine picked yields in both seasons (2013-14 and 2014-15) of this experiment, which is similar to a 10% difference in yield measurement methods observed by Brodrick *et al.* (2010). Average rows were selected for segment picking with at least eight plants per metre to present a normal population. Samples from these segments were then ginned individually at CSD. Ginning smaller amounts at a time would improve overall accuracy and increase the lint turnout percentage in the handpicked cotton compared with the machine picked cotton. Furthermore high yielding plants in the 1.5 m treatment would increase the difficulty of harvest for pickers, producing a high volume of cotton, impacting harvest efficiency, as pickers harvested 4 rows in the 1.5 m cotton and 6 rows in the 1.0 m cotton (width = 6 m) (Bennett *et al.* 2015b). Especially since

the 2014-15 cotton season was highly favourable in the Macquarie Valley with early season rain, high temperatures mid-season and no rain during harvest (CRDC 2015).

Fibre quality and fruit segment distribution

The 1.5 m row spacing produced cotton plants which were wider and taller than their 1.0 m counterparts. Brodrick *et al.* (2010) observed the opposite in UNR cotton compared with 1.0 m cotton. Individual plants in UNR cotton were shorter and had fewer mature bolls past the 1st and 2nd positions. This was attributed to lower light interception, a result of a denser canopy. Cotton plants tend to invest resources only in bolls which they intend to keep, meaning boll weight is an indication of which fruiting positions were prioritised (Jackson and Gerik 1989). Hence, as 2nd position bolls were heavier than in 1.0 m cotton, it is deduced the 1.5 m cotton plants had less competition for soil water and nutrients. Furthermore, the majority of the lint from 1.5 m cotton was found on the vegetative positions (branches) while in 1.0 m cotton the majority of the yield was found on fruiting positions 1 to 8. Thus plants in the 1.5 m row-spacing matured slower as faster maturing plants tend to have the majority of their lint in the higher fruiting positions (Brodrick *et al.* 2010).

Data from the handpicked segments revealed higher fibre length and strength in 1.5 m compared with 1.0 m row-spacing. Final fibre length is determined at the end of the fibre elongation period. This occurs around 25 days after flowering and pollination (Bange *et al.* 2009). Water stress during this time can have a detrimental effect on fibre length (Hearn 1976; Constable and Hearn 1981). The 1.5 m cotton has access to a larger profile of soil water which sustains plants through drier periods, alleviating water stress, resulting in longer fibres. Fibre was significantly better quality in the 1.5 m row-spacing in both strength and length

compared with 1.0 m row-spacing. Fibre strength is a measure of the maximum resistance to stretching forces and measured in grams force. Fibre strength has a direct correlation to fabric strength and durability. Strength is determined by maturity. Moisture stress in the later part of boll filling can reduce fibre strength. Hence the vegetative bolls had the greatest fibre strength since they were the most mature. One metre cotton fibre is less mature as the majority of the lint appears on the fruiting positions 1-8, which occur later in the season (Bange *et al.* 2009; Roth *et al.* 2013). As fibre quality impacts the price per bale growers receive at the gin, quality needs to be within certain parameters to minimise penalties (Table 4). Both the 1.0 m and 1.5 m cotton is within these parameters. However, 1.5 m cotton fibre is stronger and longer hence if downgrades due occur due to limited water and high plant stress there is an insurance policy against a loss in quality.

Table 4. Cotton fibre quality parameters (Bange *et al.* 2009).

Fibre Trait	Ideal range	Premium range
Length	> 1.125 inches	> 1.250 inches
Strength	> 29 g/tex	> 34 g/tex

Economics

There is a significant difference of \$191.30/ha in gross margins between the two row-spacings in favour of the 1.5 m cotton. The 1.0 m cotton received greater yields resulting in a higher gross income but with a higher input cost, whilst the 1.5 m cotton had a lower yield, but a lower cost per ha. Subsequently, the most expensive input cost was water for irrigation although technology fees and ginning costs also had an important impact (Table 5).

Cotton lint was given the average representative price of \$500 per bale (227 kg per bale). This price was representative of the prices being received in the Macquarie Valley in the 2014-15 season, but fluctuates depending on supply and demand. It can be affected depending on the gin, the region and the country it is sold in. Changes in cotton price would affect the outcomes of the gross margin. An increase in cotton price would reduce the difference between gross margins and make the 1.0 m cotton more competitive. It would only break even with the 1.5 m cotton at \$803/bale. In a poor cotton market the 1.5 m row-spacing would be the most competitive system.

The price of water is known to fluctuate depending on availability and the region. In a wet year it can be as low as \$50 per ML while in a dry year it can reach \$300 per ML. The price of water had the most significant impact on the gross margin. Through consultation with various growers and consultants in the Macquarie Valley a \$200/ML value was used as the average water price (Pers Comm Sustainable Soil Management, Auscott Warren, NSW DPI). A sensitivity analysis revealed that the difference in gross margins between 1.0 m and 1.5 m cotton increased with an increasing water price (Figure 24). This was due to a greater WUE in the 1.5 m cotton which reduced the irrigation requirement compared to the 1.0 m cotton. This suggests that 1.5 m row-spacing is more economically sustainable production system in regions where water is limiting.

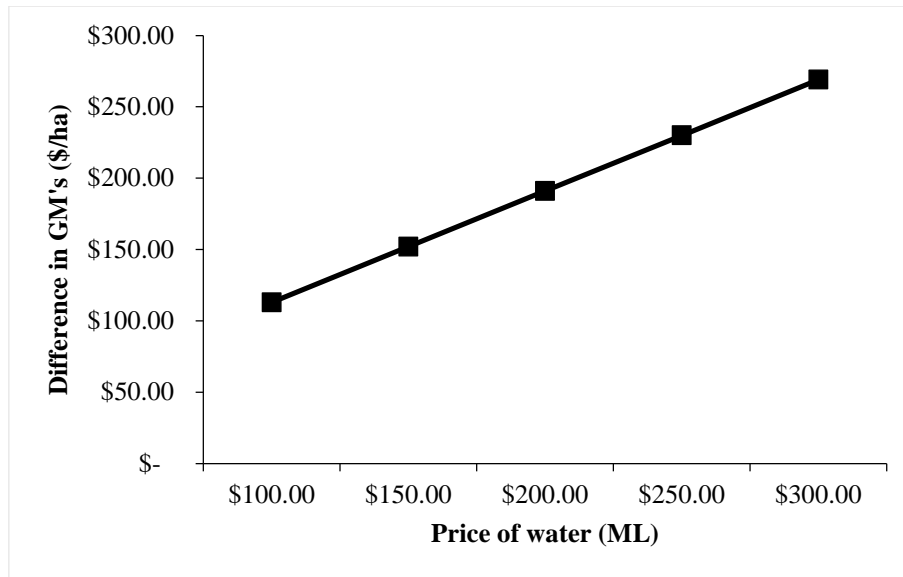


Figure 24. Sensitivity analysis which demonstrates the change in the difference between the gross margins of 1.5 m and 1.0 m cotton as a result of an increasing and decreasing price of water (\$/ML). This difference reveals that the 1.5 m has a better performing gross margin when water prices are high.

A reduction in technology fees was observed in the 1.5 m cotton compared with the 1.0 m cotton. The 1.5 m row-spacing only grows on 67% of the total area planted in 1.0 m row-spacing. Due to the large adoption of genetically engineered Bollgard IITM and Roundup Ready FlexTM cotton technology fees have become a substantial cost (\$400/green ha).

Table 5. The expected gross margins of 1.0 m and 1.5 m row-spacing (based on NSW DPI cotton gross margin template for Central & Northern NSW 2014-15).

Income	Yield	Price				Income 1.0 m (\$/ha)	Yield	Price				Income 1.5 m (\$/ha)		
Lint income	12.3	500.0				6150.0	11.6	500.0				5800.0		
Seed income	3.1	80.0				248.0	2.9	80.0				232.0		
Total income						6398.0						6032.0		
Operation	Volume	Cost	Application cost				Cost 1.0 m (\$/ha)	Volume	Cost	Application cost				Cost 1.5m (\$/ha)
Bed forming	2.0		25.0				50.0	2.0		25.0				50.0
MAP	100.0	1.0					96.0	84.0	1.0					80.6
Seed	13.0	8.0	9.0				113.0	8.7	8.0	9.0				78.3
Nitrogen fertiliser	275.0	1.1					298.9	231.0	1.1					251.1
Water	8.1	200.0					1620.0	7.3	200.0					1460.0
Herbicide	4.0	9.0	6.0				60.0	4.0	9.0	6.0				60.0
Insecticide	1.0	15.0	15.0				30.0	1.0	15.0	15.0				30.0
Defoliation	3.0	25.0	15.0				120.0	2.0	25.0	15.0				80.0
Picking			272.0				271.8			272.0				271.8
Module wrap	11.5	6.0					69.1	9.7	6.0					58.4
Ginning	11.5	60.0					691.2	9.7	60.0					583.8
Technology	1.0	400.0					400.0	0.7	400.0					266.7
Levies	11.5	4.5					51.8	9.7	4.5					43.8
Consultant		60.0					60.0							60.0
Total costs						3931.8						3374.5		
Gross margin						2466.2						2657.5		

Limitations

The WUE component of this experiment is limited by having only one large replicate field block. Measurement of irrigation applications could not be separated into the individual blocks. To alleviate this problem flume meters would be required to measure water flow into and out of each row. Otherwise multiple fields with a complete block design would provide several replicates to enable statistical analysis of the water balance. Extrapolation of the data from this experiment would be useful in informing further work in other regions.

Future research

This experiment has collected two years of data which improves the reliability of the data. However this only occurred in the Macquarie Valley, limiting the practical transfer of this information into other cotton growing regions (e.g. Gwydir Valley, Riverina and Macintyre Valley). The Macquarie Valley receives 513 mm of annual rainfall (BOM 2015) and water allocations for irrigators were low in the 2014-15 season. The 1.5 m row-spacing performed better in these water limited conditions than the 1.0 m row-spacing as it had a greater WUE and required less irrigation per ha. The Riverina has an annual rainfall of 236-617 mm and has a large irrigation resource in the Murray-Darling basin and conjoining river systems (Office of Environment and Heritage 2015). If water prices are lowered revaluation of the economic sustainability of the 1.5 m row-spacing in this new environment would be required. However, 1.0 m row-spacing does not allow for CTF, increasing compaction of soils. In areas where water is not entirely limited, compaction may be; hence performing this study in those regions would provide a better indication of the suitability of the 1.5 m production system to other climates and environments (Tullberg 2010; Bennet *et al.* 2015b.; Antille *et al.* in press)

Conclusions

This experiment demonstrated that 1.5 m cotton had a greater WUE by producing 0.09 more bales per ML (\$20.43 /ML; \$227 /bale), compared with 1.0 m cotton. This small difference meant a lower irrigation requirement resulting in 1.5 m cotton outperforming 1.0 m cotton in terms of gross margin (\$2657.50/ha and \$2466.20/ha, respectively). This outweighs the fact that 1.0 m cotton out yielded 1.5 m cotton by 1.8 bales/ha (16%) in 2013-14 and by 1.09 bales/ha (6%) in 2014-15, and reinforces the fact that yield should be considered in terms of system inputs.

Segment picking revealed that the majority of the fruit from the 1.0 m cotton was from fruiting positions 1-8, while the majority of the lint yield for 1.5 m cotton originated from vegetative branches. However, there were only minor differences in fibre quality between 1.0 m and 1.5 m cotton that were considered within industry parameters.

The use of 1.5 m row-spacing cotton appears to be best suited to water limited environments based on its ability to enhance WUE. It should be noted that much of the Australian cotton industry would be historically categorised as water limited in terms of both irrigation allocation and rainfall. Hence, future research should replicate this experiment in other climates and environments of dominant cotton regions to see which row-spacing configuration is most suitable in different situations. Importantly, the 1.5 m system lends itself to incorporation of true CTF capable of integrating with the wheel track of 3 m found in the majority of machinery.

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