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Part 1 - Summary Details

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Part 3 – Final Report

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Background

The period between 2008 and 2012 in the Central Queensland (CQ) region was dominated by wetter than average conditions associated with consecutive La Niña events (Figure 1a). Punctuated by two significant riverine flooding events (2008 & 2011), this period also incorporated widespread yield reductions (Figure 1b) combined with higher incidences of lint quality discounts for Central Highland and Dawson growers. By 2012, concerns had begun to emerge regarding the future of cotton production in CQ as yield and quality issues combined with reduced acreage cast a shadow on the viability of having two ginning facilities in the Central Highlands region. The stark contrast with southern regions, which had experienced a near universal increase in average yields during the same period off the back of improved Bollgard II® varieties only served to highlight the problems faced by CQ growers and their associated service industries.

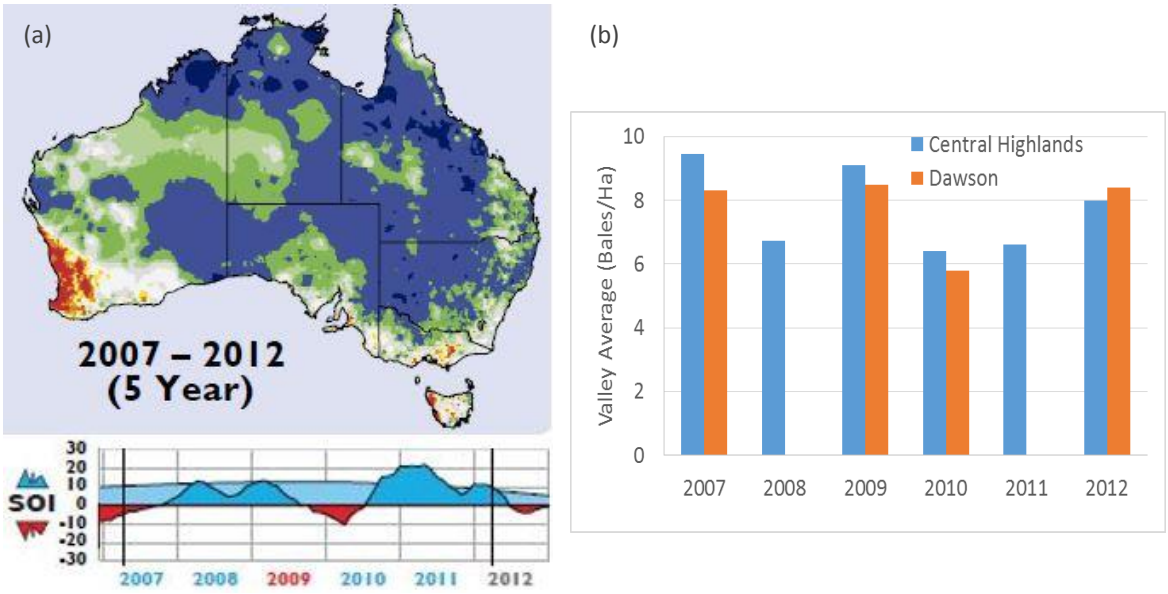


Figure 1. CQ climate and cotton yields in the period 2007-2012
(a) Rainfall classification for Australia together with the SOI moving average and average yields (bales/ha) for the Central Highlands during 2007-2012. This period was characterised by wetter than average conditions (*www.longpaddock.qld.gov.au/queenslanddroughtmonitor/droughtresearch/wetdryposter.pdf*)
(b) Crops were severely affected by wet weather conditions during boll opening and picking in 2008, 2010 and 2011 (right). Dawson averages are omitted for 2008 and 2011 due to flooding (*Australian Cotton Grower year books 2007–2012*).

A grower practices survey was conducted in 2012 by the Central Highlands Cotton Growers and Irrigators Association and Roth Consulting with the aim of identifying trends in production practices that might highlight potential solutions. Examining the range of practices and inputs used during the five year period, the survey attempted to correlate these with yield over time to see whether some approaches to crop management were providing better outcomes than others. The survey found that yields and lint quality discounts were highly variable both between and within farms across years. The highest yielding survey participants in any given year did not necessarily grow high yielding crops in previous or subsequent seasons, and no individual enterprises were consistently out-yielding their peers across seasons, suggesting that agronomic management factors were not sufficient to overcome local conditions. The survey confirmed that local climatic factors were having a large impact on yield and quality and that existing agronomic management practices provided limited respite.

Geographically, the Central Highlands as a cotton production region is unique. Unlike the southern production regions, Emerald sits within the coastal plain east of the Great Dividing Range and virtually on top of the Tropic of Capricorn at a latitude of 23.52°S. A comparison of

other cotton-producing countries around the world show minimal production along either the tropics of Capricorn or Cancer with most cotton production occurring in either more temperate or tropical latitudes.

Given the unique latitude of the Central Highlands and its location on elevated coastal plains this project started with the very simple question of "*If you were going to grow cotton on the Central Highlands for the first time what would be the best production approach and why*"?

In an attempt to answer this question, a detailed analysis of the Emerald climate was conducted and comparisons made with Narrabri (a reliably high-yielding environment). This analysis highlighted stark differences between the temperatures, rainfall and radiation that a crop growing in Emerald might be subjected to when sown between September and October compared to a crop sown at a similar time at Narrabri. The analysis suggested that cotton would be regularly compromised by unfavourable weather conditions during boll filling at Emerald compared to Narrabri and that a different time of sowing should be considered. In particular the climate analysis highlighted that the period between late December and late February is subject to elevated rainfall, temperature and radiation variability. The Central Highlands Bollgard II® planting window inadvertently placed crops at the greatest risk of exposure to this period with cut-out and peak boll demand occurring after late December and boll opening occurring during late January and throughout February. Disruption to photosynthesis around cut-out can result in excessive fruit shedding and boll rots are more likely to be prevalent leading up to and during early boll opening. There is very little that a crop manager can do to ameliorate weather affects during these growth stages.

The climate analysis also highlighted an opportunity: the period between September and late December had the highest and least variable radiation, fewer rain days, lower humidity and milder temperature range, which is generally more favourable for boll setting and filling. In order to capitalise on this opportunity a crop would need to be sown much earlier (during August) to bring forward boll setting and filling. While this approach would not avoid the possibility of rainfall at picking, it reduced the potential period of exposure by nearly 50% compared to the status quo of mid-September to end of October sowing. When this project commenced it was unknown whether August sowing would be reliable for crop establishment due to cool temperatures although the success of cotton in the far south (Griffith) suggested that it could be a viable tactic.

This project set out to examine the opportunity to utilise late winter planting as a mechanism to better coincide boll filling and maturity with a time of year when conditions are more optimal and less variable whilst reducing the period for which the crop might be exposed to monsoonal conditions during picking.

The project also examined two auxiliary issues: (i) the pest status of soil-dwelling symphylids, which had been considered to cause crop establishment problems in some seasons in CQ, and (ii) how boll rots might be better managed under local conditions.

Objectives

1. Analysis of existing Central Highlands data and modelling scenarios

This objective was fully achieved with a review of previous research data and detailed climatic analysis. This analysis determined key factors within the historical weather records that were highly relevant for cotton production at each of the crops' growth stages. This information formed the basis for the climate crop physiology experiments and extension messages over the life of the project.

2. Consultation between project team and local growers

This objective was fully achieved through a process of continual consultation with local growers. On average, 2-4 field walks were held each season along with specific end-of-season reviews where growers could see results first hand and relate these to experiences that they might have had in their own crops that season. All of the research conducted during this project was located on commercial properties in collaboration with key growers, which also provided additional extension opportunities.

3.1 Field experiments to evaluate climate/crop physiology interactions

This objective was fully achieved with a detailed experiment being conducted each year of the project and additional data derived in latter seasons from benchmarking commercial crops.

3.2 Field experiments to evaluate mechanisms for and management of boll rots

This objective was mostly achieved with specific experiments conducted during the middle two years of the project. The first of these experiments examined infection pathways for boll rot/tight lock pathogens whilst the second experiment examined potential fungicide agents for the control of specific fungi. This work highlighted that the control of boll rot pathogens is complex and that the best mechanism may be to avoid circumstances that give rise to disease outbreaks in the first instance. The best solution would appear to be planting the crop earlier (in August).

3.3 Field experiments to evaluate management of symphyla

This objective was mostly achieved. Instead of field experiments (as symphyla are very difficult to manipulate), evaluations of symphyla abundance were made across a wide range of fields and related to crop damage symptoms in an attempt to correlate abundance with damage symptoms. In all instances where crop damage was recorded, a complex of soil pests were present. The results of these surveys would indicate that symphyla alone are unlikely to be the cause of establishment issues, although in the presence of other soil pests and disease organisms, symphyla may exacerbate crop symptoms.

4.1 Conduct regular extension activities

This was fully achieved with numerous extension activities conducted throughout the life of the project. An annual update from each seasons results were also presented to growers at an annual workshop each year (presented at both Emerald and Theodore).

Methods, results and discussion

For the purpose of this report, the climate analysis, early planting research, crop benchmarking, boll rot research and symphyla sampling components of the project will be reported in discrete sections.

Climate analysis

A climate analysis for Emerald and Theodore was conducted by Dr Stephen Yeates using the regions' historical weather records and an in-house SAS statistical package to calculate median, mean and probability factors for the weather variables of temperature, radiation, rainfall and rain days. These outputs were compared with similar calculations for Narrabri to enable comparative benchmarking and so that growers could distinguish the differences between the CQ climate and a high yielding temperate region environment, and how this may influence plant growth, development and phenological responses.

Radiation

Median radiation expressed as megajoules of energy per m^2 (MJ) is given for fortnightly periods for Emerald, Theodore and Narrabri in Figure 2. It is clear from the diagram that Narrabri has a higher level of radiation than Emerald and Theodore over the summer period; a function of diurnal variation (longer days) and less cloud. However, the key issue, particularly for Emerald is the variability in radiation for the period from late December to the end of March. This variability is due to cloud cover associated with monsoonal weather and a general increase in lower level cloudiness that occurs between mid-morning and mid-afternoon on many summer days in the Central Highlands. This cloud would appear to be a function of Emerald's topography and proximity to the coast (200 km to the north-east). For the cloudiest 10% of years some fortnightly periods only register 17 MJ of daily radiation (late January). Theodore has a similar pattern of radiation although the variability around the median is less during summer. When the expected crop phenology timeline for a mid-September to late October-sown crop is considered, the period of greatest radiation variability would coincide with the second half of boll filling. It is at this stage that a cotton crop is at peak assimilate demand and therefore highly susceptible to impacts from cloudiness (typically manifested as excessive shedding just prior to or after cut-out and reduced boll size). Limited opportunity for compensation exists for fruit losses or reduced boll size that occur at this stage.

In comparison, recorded radiation for Narrabri is less variable, particularly during the second half of the boll filling period in February and early March.

The potential impact of variable radiation become clearer when particular levels are compared to studies conducted elsewhere. Research conducted in the Burdekin between 2008 and 2012 (CRC 1.04.14) indicated that reductions in radiation to below 20 MJ for a period of 2-3 days were sufficient to cause the shedding of squares and young bolls. The analysis for Emerald shows that with the current planting date the median number of days with less than 20 MJ would peak around crop cut-out with a September/October planting date. Two or more consecutive days below 15 MJ will begin to induce shedding; there is a median value of 2 days per fortnight during most of the boll filling period with up to 5-6 days per fortnight in 10% of years. A similar pattern for Theodore was evident although occurring a little later in the season and with slightly less variability.

Narrabri has far fewer days per fortnight that fall below 20 MJ (or 15 MJ during the critical peak assimilate demand period), and the frequency of days with low light levels only increases later in the season when assimilate demand for boll filling is decreasing (Figure 3).

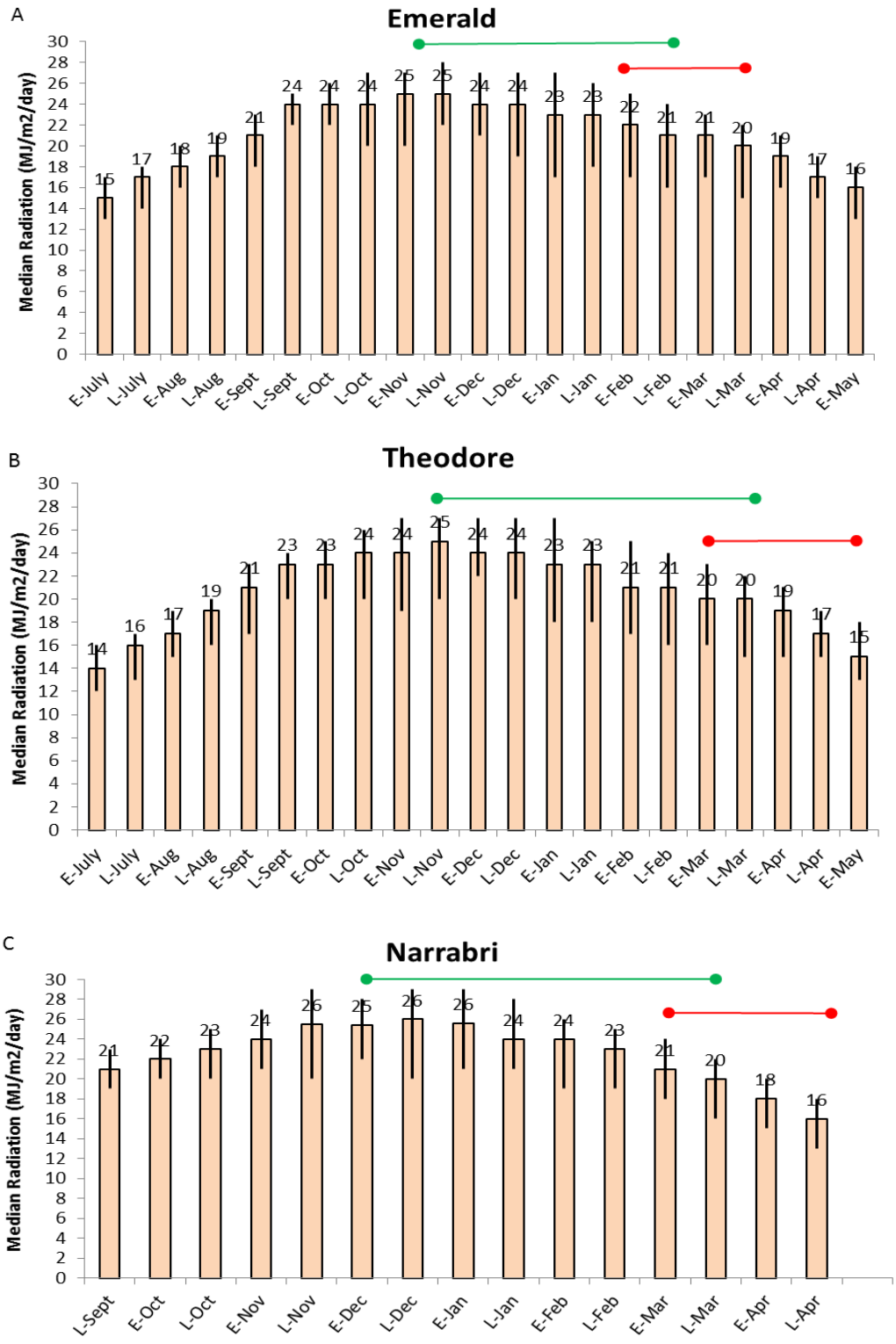


Figure 2. Median radiation values for Emerald (A), Theodore (B) and Narrabri (C) for fortnightly periods using historical data from 1957-2012.

The error bars denote the highest and lowest 10% of seasons with larger bars signalling an increased range of variability. Approximate crop phenology with the usual historical planting date (mid-September–late October) is shown by the green and red lines (green denotes the flowering and boll filling period and red the defoliation and picking period).

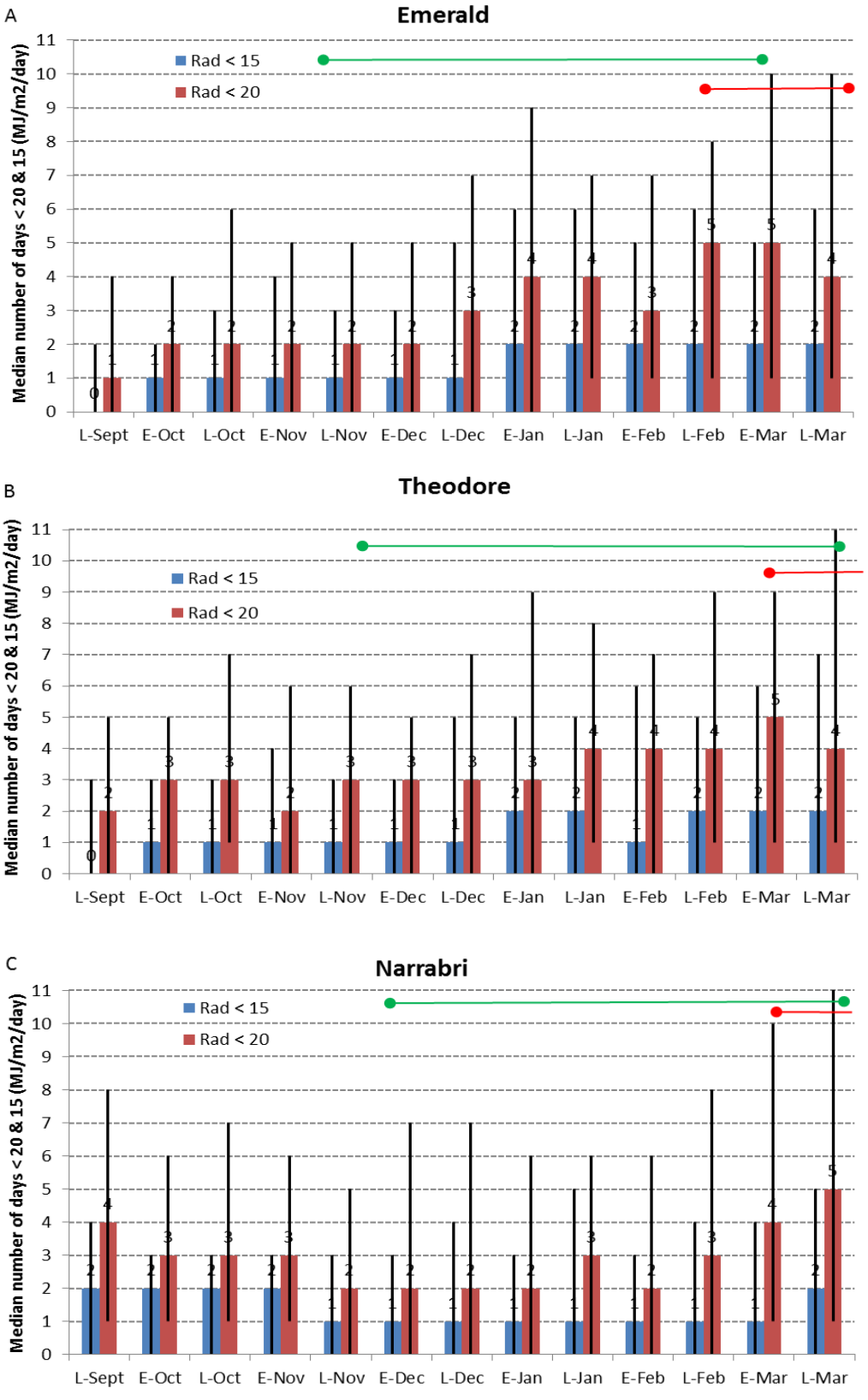


Figure 3. Median number of days where radiation falls to 20 or 15 MJ or below for fortnightly periods using historical data from 1957-2012.

Radiation values are given for Emerald (A), Theodore (B) and Narrabri (C). The error bars denote the highest and lowest 10% of seasons with larger bars signalling an increased range of variability. Approximate crop phenology with the usual historical planting date (mid-September–late October) is shown by the green and red lines (green denotes the flowering and boll filling period and red the defoliation and picking period).

Rainfall

A comparison of rainfall between Emerald, Theodore and Narrabri demonstrates stark differences in rainfall patterns and how it might relate to boll filling and picking. With the traditional Bollgard II® September/October planting window, boll filling and picking completely overlaps the historical peak in wet weather for Emerald. This leaves crops fully exposed to boll rot losses, lint quality downgrades and general picking losses (Figure 4). The pattern of wet weather for Theodore is very similar although it tails off less sharply at either end, reflecting the higher incidence of storm rain associated with weather fronts in spring and autumn compared to Emerald. When comparing the number of rain days per fortnight, Theodore has a lower frequency of rain days for similar rainfall totals overall (indicating shorter sharper storm events) compared to Emerald (Figure 5). The highest fortnightly totals recorded for each location show that both Emerald and Theodore can be subject to extreme rainfall events associated with the monsoon and tropical depressions By contrast Narrabri has much lower summer rainfall and far fewer rain days. Even in New South Wales' wetter seasons, the fortnightly values recorded at Narrabri are well below the totals seen in central Queensland.

The potential for wet weather over consecutive days is a significant driver for the issues observed with boll rots and lint quality at Emerald and Theodore over many years. In comparison, boll rot losses are infrequent at Narrabri.

Temperature

Temperature records for Emerald show the intersection of unfavourable temperatures (hot nights and days) with likely variability peaks for radiation and rainfall. Hot nights that increase cellular respiration (reducing photosynthesis efficiency) often go hand in hand with cloudy weather in tropical areas, with cloud cover enabling the retention of daytime heat. A combination of cloudy days and hot nights during the boll filling stage can lead to shedding of fruiting structures and reduced boll size. In Emerald, the incidence of hot nights peaks in the last fortnight of January with a general increase in intensity between late December and early February (Figure 6). For crops planted at the traditional time, the peak in hot nights is most likely to coincide with or just after crop cut-out. This is a time with the plant is at peak susceptibility to disruptions for assimilate production.

Theodore benefits from having far fewer hot nights, which is a function of it being further south and situated in a valley with surrounding rangeland topography that encourage katabatic winds at night time providing cooler overnight temperatures.

In terms of hot days that exceed 35°C, the frequency in Emerald peaks during January with a rapid rise during late December (Figure 7). Theodore exhibits a similar pattern of hot days with a lower frequency of above 35°C. This would also coincide with peak boll filling for most crops planted in the traditional CQ Bollgard II® sowing window (15 September to 31 October).

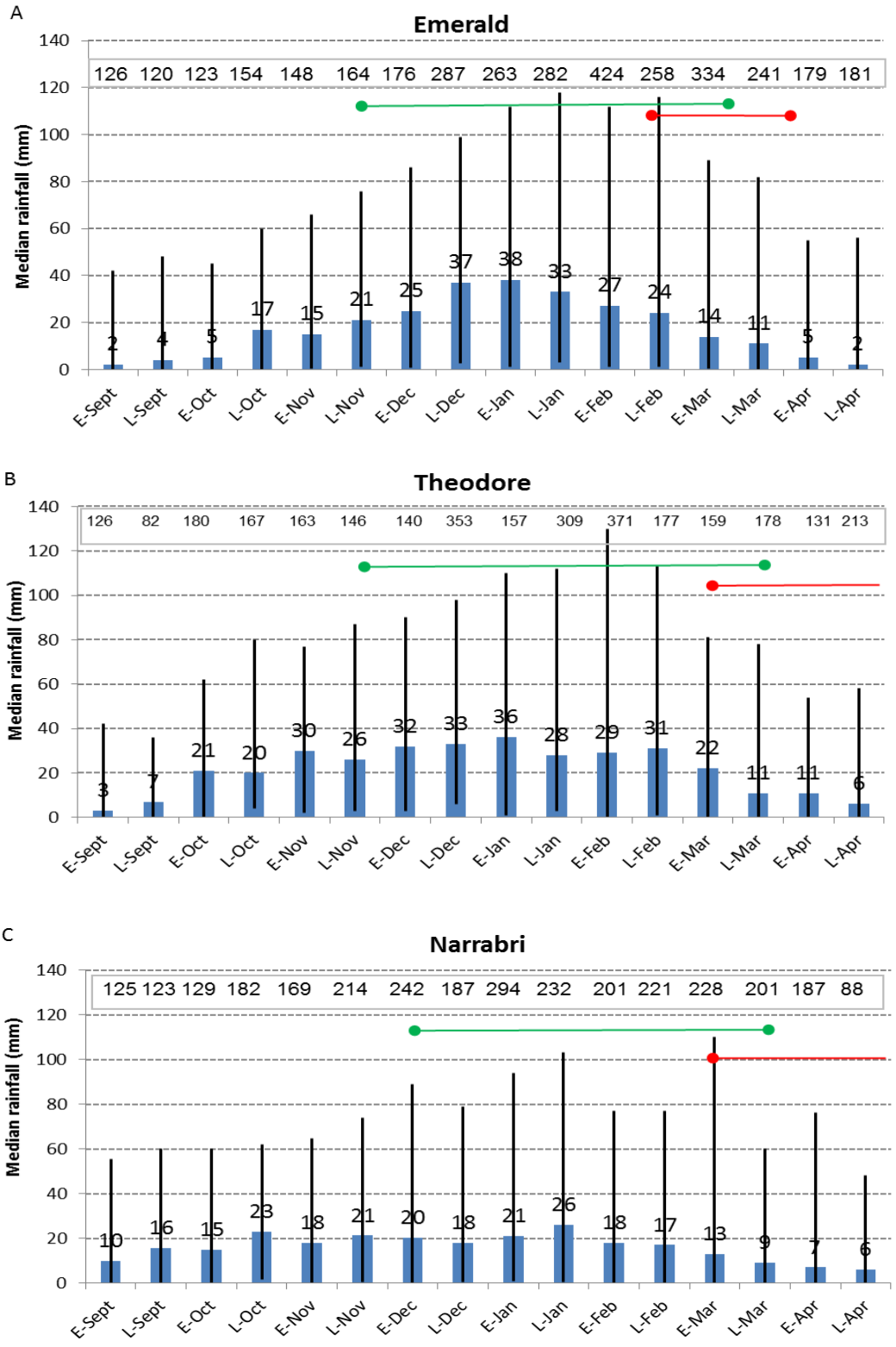


Figure 4. Median rainfall for fortnightly periods using historical data from 1957-2012.
The values given are for Emerald (A), Theodore (B) and Narrabri (C). The error bars denote the highest and lowest 10% of seasons with larger bars signalling an increased range of variability. Approximate crop phenology with the usual historical planting date (mid-September–late October) is shown by the green and red lines (green denotes the flowering and boll filling period and red the defoliation and picking period). The numbers at the top represent the highest ever recorded rainfall totals for each fortnightly period

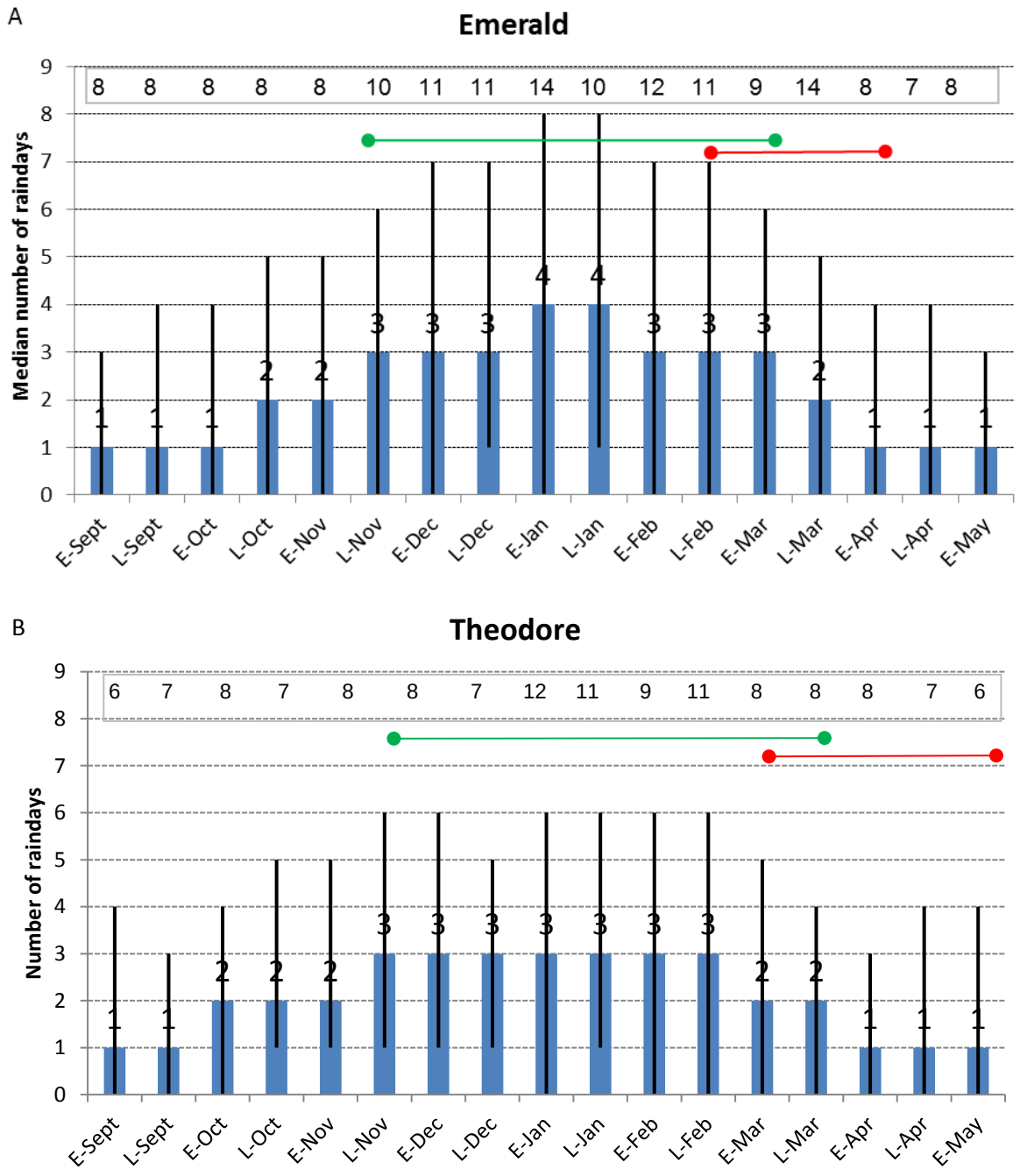


Figure 5. Median number of rain days (>1 mm) for fortnightly periods using historical data from 1957-2012.

The values given are for Emerald (A) and Theodore (B). The error bars denote the highest and lowest 10% of seasons with larger bars signalling an increased range of variability. Approximate crop phenology with the usual historical planting date (mid-September–late October) is shown by the green and red lines (green denotes the flowering and boll filling period and red the defoliation and picking period). The numbers at the top represent the highest ever recorded rainfall totals for each fortnightly period.

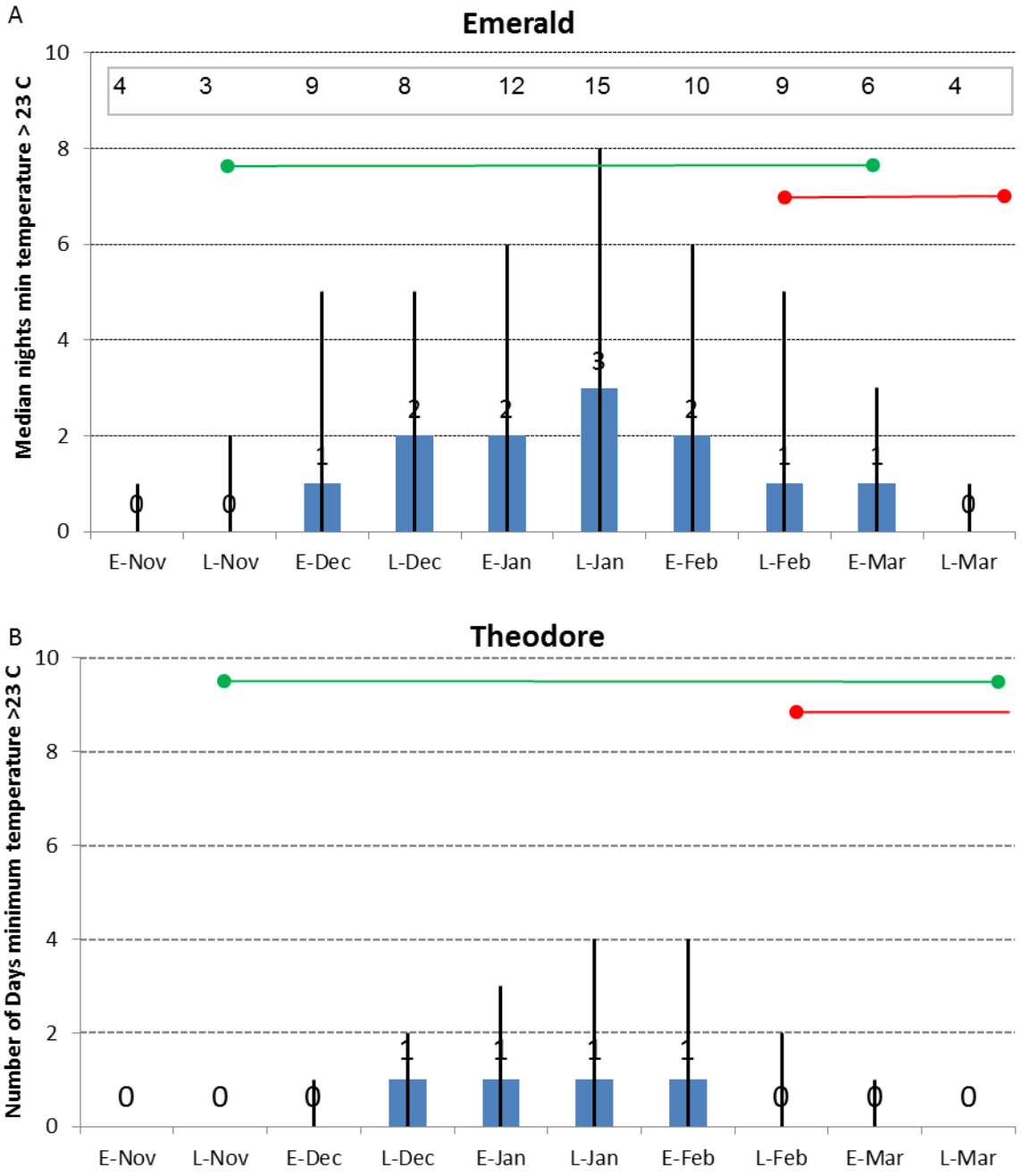


Figure 6. Median number of hot nights (minimum temperature >23°C) for fortnightly periods using historical data from 1957-2012.

The values given are for Emerald (A) and Theodore (B). The error bars denote the highest and lowest 10% of seasons with larger bars signalling an increased range of variability. Approximate crop phenology with the usual historical planting date (mid-September–late October) is shown by the green and red lines (green denotes the flowering and boll filling period and red the defoliation and picking period). The numbers at the top represent the highest ever recorded number of hot nights for each fortnightly period in Emerald.

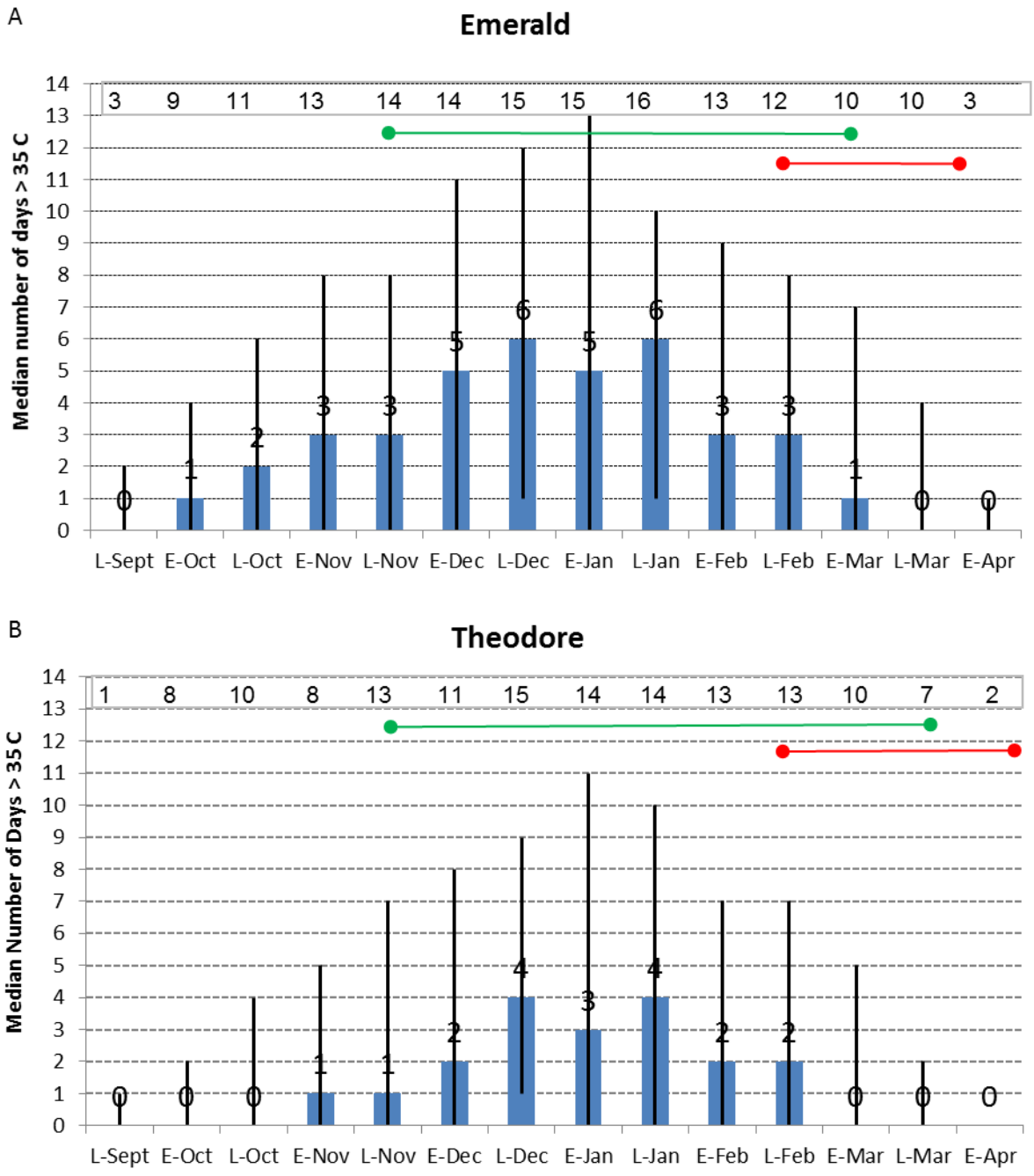


Figure 7. Median number of hot days (maximum temperature >35°C) for fortnightly periods using historical data from 1957-2012.

The values given are for Emerald (A) and Theodore (B). The error bars denote the highest and lowest 10% of seasons with larger bars signalling an increased range of variability. Approximate crop phenology with the usual historical planting date (mid-September–late October) is shown by the green and red lines (green denotes the flowering and boll filling period and red the defoliation and picking period). The numbers at the top represent the highest ever recorded number of hot days for each fortnightly period.

Climate analysis discussion and conclusions

The analysis of the Emerald and Theodore climate records identify key constraints for boll setting, boll filling, boll opening and picking during the period spanning late December to the end of February. The CQ Bollgard II® planting window inadvertently caused crops to be fully exposed to this period during the second half of boll filling whilst boll opening and picking is completely exposed to the period for when rain is most likely. Compounding these climatic issues is the high likelihood that one or more of these factors will occur at the same time. A typical example is a period of cloudy weather, rainfall and hot nights. In comparison, Theodore largely avoids hot night effects, however both situations are in significant contrast to Narrabri.

There are very few management tactics that can overcome periods of low radiation, hot nights and rainfall during the latter half of boll filling. The best tactic to deal with these climatic issues is to try and limit crop exposure to monsoon-dominated weather patterns during the critical stages of flowering, boll filling and boll opening. This has been the approach utilised in other tropical regions where the crop is grown during the milder dry season or a wet season planting window is used to expose the crop to the worst of the weather during the early vegetative and flowering stages, allowing time for a crop to compensate from any losses that occur.

However, these tactics do not really fit the Central Queensland climate. The dry season (winter) is too cold for boll formation compared to more tropical latitudes. Planting at the start of the expected monsoonal period (December) presents some opportunity for avoidance, but in seasons where climate variables are more extreme (particularly during February), temperatures and radiation are unlikely to be fully conducive to overcoming early season fruit losses as temperatures rapidly cool from March to May, limiting compensation potential. Experiences with this approach from the Burdekin and far north Queensland have also highlighted that agronomic management for crops during the vegetative and early flower stages under monsoonal conditions can be extremely challenging with regards to nitrogen, irrigation and canopy management as environmental conditions predispose crops to have rank growth and excessively shed fruiting positions. Indeed, December and November sowing was tested by Sequeira (2008) in Emerald over three seasons between 2005 and 2008 with unfavourable results.

Mid-summer conditions present a significant conundrum for cotton production in Central Queensland as the cold weather constraints of winter make it difficult to completely avoid the 8-10 week period of weather from late December until early March that is both unpredictable and historically variable.

Given the experiences with the wet season cropping approach in the Burdekin and potential shortcomings of applying this model to Central Queensland, an alternative hypothesis was to bring boll filling forward as much as possible to reduce crop exposure during January and February by planting in August to enable earlier maturity. The radiation, temperature and rainfall profile for the period spanning October to mid-December is very favourable for boll formation and filling. There was minimal information available regarding how successful an August sowing window would be and therefore it was decided that such a tactic was worth investigating. Planting early might limit crop flowering and boll filling exposure to monsoonal conditions, and while the possibility of a wet pick in January remains for some seasons, such an approach has the potential to halve a crop's exposure during this period compared to the status quo, with picking being mostly complete by the beginning of February. Historically February has a higher incidence of monsoonal rain events (rainfall over more consecutive days) compared to January (which has a higher median but more likely to have dry days in between). Key research questions would be:

1. How viable is planting in August with the spectre of multiple cold shocks?
2. Would August sowing enable earlier flowering?
3. Would earlier flowering improve yield potential and enable earlier crop maturity?

How cold is August in Central Queensland?—The historical record

The prospect of achieving earlier flowering and boll filling in Central Queensland depended on whether cotton could be reliably sown and established during August. The key constraint for reliable establishment at this time is ambient air temperature and its relationship with soil temperature. Ideally cotton requires soil temperatures of above 14°C at 8 am at 10 cm depth for reliable germination and emergence.

In the absence of relevant soil temperature data, an analysis of minimum air temperatures was conducted for Emerald and Theodore. As expected, Emerald is significantly warmer than Theodore during the month of August. Using a traditional cold shock model with a base temperature of 12°C would suggest that both locations would be too cold to attain reliable establishment with a median number of 11-14 cold shocks per 15 day period for Emerald or Theodore in August (Figure 8). However, a comparison with other southern sites such as Griffith and Narrabri (Figure 9) for the period of late September and October where careful sowing practices are successful suggested that Emerald was no cooler than these regions, and therefore with a mindful approach to sowing, August planting should theoretically succeed.

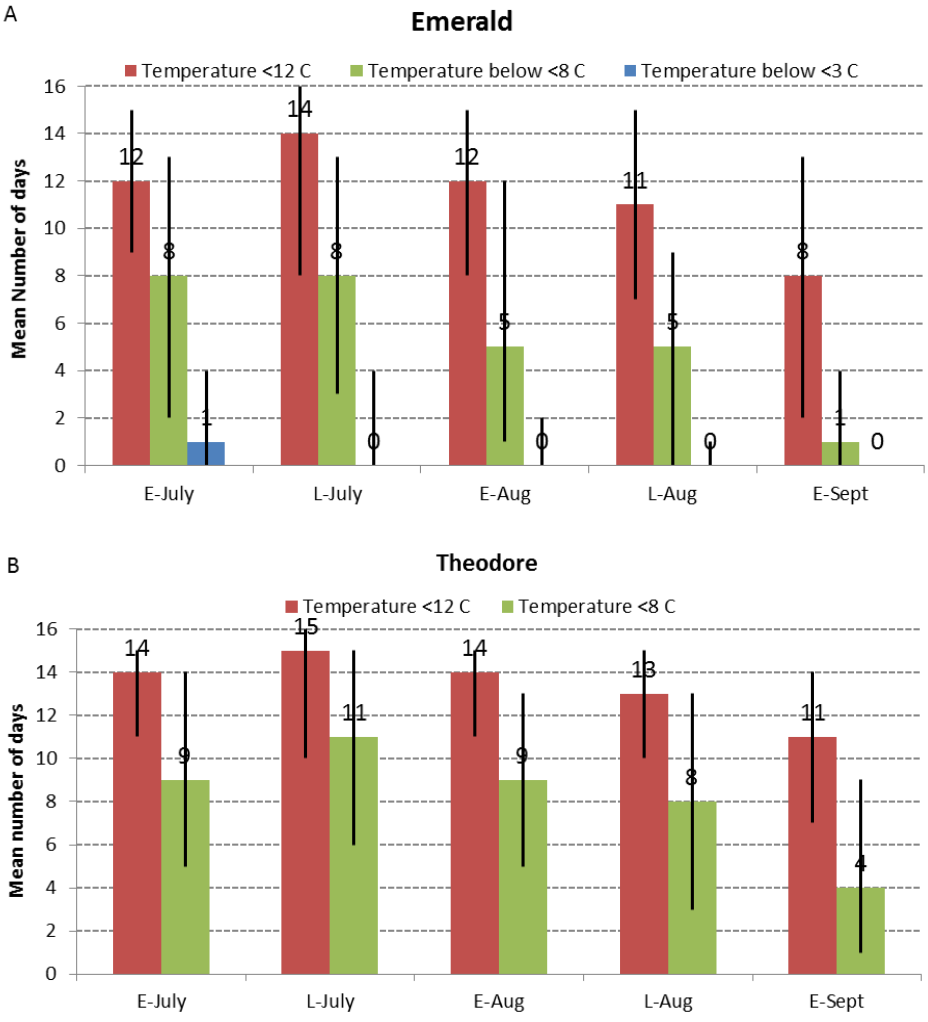


Figure 8. Median number of cold nights with minimum temperatures falling below 12, 8 and 3°C for Emerald and 12 and 8°C for Theodore.
The error bars denote the highest and lowest 10% of seasons with larger bars signalling an increased range of variability.

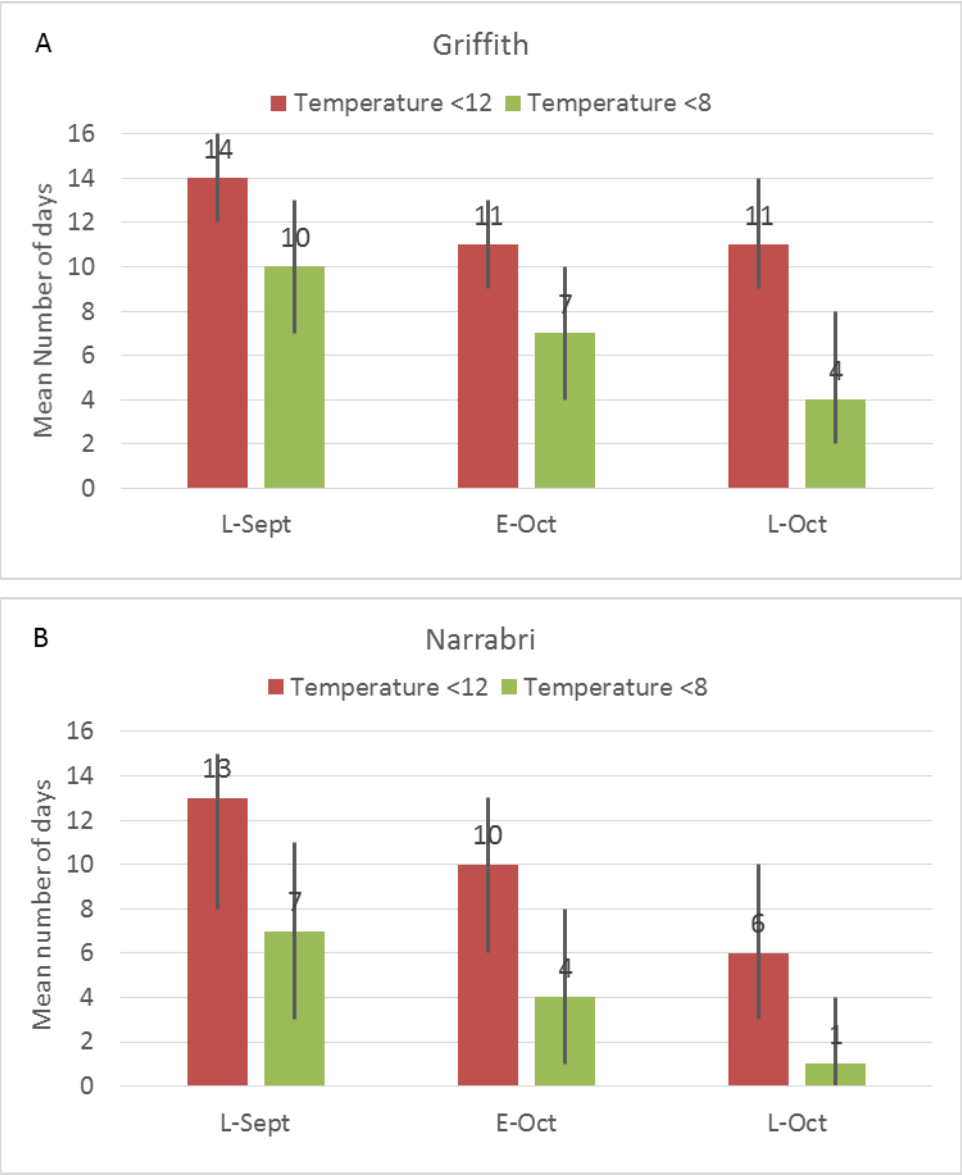


Figure 9. Median number of cold nights with minimum temperatures falling below 12 and 8°C Griffith and Narrabri.
The error bars denote the highest and lowest 10% of seasons with larger bars signalling an increased range of variability.

Early planting research

The primary planting date experiment was conducted at 'Orana' (Cowral Agriculture) located on the western side of the Emerald Irrigation area 5 km north-west of the township of Emerald. The site was an alluvial clay soil overlaying a partly sodic subsoil at about 750 mm depth.

Methods

The experiment utilised a split plot randomised complete block design, where main plots were the sowing date with four replications in randomised blocks. During year one the subplots consisted of two different row spacings (1 m and 0.37 m) with and without degradable clear plastic. For the second and third year only degradable plastic was used as subplot treatments (with and without degradable film) on 1 m row spacings. For the fourth season due to film unavailability, two different cotton cultivars were used as split-plots instead. The first two seasons utilised four sowing dates approximately 14 days apart. During the final two years of the study this was reduced to three dates approximately 21 days apart (Table 1).

Table 1. Sowing dates for the 4 years of the study

Season 1	Season 2	Season 3	Season 4
5 Aug 2013	3 Aug 2014	1 Aug 2015	1 Aug 2016
19 Aug 2013	14 Aug 2014	21 Aug 2015	21 Aug 2016
2 Sep 2013	2 Sep 2014		
15 Sept 2013	15 Sept 2014	15 Sep 2015	15 Sep 2016

Sicot 74BRF was used for the first three years of the experiment. During the final year two new Bollgard® 3 Flex cultivars (Sicot 746B3F and Sicot 748 B3F) were utilised in place of the degradable plastic split plot variant.

In Year 1 the experiment was conducted as a small plot experiment with individual split treatment plots 8 rows wide by 15 metres in length. During the second year the scale of the experiment was increased to field length plots (approx. 400 m) 16 rows in width (8 rows per split plot), which allowed better tailoring of agronomic practices such as irrigation, fertiliser and chemical application. During the final two years of the experiment larger plots were used with plots 24 rows wide by the length of the field using a split plot (2015/16 film vs no film and 2016/17 cv 746BRF vs 748BRF). The larger plots enabled agronomic management to be tailored more easily to commercial practices as 24 rows neatly fitted planter, ground spray rig and picker configurations.

During the first season, the degradable film was laid by hand (Photo 1). The film was manually slotted to allow cotton seedling emergence and fitted carefully to the beds after planting so that the slots aligned with the planted rows. Manual film laying was a major undertaking as difficulties were encountered with correctly aligning the slots in the film so that seedlings could easily emerge together with problems securing the film across the beds during windy conditions. The plots were regularly inspected and the film re-attached during the first weeks of the experiment. It was therefore decided that laying film on beds would be an unviable tactic commercially and that laying much narrower sections of film on hills spaced at one metre would be simpler. Film could be held more tightly against the soil surface due to the curve of the hill unlike the wider film spanning the centre of the bed, which typically vibrated with the wind and shook loose over time. The amount of film required per hectare was reduced by applying it to hills (to approx. 4000 m^2 film per ha) and the smaller span of film on each row was more easily weighted with soil from the sides of each furrow. The other key advantage was that it was easier to align the slots with each planted row. This enabled the design and construction of a very basic two row tractor-drawn device that could apply film to the plots post-planting (Photo 2). This facilitated the use of field length plots, allowing commercial-scale comparisons to be made regarding the effects of film on crop growth and yield.

Photo 1. Laying film on 2 metre beds with manual labour post-sowing.

Photo 2. Laying film mechanically to 1 metre hills post-sowing. Mechanisation allowed field length plots. Layer design by Carlo Stangherlin, Cowral Ag.

The initial field (which had contained irrigated cotton in the season prior to this research) was utilised for the first two seasons, then the experiment was relocated to a directly adjacent field for the remainder of the project (Photo 3). The second field had undergone laser levelling and then grew a late summer/autumn mungbean crop prior to being planted to cotton for the experiment commencing in August 2015.

Photo 3 The mechanisation of film laying enabled the experiment to be scaled up to field length split plots (2015/16 experiment shown).

The intent when sowing was to establish a uniform plant population between 8-11 plants per linear metre of row across each of the sowing date treatments. Much higher seeding rates were used for the August sowings with approximately 14-16 seeds sown per metre row to compensate for an expected poorer rate of seedling establishment due to cold conditions. Seeding rates were reduced to 9-10 seeds per linear metre for the September treatments as a higher rate of establishment was expected. Seed treated with Cruiser™ and Dynasty™ (thiamethoxam, azoxystrobin, fludioxinil, metalaxyl-M and acibenzolar-S-methyl) was used during the first 3 years of the experiment. During the fourth year only Cruiser™ seed was used due to unavailability of the Dynasty™ treated seed from CSD in time for an August sowing.

The field area was pre-irrigated prior to planting each season during early July. During the fourth year pre-irrigation was unnecessary as 135 mm of rain fell on the trial field during early July. The first August sowing was planted into soil moisture each season. The remaining planting treatments were sown shallow (2-3 cm) and a quick flush of irrigation applied so that the seed could readily imbibe moisture.

During year one, raised beds on 2 metre centres were used to accommodate the 2 x 1 m and 4 x 0.37m rows sown on each bed. For the remaining three experiments, standard 1 metre spaced hills were utilised. Furrow irrigation was used for each experiment.

Day to day agronomic issues were managed by Mr Jamie Iker (Spackman Iker Ag Consulting) in consultation with the Project Leader (Paul Grundy) and Mr Carlo Stangherlin (the 'Orana' farm manager). Mr Iker was responsible for making weekly assessments of insects and crop agronomic input needs (irrigation, mepiquat chloride, nutrition). Insect pests were managed by scouting two times each week; insecticide decisions were made when pest densities reached levels that were typically just below commercially accepted thresholds (Williams *et al*. 2013) to

ensure that insects had limited impact on fruiting site abortion. During the 2016/17 season, insect thresholds were relaxed early season as it became clear that it would be impossible to maintain high level crop retention due to repeat early season infestations of mirids and *Helicoverpa*. Despite early season retentions falling to around 50%, final boll counts and crop maturity was equivalent to previous seasons.

Fertiliser (220 kg/ha N as urea, plus 30 kg/ha P and 85 kg/ha K as muriate of potash) was placed in a band 300 cm deep and within 15 cm of the crop row several months before planting each season. A further 90 kg/ha N as urea was applied as a side-dressing during the squaring crop stage each season.

Mepiquat chloride (MC) was only applied to the 15 September sowing treatment in 2014/15 and 2015/16 due to excessive vegetative growth that occurred during cloudy weather (which also exacerbated fruit shedding in this treatment). The rate and timing for these applications were conducted according to guidelines determined for MC usage (ACPM 2012).

Measurements

Date of first squaring was defined as when 50% of plants within a metre of row had one square with an unfurled subtending leaf. Dates of first flower and first open boll were defined as when one was present per metre of row. The total number of nodes and nodes above the uppermost first position white flower (NAWF) were counted on five plants in each plot at approximately weekly intervals from first flower. Cut-out or last effective flower was defined as when NAWF<4 (Bourland *et al.* 1992). Crop maturity was determined when 60% of the bolls were open and pickable. This was determined by counting and hand harvesting open bolls from 3 metres of row within each plot every 4-7 days from first open boll to complete crop maturity.

Above-ground biomass was recorded by taking 1 m^2 samples from each plot (four samples per treatment replicate; 16 in total). Each field sample was weighed and then subsampled for partitioning into stems, leaves, squares, flowers and bolls prior to drying at 65°C for 7-8 days in a fan-forced oven. The subsample was taken to represent approximately 60% of the fresh weight sample with the total weight and sub sample weight used to later multiply the partitioned dry weights back to a 1 m^2 equivalent. Prior to partitioning, fruit retention was assessed (total sites and fruit present) and recorded for every plant within each 1 m^2 sample. Biomass samples were taken from the plots at the crop stages of first square, first flower, approximately 21 days after first flower, cut out, first open boll and when approximately 60% of the bolls were open (1-4 days prior to the commencement of defoliation).

The proportion of light intercepted was measured at 7-10-day intervals from first squaring until a maximum was reached. A 0.9 m line sensor (Licor Industries, Nebraska, USA) was placed across the centre of one row in each plot. Readings were taken at ground level and above the crop at two locations in each plot within 30 min of solar noon. The proportion of radiation intercepted at noon was calculated as RIn = ((I above - I below)/I above). Because noon measurements were taken, the proportion of intercepted radiation was adjusted for diurnal changes using the method of Charles-Edwards and Lawn (1984), i.e. RI = 2RIn/(1 + RIn) where RI = the daily fraction of radiation intercepted. Incoming solar radiation was measured 50 m from the field as part of the meteorology station (Campbell Scientific).

The contribution of different boll cohorts to overall yield was measured using a segmented handpicking technique just prior to machine picking. The fruiting branches (FB) of each plant within 2 m of row were numbered from the base to the top and grouped into subsets of 4 nodes resulting in FB categories 1-4, 5-8, 9-12, and 13 and above. For each of these FB groups on each plant, the number of bolls in the first position (P1) and ≥P2 locations were counted, and seed cotton was handpicked for weighing. In this way, the number, size and contribution to overall yield could be calculated relative to each canopy section of the crop.

During the first season, seed cotton was machine-harvested with a trial plot spindle picker from the entire length of three plot rows that had not been used for other destructive plot assessments. Larger plot end plants were manually removed prior to machine picking. Lint yield was calculated by ginning a 400 g subsample with a 10 saw mini-gin at the DAF Toowoomba laboratory. Because the turnout from a small 10 saw gin is higher than a commercial scale gin, the gin turnout was adjusted to a commercial value using data from the remainder of the field that had been planted to the same variety on the same day as the trial's mid-September sowing and commercially picked and ginned at the Queensland Cotton companies Emerald ginnery. The turnouts from the 10 saw mini-gin were 4% higher than the industrial scale gin so plot picked yields were adjusted accordingly for all treatments.

For the other seasons the plots were harvested with a commercial JD7760 picker, with separate modules produced for each picking pass to allow plot yields to be accurately determined (Photo 4). Each module was weighed individually with electronic scales (10 tonne scales with accuracy of +/- 10 kg) to determine seed cotton yield picked from each plot. The modules were then recorded and tracked through the commercial ginning process courtesy of Queensland Cotton. The modules from each planting date were ginned as separate gin runs, enabling a commercial lint turnout to be calculated for each planting date treatment as well as an assessment of lint quality for every bale produced from each gin run. Each gin run consisted of 6 round modules of seed cotton at a time.

Photo 4. Picking the 2015/16 trial with JD7760 picker. A module was made for each pass (4 modules per 24 m wide plot).

Lint samples from the cotton picked during the first season were classed for length, strength and micronaire by CSIRO's Narrabri laboratory. Every bale produced from the trial area for seasons 2-4 was commercially classed for colour, leaf, staple length, fibre strength and micronaire.

Weather, soil temperature and water recording

Field conditions were monitored with an automated weather station (Campbell Scientific) which recorded temperatures, rainfall, humidity, solar radiation wind speed and wind direction. This station was located directly adjacent to the trial fields during the four seasons.

Each season soil temperatures were measured and recorded using Tinytag data loggers (TGP-4020) equipped with a soil temperature probe. Several of these loggers were installed for each planting date with and without film and used to record soil temperature at 10 cm depth every 3 minutes. These probes were removed at the end of September.

Soil water was also monitored for the experiments in years 2, 3 and 4 using an EnviroSCAN capacitance probe in the early August sowing date and the mid-September sowing treatments. Physical soil cores were taken from each of the treatment replicates of early August and mid-September to conduct gravimetric soil water measurements. These measurements were taken within a couple of days of emergence to determine the starting field water content as well prior to the majority of the irrigations that were applied to the field over three seasons. Soil cores were taken two days after an irrigation during October to calculate the upper filled limit of the soil together with cores taken straight after picking to determine final soil water at crop completion. The soil cores taken for gravimetric soil water together with irrigation records, C probe data, weather station data and crop leaf measurements enabled accurate assessment of crop water use throughout each experiment.

Comparison of different degradable film types for improving soil temperature

Whilst the clear oxy-degradable film was deployed in the main planting date trial due to the commercial availability of product, a small plot experiment to compare a range of films was also conducted in the first season. The films tested included:

- Transparent/clear oxy-degradable film
- Semi-transparent biodegradable Mater-Bi film (based on starch)
- Black oxy-degradable film
- Control (no film)

These film types were applied to small plots of cotton (3 beds x 15 metres) and comparisons made of soil temperatures and crop growth. Crop growth measurements in the end were compromised be the inability to keep the film secured to the beds (some film types were barely wide enough to ensure a secure fit to the beds). The aspiration to measure crop growth was consequently not followed through for the small plot film comparison experiment. Only the impacts of these films on soil temperature will be reported here.

Results & Discussion

To simplify the reporting of the early planting research, the trials conducted with film and specific film results will be presented first. As the film failed to provide significant benefits in terms of crop growth and yield specific film related data will be presented first and for the remainder of the report the results from the planting date studies will pertain to the treatments planted without film (controls).

Degradable film research

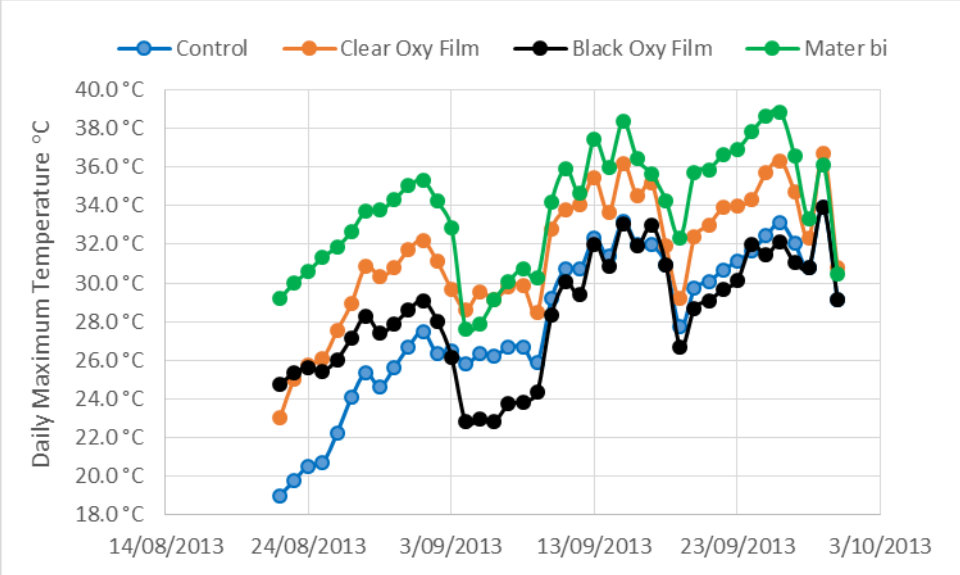
The impact of different film types on soil temperature

A range of films were tested during the first year for soil solarising qualities. The temperatures recorded in the film comparisons are given in Figure 10. The temperature increases recorded in this experiment were the highest recorded during the three seasons where film was utilised. We assume the reason for this was that the film was fitted to whole beds in the first season (increasing the solarisation surface area) compared to narrow width plastic laid on hills during successive seasons.

Transparent films were found to provide the greatest benefits in terms of raising soil temperatures (Figure 10). Surprisingly, the black oxy-degradable film tested did little to heat the underlying soil, except for the period immediately after its application to the beds. The film was observed to 'stretch' post laying leading to a less 'snug' fit on the bed. This resulted in the film shading the underlying soil without conferring heat. The black film also caused foliar damage to the seedlings as they emerged through the slots, most likely because the black film itself became very hot during the day. The transparent Mater-Bi film gave the best performance, possibly because it was a thicker film (14 uM) compared to the clear oxy-degradable film (Degricover) at 10 uM. However the clear oxy-degradable film was used for the remaining experiments due to both its ready availability and the preparedness of the manufacturer to work with us and create a pre-slotted film product that could be laid mechanically. Mater-Bi could not be acquired in a width suitable for laying on 1 metre hills or with slotting.

Due to poor establishment in a number of plots with the different film types (major difficulties were encountered fitting different width products to the same shaped beds) the plots were not continued on to assess crop impact. As oxy-degradable clear film had been laid in the main experiment (this film was available in a suitable dimension) assessments of crop development under film were conducted in that experiment.

(a)



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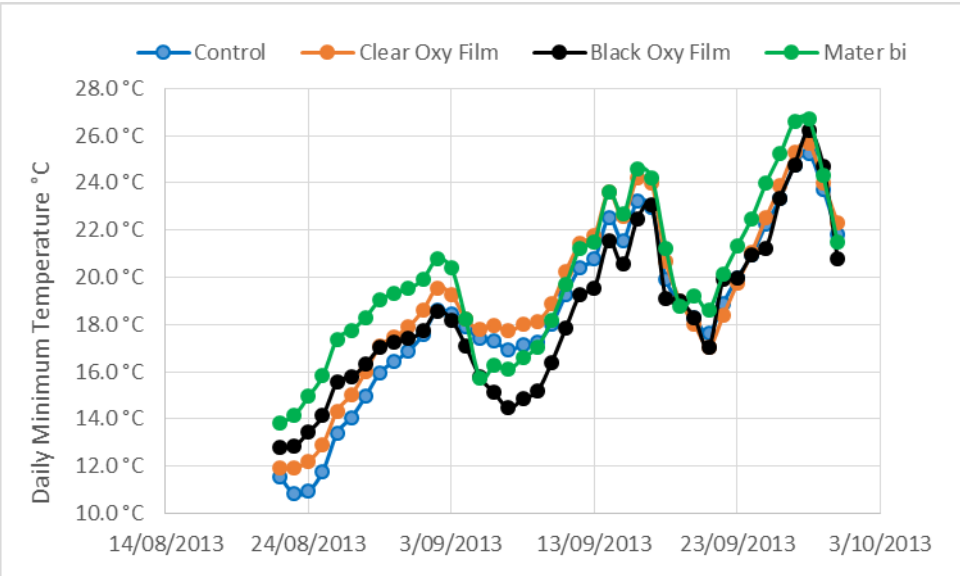

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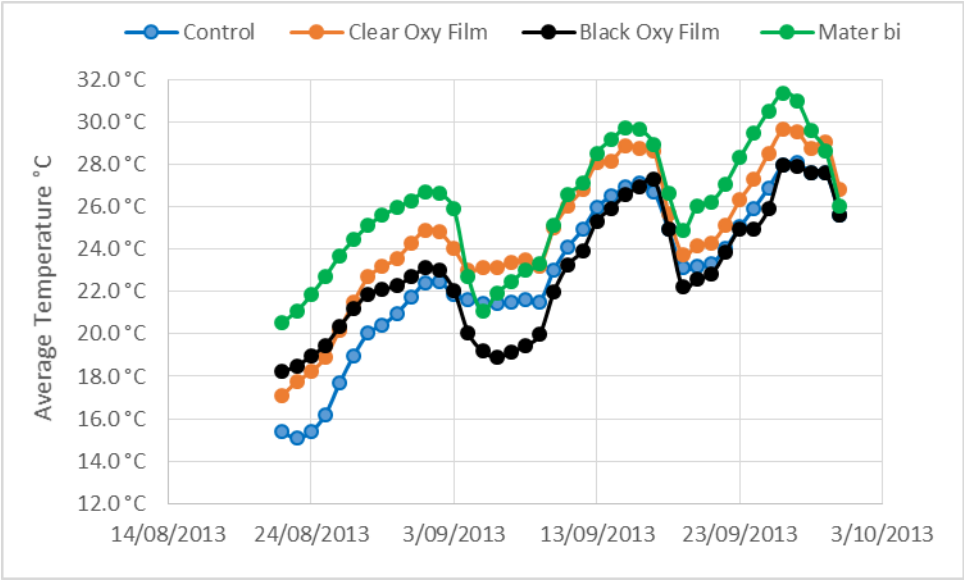


Figure 10. Temperature recordings of (a) daily maximum (b) daily minimum, and (c) daily average with the three different film types (clear and black oxy-degradable film and starch-based biodegradable Mater-Bi film) compared with uncovered soil (Control).

Photo 5. Oxy-degradable black film laid as part of the film testing plots (UNR configuration).

Photo 6. Starch-based biodegradable Mater-Bi film laid as part of the film comparison experiment (Conventional configuration).

Impact of clear oxy-degradable film for soil temperature when laid on hills

Temperature measurements made in the main experiment during 2014 and 2015 found that the addition of clear oxy-degradable film to 1 metre hills augmented an average increase in soil temperatures of about 2-3 degrees compared to the controls. The majority of this increase occurred during daylight hours with the minimum temperatures recorded being virtually the same as the sensors located in bare soil. The soil profile heated up more rapidly during the day under film, reaching a higher maximum before falling overnight to reach the same minimum point, albeit for a shorter period of time. The slotting of the film over the seedling line (necessary to enable seedling emergence) would appear to counteract the thermal gains achieved during the day by providing an exit point for heat loss overnight. Figure 11 shows the typical pattern recorded for film versus no film throughout August and early September.

Photo 7. Clear oxy-degradable film applied to 1 m spaced hills. Photo shows Tinytag data logging equipment.

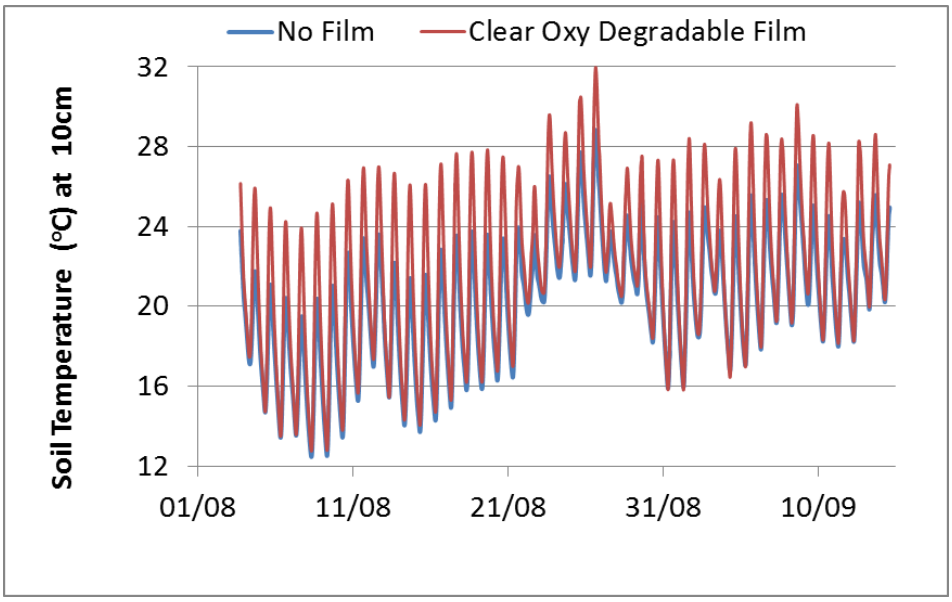


Figure 11. Soil temperature recorded with and without the overlay of film on 1 m spaced hills (2015 data).
The film increased daytime maximums achieved leading to an overall increase in average temperature over time. The minimum temperatures recorded though are virtually the same with the film failing to prevent losses of the heat gained during the day.

Impact of clear oxy-degradable film spacing on crop phenology, biomass accumulation, crop maturity and yield

Film had limited effect on crop phenology. In general terms the film caused a short term increase in crop development rate resulting in the production of two additional nodes compared to the control treatments at the time of first flower. However, this difference was barely discernible by the end of each season with maturity picks indicating no difference across all seasons (Figure 13).

The effect of film on crop biomass was marginal with differences typically being observed throughout the growth of each sowing date (with and without film) but reducing over time. The relatively higher accumulation of biomass associated with the use of film did not confer significant yield increases (Table 2 on page 38), although the means for the film plots were always greater than the controls. Figure 12 shows the typical pattern of biomass accumulation for an August-sown crop with and without film. If Emerald were to remain cooler for longer or if the initial biomass gains could be extended it is likely that significant yield differences would be achieved. However, in the Emerald environment, with the planting dates and method of film application used, the biomass gains did not confer statistically significant yield gains.

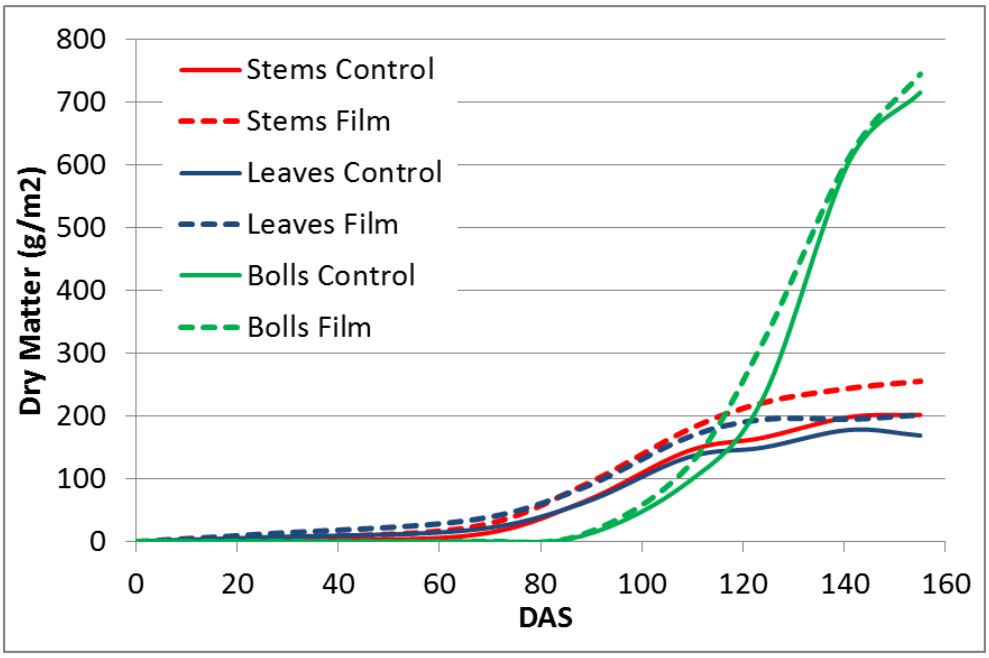


Figure 12. Dry matter accumulation for early August sown cotton 2014/15.
The rate of biomass accumulation occurs more quickly with the use of film at each of the sample points and final biomass is noticeably higher. However, the final biomass differences are insufficient to create significant yield differences (see Table 2 on page 38).

Photo 8. The application of film caused plants to have a higher biomass and flower several days earlier, but these differences (seen here with a control plant left and film plant right sown at same time at first flower) were not sufficient to give significant differences in crop yield.

Impact of UNR on crop phenology, biomass accumulation, crop maturity and yield

Similarly, the planting of cotton on ultra-narrow row spacing (UNR) did not alter crop maturity compared to conventionally spaced cotton. Figure 13 shows the rate of boll opening in percentage terms over time for the conventional with and without film and UNR treatments for the early August and mid-September sowing times in 2013/14. These figures show no crop maturity advantages were gained through either the use of film or UNR row spacing for either planting date. No significant yield advantages were measured in the UNR treatment plots relative to the conventionally spaced controls (Table 2). The investigation of UNR row spacing as a treatment variable to encourage earlier maturity was discontinued after the first season.

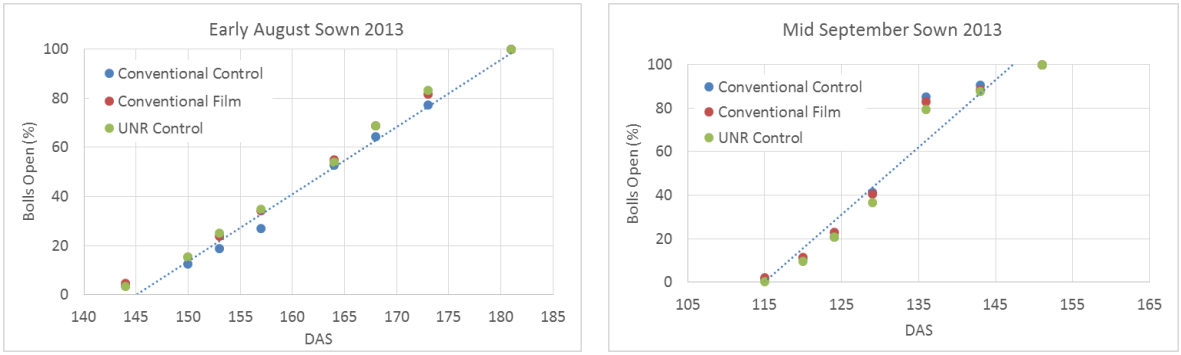


Figure 13. Percentage open bolls derived from maturity hand picking for the conventionally spaced cotton with and without film and UNR spaced cotton without film for early August and mid-September sowing treatments.

There was no discernible difference for crop maturity with film or UNR spaced rows. The blue dashed line shows the trend for the conventionally spaced cotton control.

Practical issues for utilising film for cotton

Whilst the use of degradable films proved ineffective in terms of augmenting crop biomass in a way that provided significant yield advantages at Emerald, the experiences had with utilising degradable films is worth recording in this report for the benefit of others who might consider utilising film in other regions under different climatic conditions.

A number of practical limitations were encountered when applying film in the field. The first issue was to ensure that the perforations or slots in a type of film aligned accurately with the planted seed line. If the slots and plant line are not well aligned, cotton has difficulty emerging past the film (Photo 9). Laying film as a separate operation to planting is unlikely to ever be commercially viable unless it included a system that would allow two separate items on different tractors to align perfectly (within 10-15mm) across eight or more rows. The more feasible solution is equipment that could plant and lay film simultaneously. Norseman Engineering have developed a prototype and are currently testing the market for its potential.

Photo 9. A key challenge with films for cotton is that cotton is poor at emerging past any obstacles. Unless the cotton was perfectly alligned to the slots (as it is here) it was unable to emerge. Clearance of the film typically took 2-10 days.

Even with mechanised application of film, the addition of this task to the planting operation is likely to reduce planting operation efficiency (including replacing film cartridges and intermittent stops to fix film or ameliorate laying malfunctions). The sheer scale of cotton planting in terms of hectares compared to other horticultural commodities that utilise plastic films presents a significant challenge.

Other challenges encountered with film relate specifically to some of the film versions tested but should be considered for any future film product types. The oxy-degradable products tested (across series of product batches) were found to be problematic on breakdown. Some versions degraded too rapidly (Photo 10) whilst others persisted for too long. Having the correct film formulation to suit the intended purpose and usage environment is important. It is not clear what the oxy-degradable type films break down into and field observations would suggest that the film fragments into smaller pieces at which point they are susceptible to moving around within the local environment. Challengingly, the formulation of films tested did not degrade under the soil surface. So whilst the film at the ground surface was mostly absent by crop maturity, when the field was worked, a large amount of film is brought to the surface. Even 18 months after its use, subsequent tillage operations were still bringing film to the surface (Photo 11).

Photo 10. Oxy-degradable films had a tendency to break down rapidly after a set point of time, breaking into many smaller pieces that were blown around in the wind. This particular version was one of the prototypes tested which broke down too quickly. Shown here at 28 days after laying.

Photo 11. A significant issue encounted with oxy-degradable films was its inability to degrade under the soil. The impact of that can be seen in the photo (right) when conducting a stalk pulling operation during the 2014/15 full field scale experiment. Film left on the surface would subsequently break down and get less with each working. However, film could still be found in the field 18 months after this first working.

There are questions around oxy-degradable films as a risk for plastic contamination at picking. Whilst the majority of film had broken down by picking, film at the interface of the soil where the edges were buried during laying remained intact and brittle (Photo 12). It is highly probable that fragments of plastic from these edges could be drawn into a picker at harvest resulting in contamination of fabric down the processing line. This would need to be examined thoroughly should oxy-degradable films be deployed commercially and careful attention paid to film formulation to ensure that breakdown was complete prior to picking (e.g. 100 days).

Photo 12. Remanents of oxy-degradable filmm a month prior to defoliation. The film protected by soil does not break down and is gradually exposed at a leading edge. These fragments of plastic could potentially be sucked into a picker at harvest.

The Mater-Bi film was a biodegradable film based on plant starch. This film broke down evenly over time both above and below the soil and dissolved into the soil without breaking up and moving around. However, this film was highly expensive with the prototype tested equating to $850/ha (cost estimates for the oxy-degradable product are $350/ha). It is therefore unlikely that sufficient yield benefit would be achieved to justify the cost of Mater-Bi film plus application in cotton production at current prices.

Photo 13. Mater-Bi as a starch-based film had a much more controlled process of breakdown where the film would shrink in on itself as it degraded leaving no trace either above or below the soil at picking.

August air and soil temperatures 2013-2016

Measurement of both air and soil temperatures over a four year period showed that despite air temperatures regularly falling below 8°C soil temperatures mostly remained above 14°C (Figure 15). A conclusion from measuring air and soil temperatures at Emerald is that the absolute minimum and maximum temperature records that feature prominently in BOM data are only of partial value for determining potential crop impacts and that the more important factor is a given period of time at temperature. Overnight minimum temperatures at Emerald are typically recorded within hours before sunrise as temperatures typically begin to fall more precipitously after midnight. After sunrise the days heat up rapidly which is evidenced by the excellent radiation values recorded for August (Figure 2). This is well demonstrated by Figure 14, which shows the overnight temperature profile recorded at Orana on 21 August 2017 for what has been the coldest evening recorded since the installation of monitoring equipment in 2013. On this occasion temperatures fell quickly overnight but despite the cold conditions, temperature still increased rapidly the next morning and corresponding soil temperature logging equipment operated at 'Braylands' by CSD (20 km away in a similar low lying area to 'Orana') measured soil temperatures that only briefly dipped below 14°C before rapidly heating back up again (Figure 14).

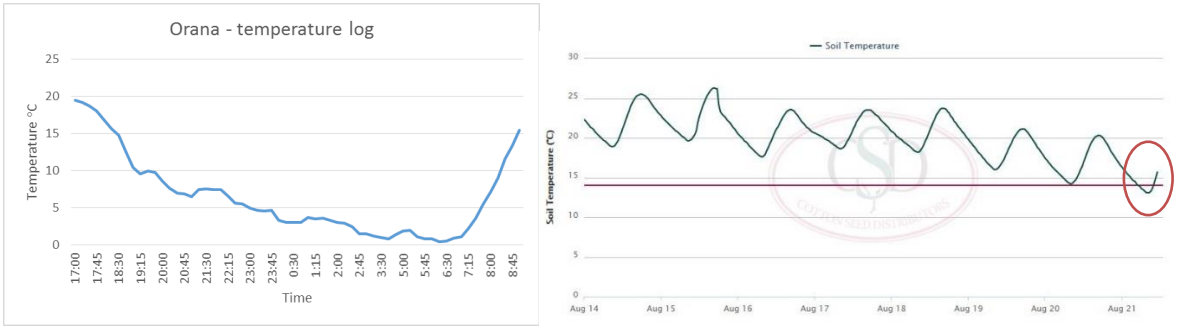


Figure 14. Temperature log for 'Orana' 21/8/2017 showing the coldest evening recorded in 5 years (left) and CSD soil temperature log for nearby 'Braylands' at Emerald.
Note the rapid increase in air temperature by 9 am and a corresponding dip in soil temperatures to below 14°C briefly before beginning to warm up rapidly after sunrise (graph captured at 11 am same day).

Soil temperature data over 4 years showed that solar radiation absorbed by the soil profile during the day provides a buffer against overnight minimum air temperatures that often fell briefly to 1-5°C. This can be clearly seen in the following figures showing soil temperatures over four seasons during August and early September recorded in the trial field located at 'Orana' where ambient temperatures often fell to 2-5°C (Figure 15).

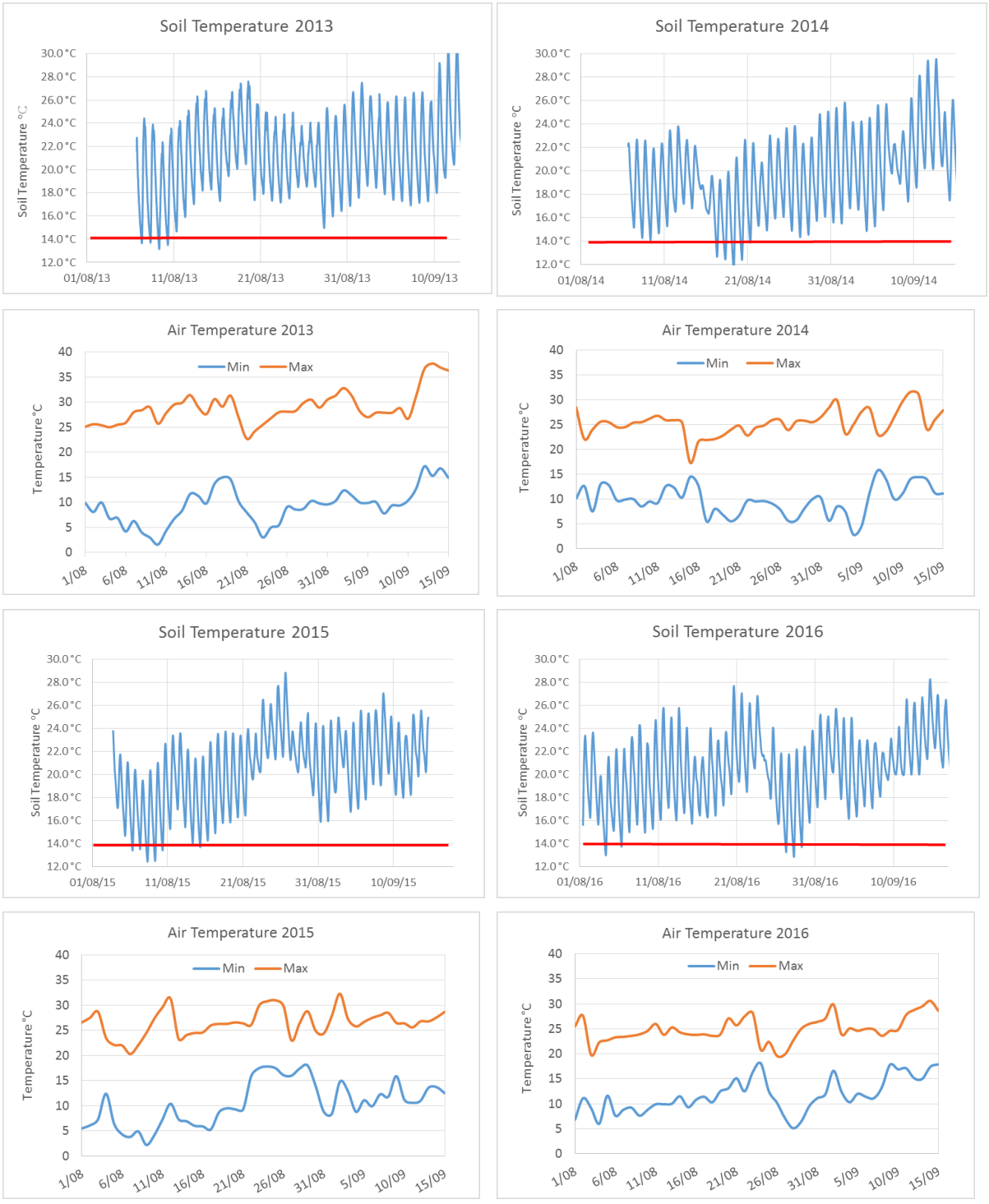


Figure 15. Soil and air temperatures recorded for the first planting date of each experiment over 4 years. Soil temperatures were found to only drop below 14°C for brief periods each season despite overnight temperature often falling to below 5°C. The red line on the soil temperature figures denotes 14°C.

Early planting experiment results

Unless otherwise specified, the results presented herein are from the treatment plots *without* oxy-degradable film.

Crop establishment

Crop establishment was successful across all planting dates for each season with densities of at least nine or more plants per metre row for each treatment (Figure 16a). The establishment rate expressed as a percentage of seed sown shows that the establishment rate for August sowings varied between 63-80% (Figure 16b), demonstrating the need to utilise a higher seeding rate to compensate for anticipated seedling losses and still achieve a target population of 8-10 plants per metre row. The establishment rate for the September sowings was typically higher for most seasons except 2015. Generally seed bed conditions are more favourable for seedling establishment during September. Soil pests were more active during 2015, causing an increase in seedling mortality. This was due to the crop being sown after an autumn mungbean crop; the mungbean residues supported the build-up of a false wire worm larvae population.

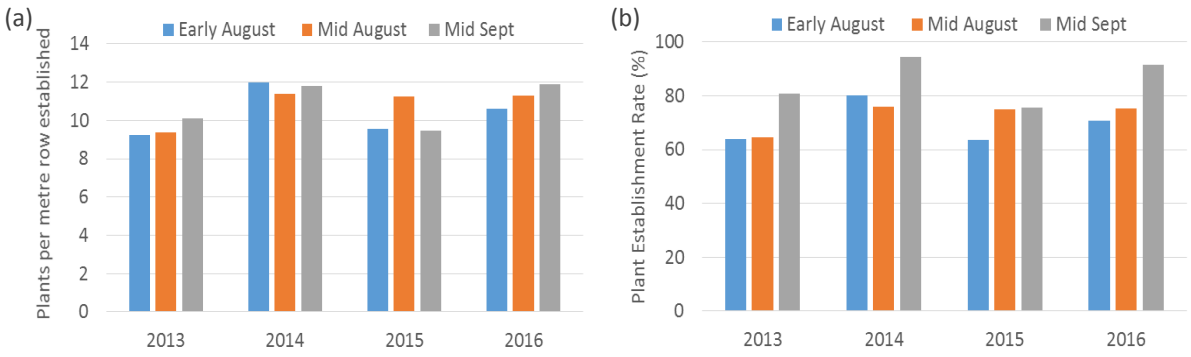


Figure 16. Establishment at first square for the early August, mid-August and mid-September planting dates across the four seasons. (a) Number of plants established per metre row, and (b) establishment rate as a percentage of seeds sown.

Lint yield and quality

Crop yield during the project spanned a range from 9.2 to 14.6 bales/ha; the lowest yields were consistent with the long term average and upper yields compared favourably with the very highest commercial yields ever recorded at Emerald since the introduction of Bollgard II®. ANOVA for yield data from each season's experiment showed that the two August sowings in seasons 1, 3 & 4 yielded significantly more than the mid-September sowing treatment ($P<0.01$). There were no significant differences recorded between the early or mid-August sowing for any of the seasons across the four year program (Table 2).

No significant differences were recorded for yield between any of the treatments for season 2. Despite the lack of treatment differences, an analysis of biomass accumulation data later in the body of the report show that the September sowings should have performed much better than it did and provided significantly better yields than the August sowings for that season. The reasons for why this occurred are discussed in the biomass section, starting on page 44.

The use of oxy-degradable film did not provide any significant yield improvements for cotton sown at the same planting date without film (control) for any season across the four years.

Collectively the August sowings provided an average gain of 2.2 bales/ha per annum (23%) over the four years of the experiment compared to yield average from the mid-September sowing treatment (the early September sowing treatment was discontinued after year 2) (Figure 17 and Figure 18).

Table 2. Picked lint yields from different planting dates and split plot treatments over four years.

	Sowing time			
	Early-Aug	Mid-Aug	Early-Sept	Mid-Sept
	Year 1 (*P*<0.001; LSD 0.83)*			
Control	10.52a	10.05abc	9.46cd	8.87de
Film	10.88a	10.38ab	9.63bcd	9.57bcd
Ultra Narrow Row	10.79a	10.19abc	9.37cd	8.25e
	Year 2 (*P*=0.87; LSD 1.22)*			
Control	10.47a	10.15a	9.92a	9.75a
Film	10.43a	10.24a	10.16a	10.43a
	Year 3 (*P*<0.001; LSD 0.88)*			
Control	14.13a	14.41a	*	9.29b
Film	14.21a	14.71a	*	9.84b
	Year 4 (*P*<0.001; LSD 0.49)*			
Sicot 746B3F	11.95a	11.05b	*	9.04c
Film (Sicot 746B3F)	12.42a	*	*	*
Sicot 748B3F	*	12.40a	*	9.48c

*Statistical comparisons are made between treatment variables within each year (not across years).

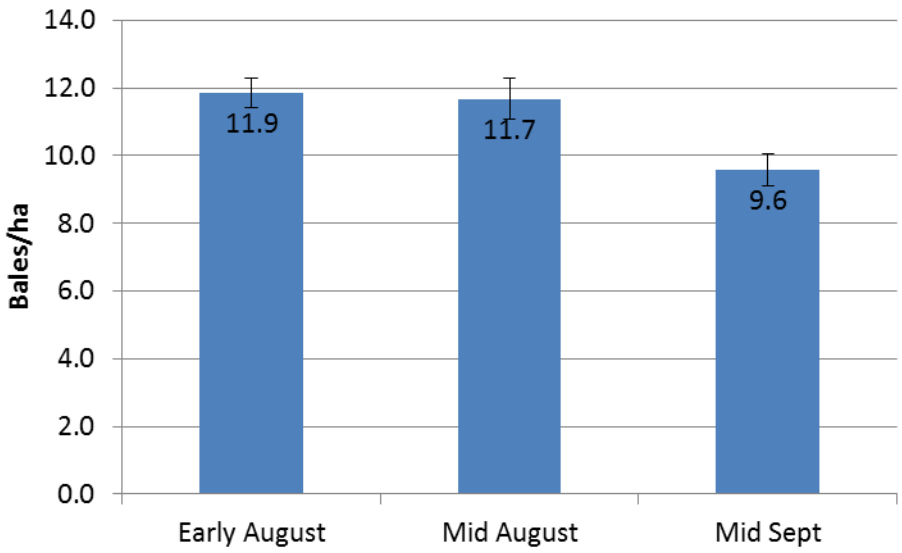


Figure 17. Average yield over four years from the early August, mid-August and mid-September sowing date treatments (no film).

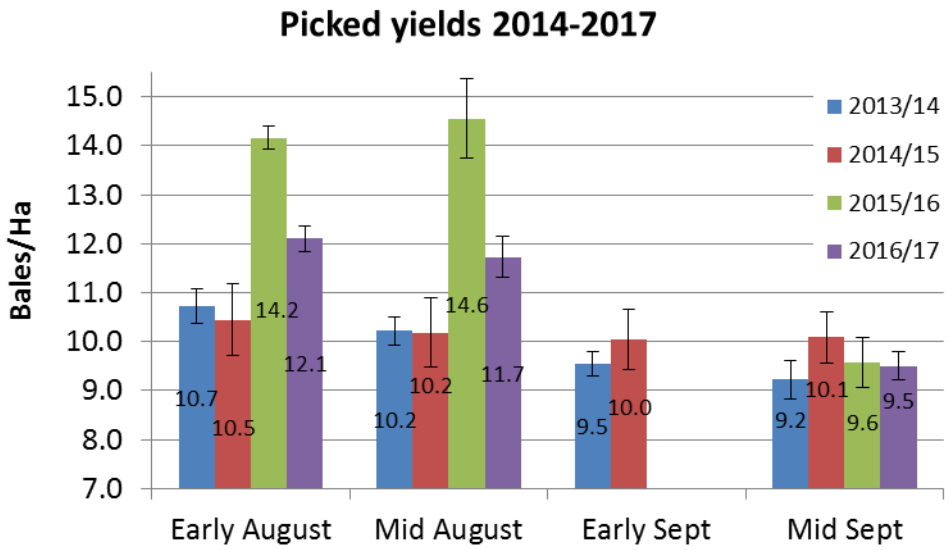


Figure 18. Picked yields from the various planting dates across four seasons. Values at each planting date are an average from pooled data (control, film & variety).

August sowing did not have any deleterious effects on gin turnout across the four years of the experiment. Lint quality was generally excellent throughout, and with the exception of leaf and colour downgrade associated with the mid-September sowing in year three (2015) due to extensive rainfall before picking. Fibre fulfilled base grade requirements for all other treatments and years (Table 3).

During the study period, this research found no yield disadvantage for the August sowings compared with the conventional mid-September sowing period. In the majority of years earlier sowing delivered improved yield. Similarly there would appear to be no negative impacts associated with earlier sowing with regard to lint quality parameters. The application of film did not provide any significant yield benefits during any season (Table 2).

Table 3. Gin turnout and lint quality parameters for cotton at each sowing time over four seasons.

Sowing Date	Length	Strength	Micronaire	Colour Leaf	Gin turnout
Early August 2016 (Sicot 746BF)	1.16	29.9	4.8	11-2	45.0
Mid August 2016 (Sicot 746BF)	1.16	30.0	4.8	11-2	44.5
Mid August 2016 (Sicot 748BF)	1.17	29.6	4.8	11-2	44.8
Mid Sept 2016 (Sicot 746BF)	1.18	30.7	4.7	11-2	42.1
Mid Sept 2016 (Sicot 748BF)	1.19	29.5	4.8	11-2	43.0
Early August 2015	1.19	32.2	4.8	21-2	44.5
Mid August 2015	1.19	31.7	4.7	21-3	45.1
Mid Sept 2015	1.17	28.0	4.6	41-4	44.1
Early August 2014	1.19	29.2	4.8	11-2	42.5
Mid August 2014	1.18	29.8	4.7	11-2	42.5
Early Sept 2014	1.18	30.1	4.8	21-2	41.3
Mid Sept 2014	1.19	29.2	4.7	21-2	41.2
Early August 2013	1.18	29.6	4.8	*	44.9
Mid August 2013	1.19	30.0	4.8	*	44.5
Early Sept 2013	1.18	29.4	4.7	*	44.5
Mid Sept 2013	1.18	30.6	4.8	*	44.7

* Leaf and colour was not assessed in 2013.

Crop development

The use of early sowing to manipulate the timing of key crop phenological stages was a fundamental objective for this study. A central aim of this research was to test whether or not sowing in August could successfully move flowering to between late October and early December; a period where records indicate the climate is likely to be the most suitable for boll setting and filling. Ideally cut-out would occur by early December with the first bolls opening in late December and therefore peak assimilate demand would be decreasing by late December as weather conditions could be expected to become more variable. Higher temperatures in January (despite the spectre of increased rainfall probability) would help to dry out the canopy after rainfall as well as speed up the boll opening and crop defoliation process. Being able to defoliate by early to mid-January would enable a crop to rapidly move past the stage where it is susceptible to boll rots and tight locking should an extended rainfall event occur.

The phenology measurements made indicate that the August sowings were mostly successful in coinciding first flower with the last week in October. Flowering was marginally delayed in the final year (2016/17) due to lower retention of early fruit from insect damage (Figure 19).

Early sowing was also successful in coinciding crop cut-out with early December prior to the summer solstice, providing a buffer against radiation variability from late December onwards. Similarly, in each season, defoliation commenced in the August sowings by early to mid-January with picking completed each year before the end of January. Crop maturity was marginally delayed in the final two years of the experiment due to changes in agronomic management that aimed to increase early to mid-season vigour causing a delay in maturity. This tactic significantly increased final yield despite the additional time required to mature a greater number of outer canopy bolls.

The mid-September sowing in comparison typically commenced flowering from mid to late November with cut out coinciding with or just after the summer solstice (late December). Defoliation in this planting date commenced at the end of January with picking occurring in February except in the first season (which had a much warmer seasonal start and shedding post cut-out removed top bolls) (Figure 19).

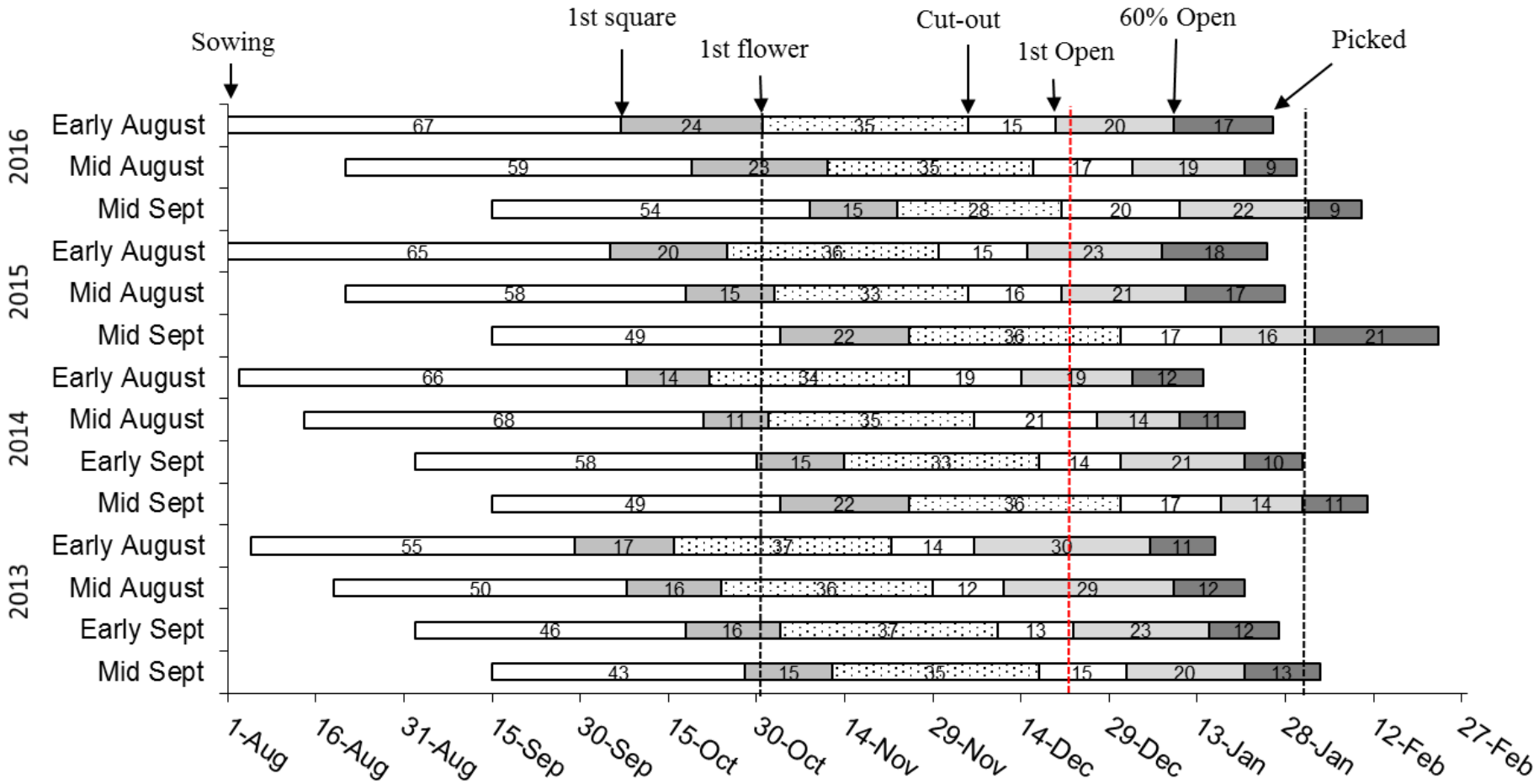


Figure 19. Crop phenology for the control treatments planted at each sowing date over four seasons.
Depicted are when the growth stages of 1st square, 1st flower, cut out, 1st open boll, 60% open bolls were reached together with the actual crop picking date. The length of each period is also given within the bar for each sowing date. The black dotted lines represent the end of October and January. The red dotted line represents the summer solstice.

Canopy light interception

Maximum light interception is given in Figure 20 for each of the sowing dates across the four seasons. During the first two seasons, the August sowings failed to reach 90% light interception representing a lost opportunity for utilising available radiation in an environment where radiation can be variable and limiting. This factor and an examination of patterns of biomass accumulation and harvest indexes for the August sowings after the first two seasons led to the conclusion that to maximise yield potential, either agronomic management needed to be adjusted to encourage greater canopy expansion or a narrower row spacing (75-80 cm) should be considered.

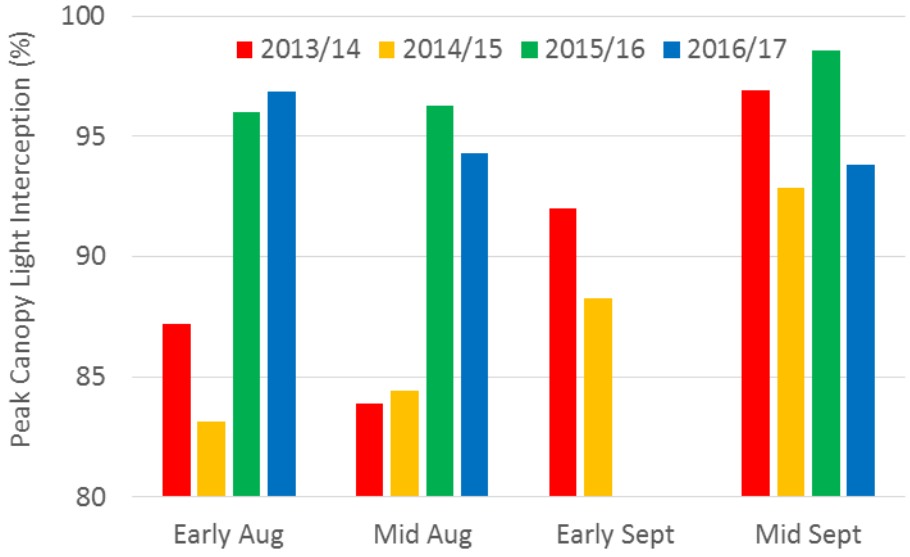


Figure 20. Light interception at maximum canopy expansion (<3 nodes above white flower). Note that light interception failed to reach 90% for the August sowings during 2013/14 and 2014/15 seasons.

Changes were made to early season crop management (reduced irrigation deficits, earlier nitrogen application and less strict insect management) to encourage greater vegetative expansion and increased vigour by first flower. These tactics were successful with canopy measurements in the final two seasons showing greater light interception at crop cut out (Figure 20).

Importantly, row closure as measured by light interception only determines the percentage of sunlight not intercepted by the crop canopy that would otherwise fall on the ground. Light interception does not measure how the intercepted sunlight is falls within the canopy architecture. How the canopy actually intercepts sunlight is also important in determining the efficiency with which incoming energy is used for boll formation. For example a rank canopy might intercept all of the incoming sunlight but the upper canopy might shade the lower leaves and reduce the ability of subtending leaves to produce assimilates to sustain lower canopy boll development decreasing radiation use efficiency. Photo 14 toPhoto 16 depict the crop canopies of several planting date treatments across different seasons. The failure to intercept sunlight is evident in the early August sowings in the first two seasons compared to the third season. The picture of the crop in the third season (Photo 15) shows a canopy that is efficiently intercepting sunlight. The interception of 96% of available sunlight is spread between the top and sides of the canopy (dome shape) allowing the lower canopy to intercept light and support lower canopy boll development. This canopy shape is utilising nearly all incoming radiation in a very efficient way throughout the entire canopy.

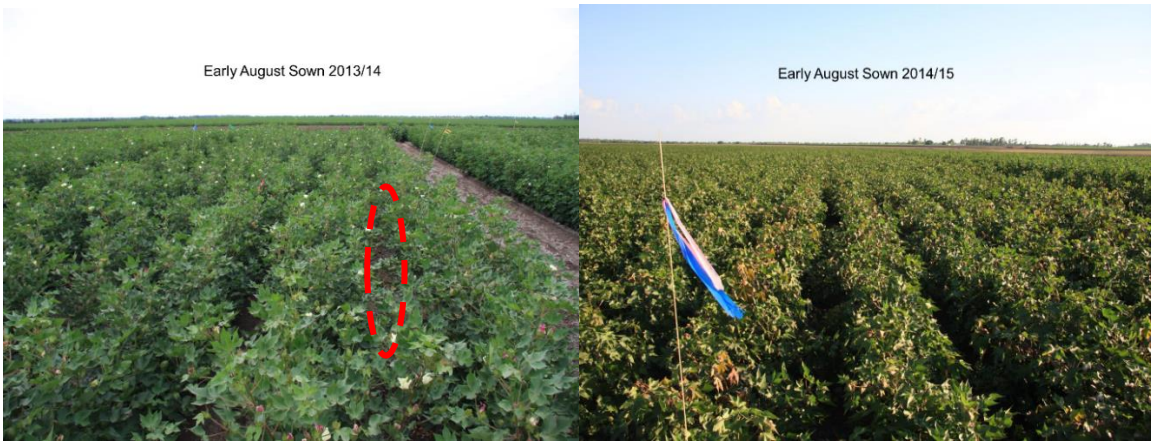


Photo 14. Crops sown during early August at peak light interception 2013/14 (left) and 2014/15 (right). These crops did not close the rows; bare dirt in the inter-row (see circle) is evident in the 2013/14 photo.

Photo 15. The 2015/16 crop sown in early August efficiently closed the rows with 96% interception, and sunlight was able to still penetrate deep into the canopy without being wasted on the ground.

Photo 16. A September sowing that had nearly closed the rows well before crop cutout, leading to innefiencies in sunlight utilisation. The September sowings tended to grow a large canopy where the lower half of the canopy was shaded by upper canopy growth.

In comparison, Photo 16 shows how the mid-September sown treatments readily closed the rows prior to cut-out. Whilst light interception was high, canopy efficiency was reduced due to the leafier upper canopy shading the lower leaves reducing overall photosynthetic efficiency. The September sowings had a tendency to grow in this way due to warmer temperatures and higher humidity during flowering encouraging larger leaves and greater stem elongation.

Crop growth, biomass accumulation and weather interactions

The yield differences observed between sowing dates are generally explained by examining how climate factors influenced the pattern of biomass accumulation, particularly for boll dry matter.

The following figures overlay the biomass accumulation and crop light interception against ambient radiation, temperature and rainfall as a series of stacked graphs allowing comparison between particular weather events and biomass accumulation patterns particularly for boll dry weights relative to days after each treatment was sown (DAS). To simplify the discussion of key points in relation to these figures annotations will be overlaid on the figures and specific comments made in the figure legends.

In each case the graphs depict crop biomass, actual and intercepted radiation, and temperature and rainfall data.

Photo 17. Partitioning plants ready for leaf area and dry matter assessments of stem, leaves and bolls.

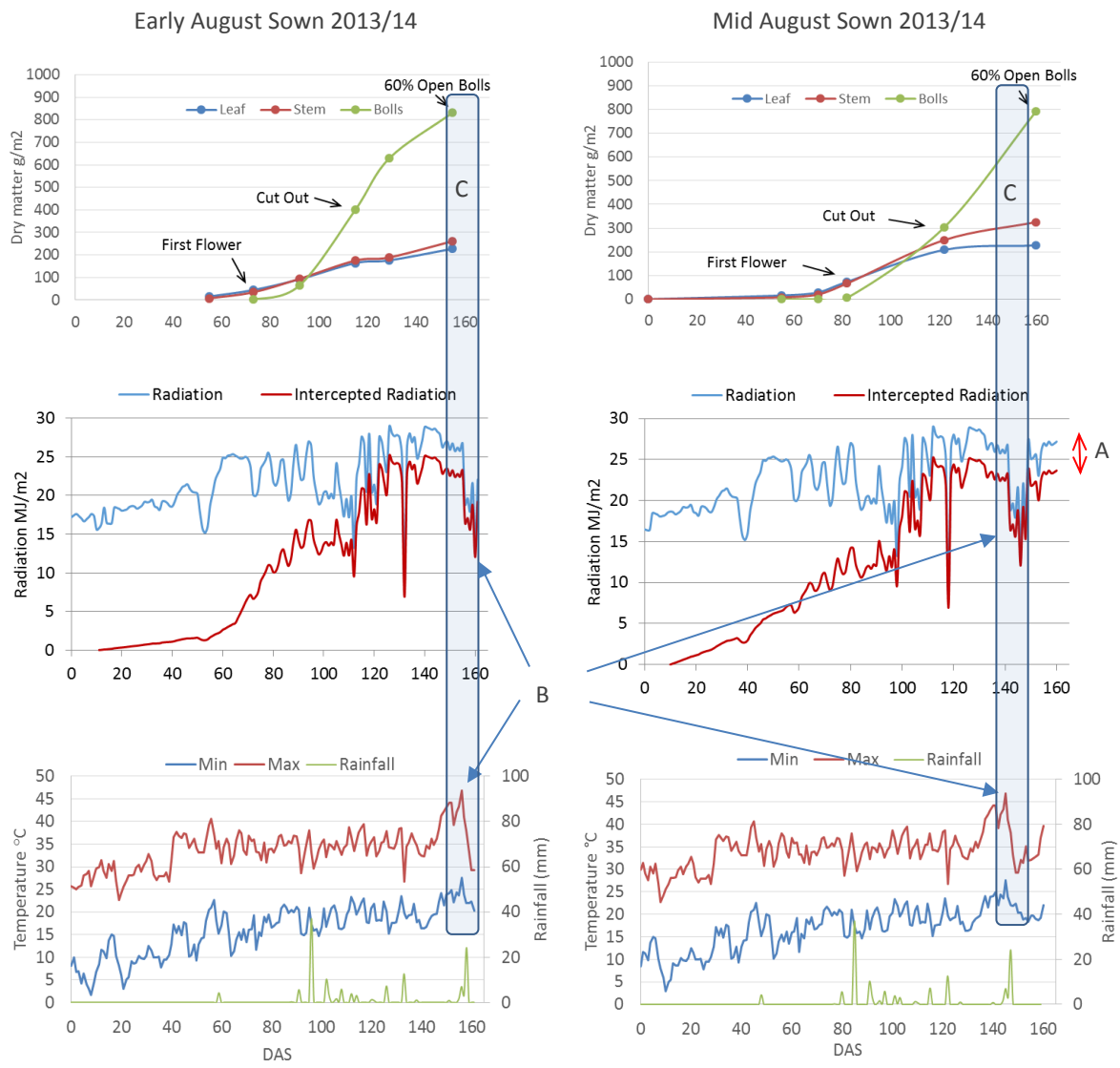


Figure 21. Overlay of crop biomass (top), ambient and intercepted radiation (middle) and daily temperature and rainfall (bottom) plotted against Days After Sowing (DAS) for August 2013 sowings.

Key points are:

1. The double ended arrow **(A)** highlighting the gap between available radiation and the proportion of sunlight intercepted by the canopy for both August sowings.
2. A significant photosynthesis disruption event **(B)** with a period of hot days and nights followed by a week of cloud reducing radiation levels to nearly 15MJ/m^2.
3. **(C)** highlighting the timing of these weather events in relation to the very final stage of boll filling.

These events occurred during late December/Early January and therefore only intersected with the late stages of boll filling. Both August sowings were well past peak boll load assimilate demand at this stage. The net result is that boll dry matter accumulation is mostly unaffected.

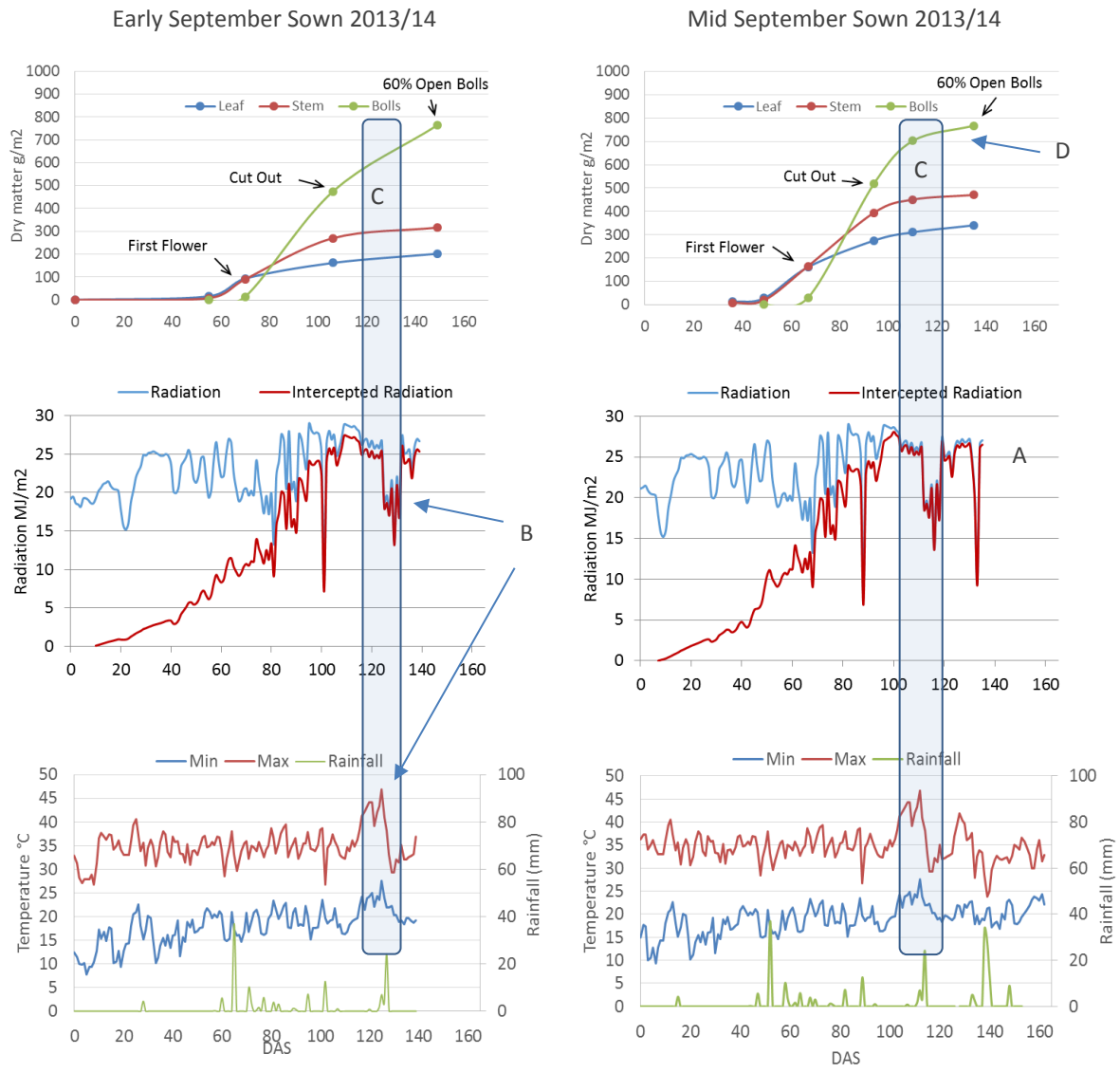


Figure 22. Overlay of crop biomass (top), ambient and intercepted radiation (middle) and daily temperature and rainfall (bottom) plotted against Days After Sowing (DAS) for September 2013 sowings.

Key points are:-

1. The September sowings are fully intercepting available radiation **(A)**.
2. Period of hot days and nights followed by a week of cloud reducing radiation levels to nearly 15 MJ/m^2 (**B**).
3. Stress event **(B)** coincides with peak boll filling **(C)**. As this event intersects boll filling at an earlier stage the impact is greater particularly for the mid-September sowing which is subject to disruption soon after cut-out and before first open boll. At this point boll demand for assimilates is at its highest. The result is significant disruption to boll filling shown by the flattening of the dry matter accumulation curve at **(D)**. Prior to this event the rate of boll biomass accumulations suggests that the mid-September sowing was on track to be a very high yielding crop.

This stress event and its relation to the boll filling of each planting date explains why yield gradually decreased from the early August sowing through to mid-September (Table 2). The timing of this event is consistent with the historical climate record.

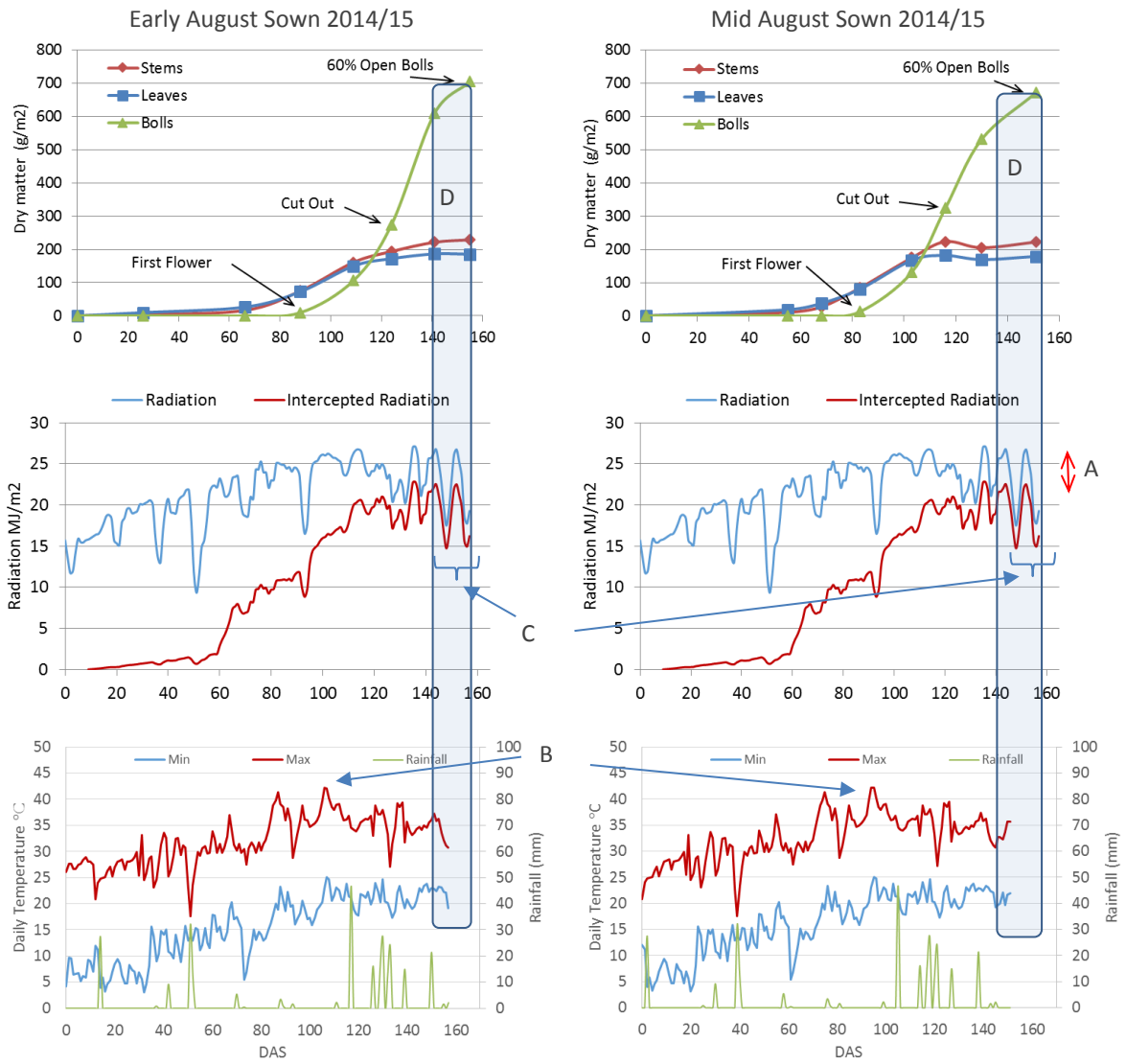


Figure 23. Overlay of crop biomass (top), ambient and intercepted radiation (middle) and daily temperature and rainfall (bottom) plotted against Days After Sowing (DAS) for August 2014 sowings.

Key points are:

1. The double ended arrow **(A)** highlights the gap between available radiation and the proportion of sunlight intercepted by the canopy for both August sowings.
2. Two significant photosynthesis disruption events occur. **(B)** denotes a short period of hot days and nights that occurred early during flowering and therefore the crop was relatively unaffected whilst **(C)** cloudiness affects the very latter stage of boll filling from FOB onwards.
3. Highlighting the timing of the cloud indicated at **(D)** against boll filling.

These events reduced final boll dry matter accumulation to a limited extent as seen in the pattern of accumulation tapering rapidly at the end. Again the August sown crops largely avoid exposure to poor conditions during peak boll demand (just prior to cut out and after first open boll).

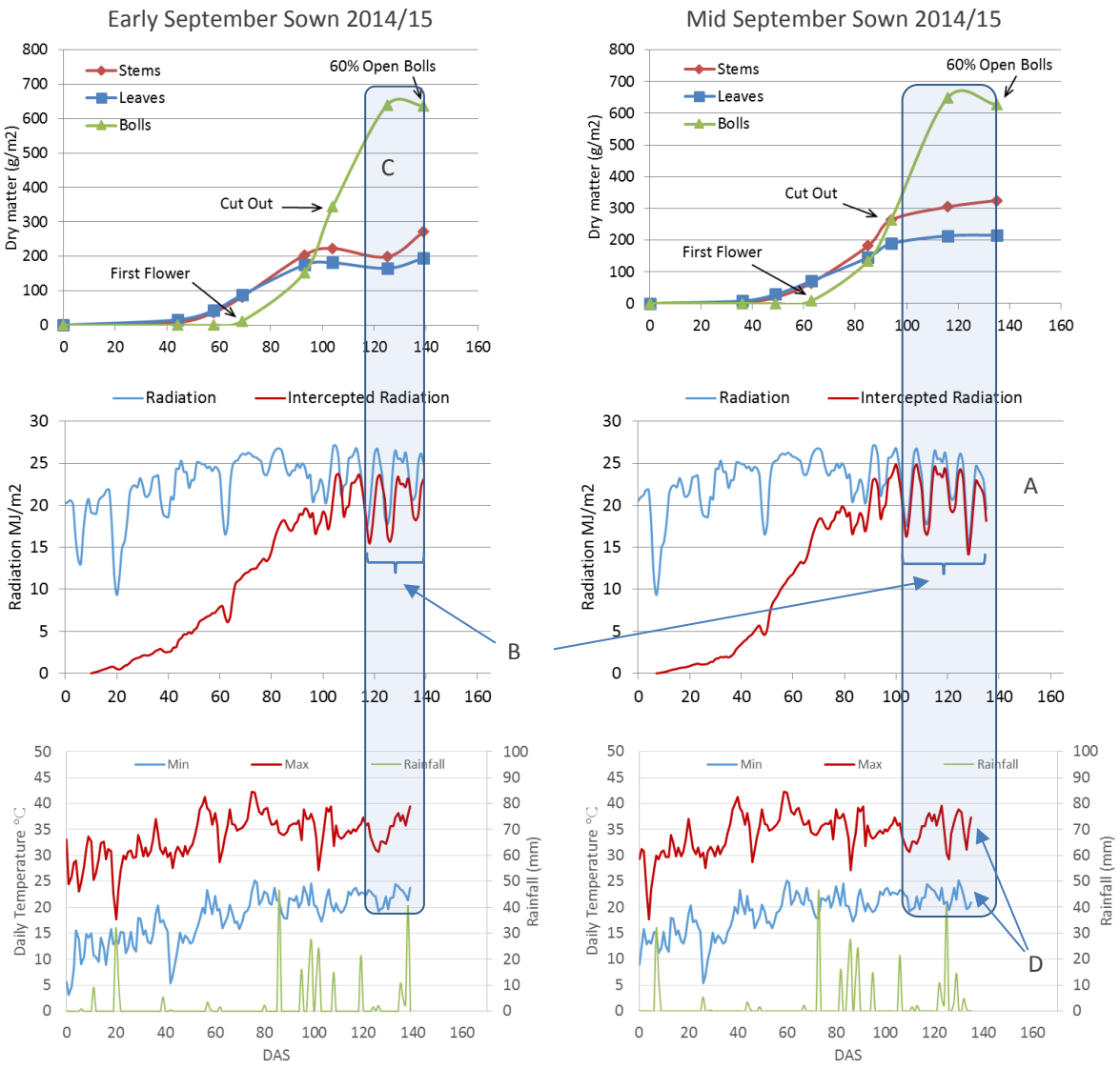


Figure 24. Overlay of crop biomass (top), ambient and intercepted radiation (middle) and daily temperature and rainfall (bottom) plotted against Days After Sowing (DAS) for September 2014 sowings.

Key points are:

1. The September sowings are fully intercepting available radiation **(A)**.
2. Period of cloudy weather **(B)** that also coincides with some hot weather **(D)**
3. The cloudy weather **(B)** coincides with an earlier phase of boll filling **(C)** and for the mid-September sowing coincides with peak assimilate demand. The mid-September is also affected by hot days and nights

The result is a significant disruption to boll filling shown by the flattening of the dry matter accumulation curve at **(C)**. Significant shedding was observed in the field during this period of time. Prior to this event the rate of boll biomass accumulations suggests that the mid-September sowing was on track to be a very high yielding crop. Whilst the yields across each of the sowing treatments were not significantly different (despite a trend of higher to lower yield) the key take home message from the 2014/15 season is that the mid-September sowing should have yielded much better than it did but was again damaged by the weather during the period of peak boll demand. The timing of this event is consistent with the historical climate record. The resultant shedding that occurred from the mid-September treatment is shown in Photo 18 on page 53.

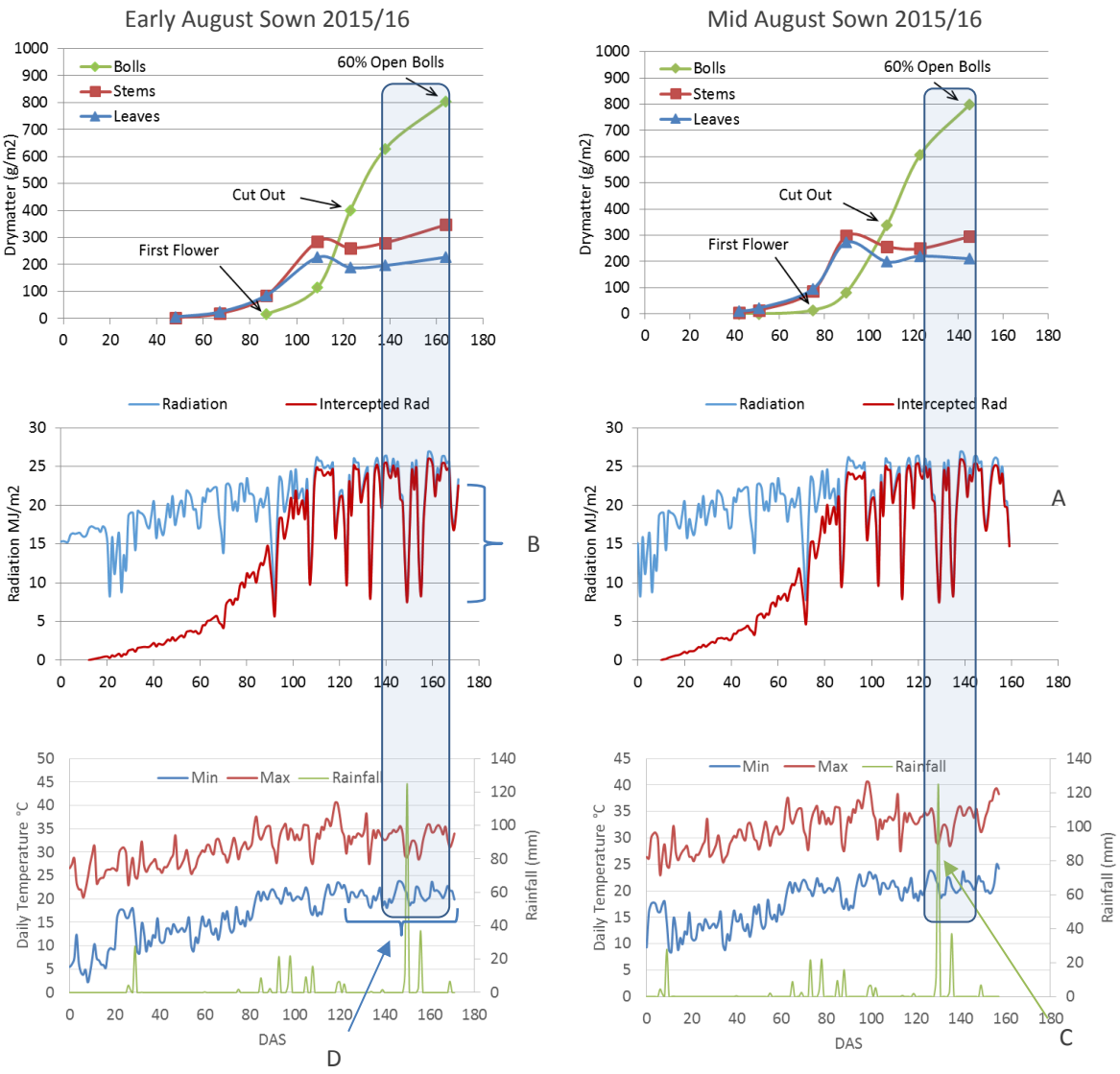


Figure 25. Overlay of crop biomass (top), ambient and intercepted radiation (middle) and daily temperature and rainfall (bottom) plotted against Days After Sowing (DAS) for August 2015 sowings.

Key points are :-

1. Changes to early season management to encourage vegetative expansion succeeded in improving light interception **(A)**.
2. Radiation during the boll filling period was punctuated by short periods of intensely cloudy weather **(B)**. However temperatures during this period **(D)** were relative mild offering a degree of respite from cloudy weather from a photosynthetic production of assimilates perspective. A pattern of short bursts of cloud occurred throughout the boll filling period which also allowed a degree of pre-conditioning.
3. A significant rainfall occurred during late boll fil and early opening **(C)**. This did not significantly affect yield or cause boll rots.

Despite the short bursts of cloud these crops yielded over 14 bales/ha which demonstrated that the crop was able to handle these short term events primarily because temperatures were milder.

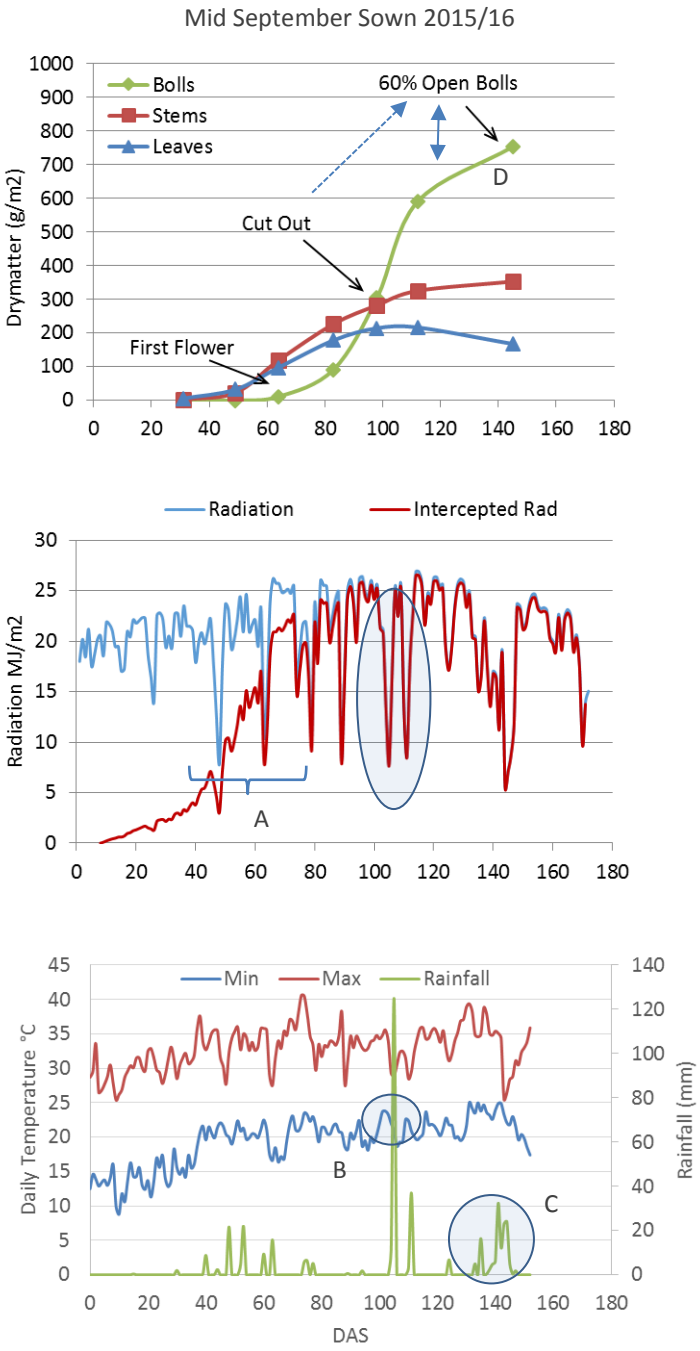


Figure 26. Overlay of crop biomass (top), ambient and intercepted radiation (middle) and daily temperature and rainfall (bottom) plotted against Days After Sowing (DAS) for 2015/16.

Key points are:

1. The early short bursts of cloudy weather **(A)** appear to have little effect on early stages of boll accumulation.
2. However, the extended period of cloud combined with hot nights **(B)** and then followed by a week of drizzly weather **(C)** caused a major reduction in yield potential due to reduced boll size and tight locking of lower bolls.

Prior to this event the rate of boll biomass accumulations suggests that the mid-September sowing was on track to be a much better yielding crop until boll filling momentum was lost due to weather **(D)**. Again the mid-September sowing has lost yield potential due to weather events that occur later in the season which is consistent with the long term weather record.

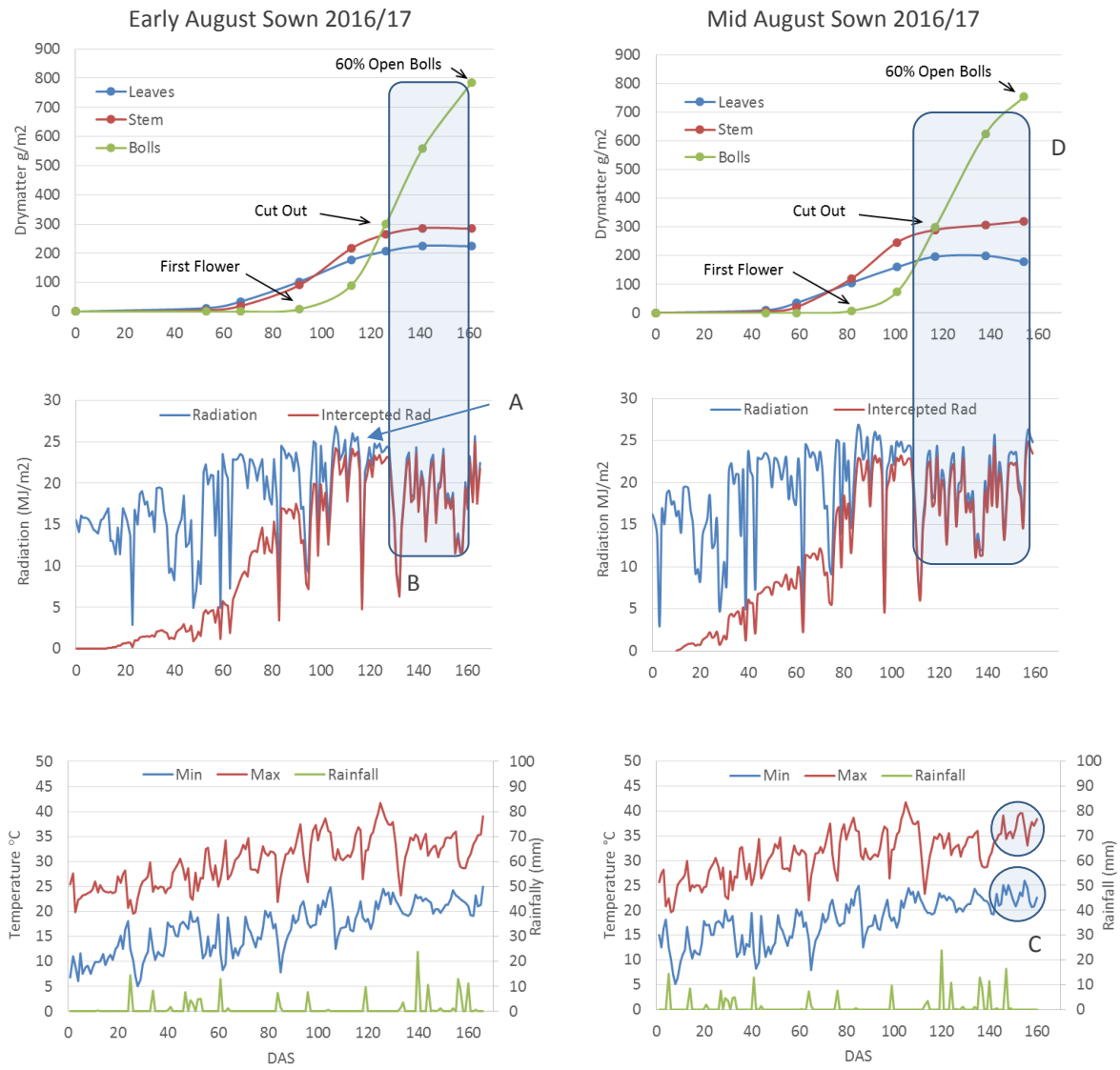


Figure 27. Overlay of crop biomass (top), ambient and intercepted radiation (middle) and daily temperature and rainfall (bottom) plotted against Days After Sowing (DAS) for the 2016/17 experiment.

Key points are:

1. Changes to management to encourage vegetative expansion succeeded again in improving light interception **(A)**.
2. Radiation during the boll filling period was punctuated by short periods of cloudier weather intensely cloudy weather **(B)**. However temperatures during this period where not hot for early August only hot right at the end of mid-August's boll filling period **(C)**.
3. The cloud and hot weather reduces boll biomass accumulation to a limited extent **(D)** although the crop yields 12 bales/ha.

Again the overall cooler weather enables the crop to better cope with cloudy weather compared to the later plantings that experience cloud combined with higher temperatures.

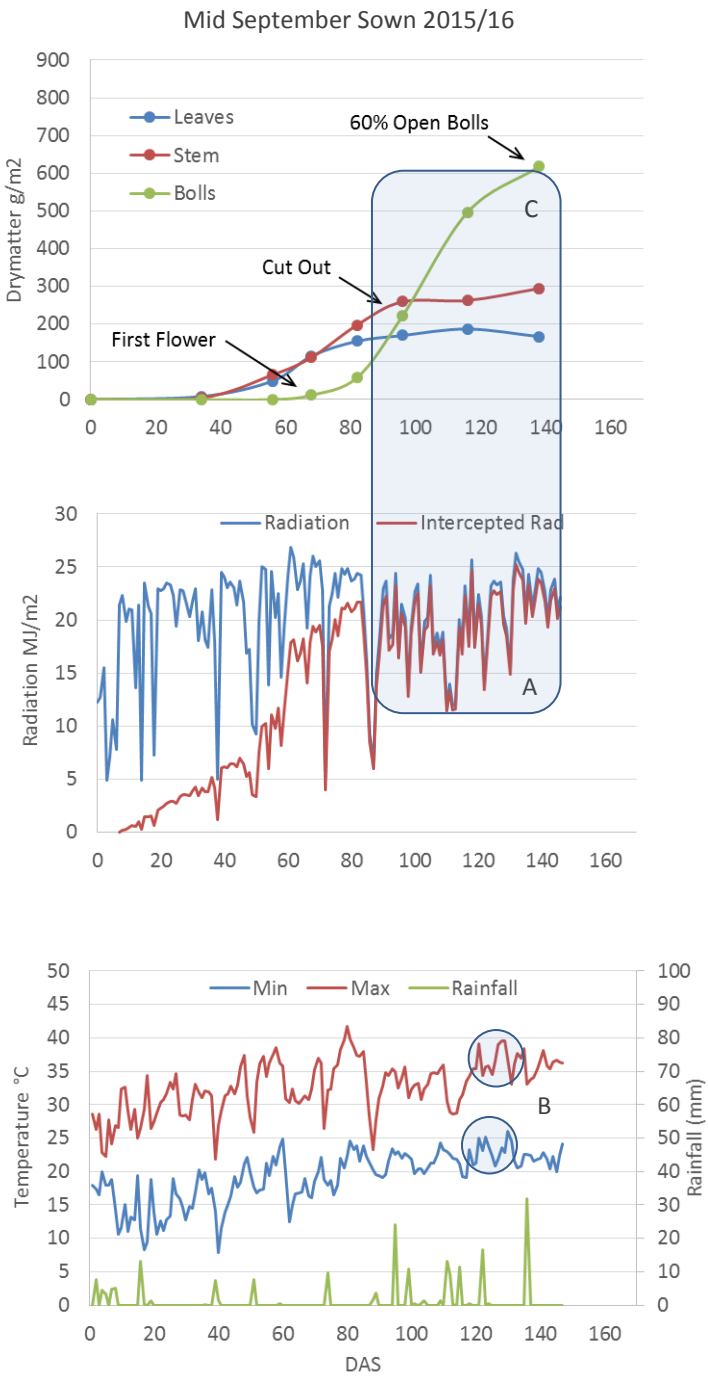


Figure 28. Overlay of crop biomass (top), ambient and intercepted radiation (middle) and daily temperature and rainfall (bottom) plotted against Days After Sowing (DAS) for 2016/17.

Key points are:

1. Variable radiation **(A)** affects most of the boll filling period but a period of hot days and nights **(B)** causes shedding of upper fruit and reduced boll size **(C)**.

Again the data suggest that the mid-September sowing was on a trajectory that suggested that it should have yielded much better than it did. The period of cloud and hot weather again coincided with peak boll demand resulting in reduced boll number and size.

Photo 18. Shed bolls in the mid-September sowing during the 2014/15 season. Shedding was due to cloudy weather and hot nights.

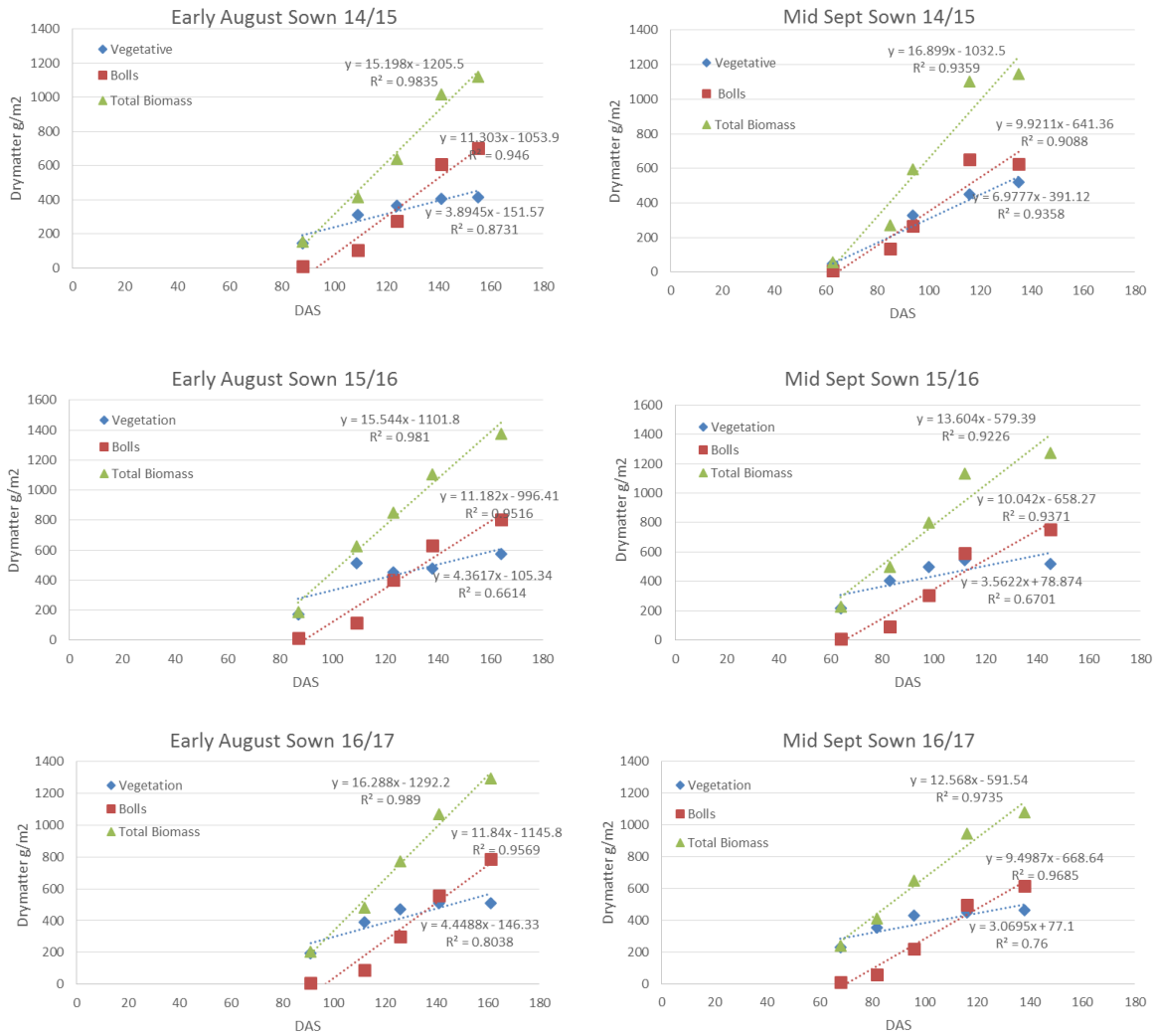


Figure 29. Relationship between reproductive, vegetative and overall biomass in relation to days after sowing for early August and mid-September sown crops.

A key characteristic of the August sowings has been the efficiency at which the crop has partitioned assimilates for boll filling. Figure 29 shows the relationship between reproductive, vegetative and overall biomass in relation to days after sowing. The early August sowings generally had a higher rate of dry matter accumulation partitioned to bolls. The regressions show a typical rate of boll dry matter accumulation of over 11 g/m^2 per day during the reproductive period. The increased yields observed in the final two years are a function of this rate of accumulation extending over a longer period. The September sowings tended to accumulate boll dry matter at a rate that was typically 1 gram less (9%) per day for the reproductive period, despite a similar flowering and boll setting period. Typically it is the period between FOB (second last data point) and maturity that falls below trend (indicative of late season shedding and reduced boll fill).

Harvest index (boll dry matter ÷ total biomass) measures for each planting date (Figure 30) show that the August sowings typically had high harvest indexes of around 60% of total biomass compared to the mid-September sowings that ranged between 45-56%. This is reflective of the late season boll losses that were particularly apparent in the first three seasons whereby the loss of bolls or reduced boll size post cut-out due to stress events changed the harvest index ratio.

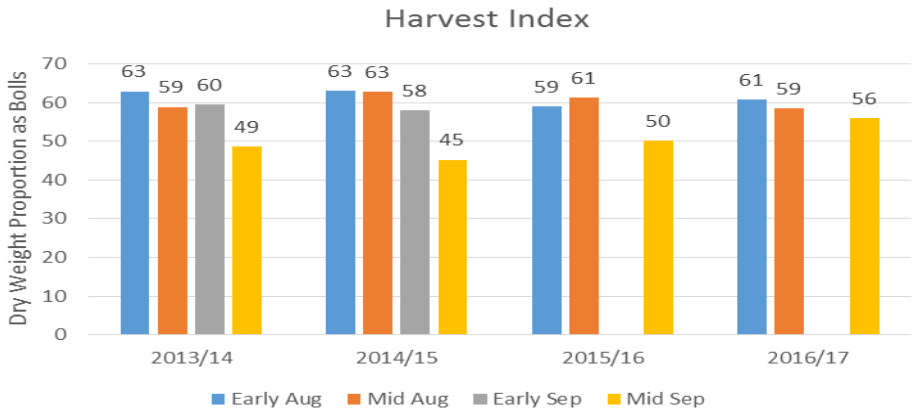


Figure 30. Final harvest index for each of the sowing date treatments.
Harvest index is calculated by (final boll weight ÷ (boll + stem + leaf weight)) × 100. Harvest index values are higher and more consistent for the August sowings showing a more efficient final partitioning to bolls.

Segmented picking

Segmented picking conducted during seasons 2, 3 and 4 provide additional insight as to how yield differences were achieved in each treatment in relation to different boll cohorts within the plant canopy. Segmented picking during season 2 did not show any real differences in either boll size or boll numbers throughout the canopies of the different sowing date treatments (Figure 31). This is reflective of there being no significant differences in treatment yields picked in that season.

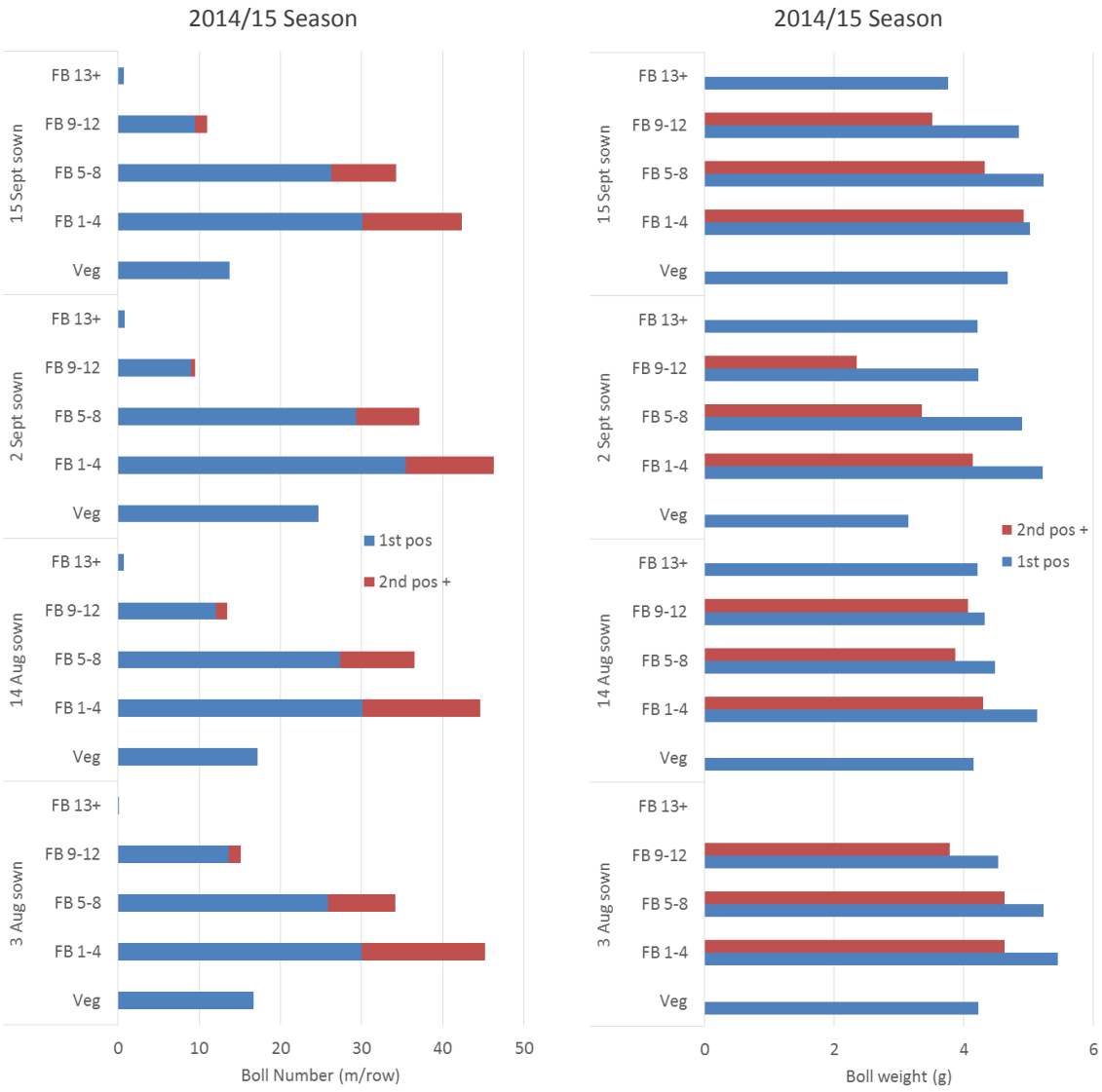


Figure 31. Boll numbers (left) and boll size (right) for different fruiting branch cohorts. The pattern of boll set and size for this season was similar across treatments. This reflects the non-significant differences for picked yield.

*Box mapping yield data for each of the sowing dates. Veg = Vegetative branches, FB represents fruiting branches with 1-4 being the first 4 fruiting branches counting from the base of the plant. Blue represents first position bolls and red bolls on positions 2 or further out.

For the 2015/16 season the August sowings were characterised by larger boll weights compared to the mid-September sowing (Figure 32). The early August sowing in particular had very large bolls that were above 6 grams in weight. What was unique for this planting date was that boll size increased higher up in the canopy so that whilst the number of bolls decreased, compensation took place through increased boll size. The boll sizes for the mid-August and mid-September sowings were similar but the mid-August sowing had a higher number of bolls in the upper canopy which contributed to the significantly higher yields that were picked.

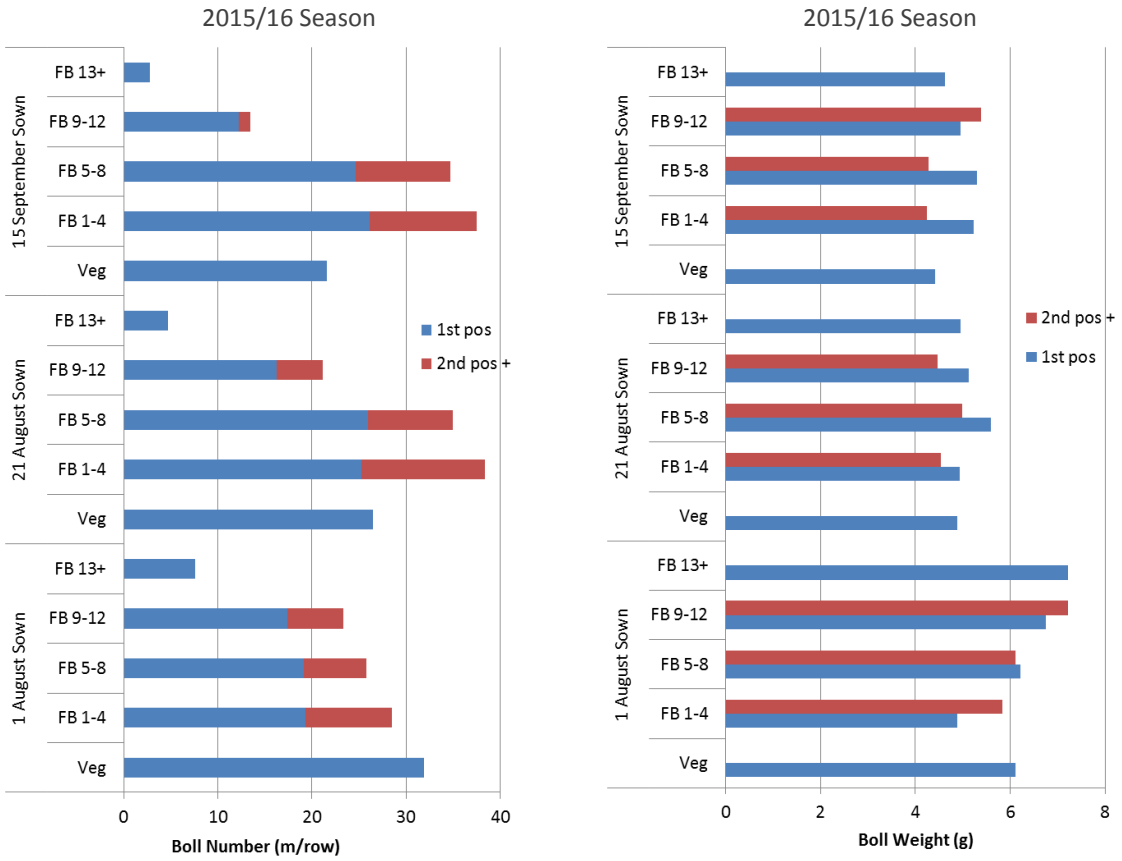


Figure 32. Boll numbers (left) and boll size (right) for different fruiting branch cohorts.
The early August sowing had a different pattern of boll set compared to the mid-August and September sowings, having a lower number of bolls but much larger boll size.
*Box mapping yield data for each of the sowing dates. Veg = Vegetative branches, FB represents fruiting branches with 1-4 being the first 4 fruiting branches counting from the base of the plant. Blue represents first position bolls and red bolls on positions 2 or further out.

For the final 2016/17 season the August sowings were characterised by larger boll weights particularly in the lower canopy sections compared to the mid-September sowing (Figure 33). This is indicative of the good radiation conditions during boll formation and the dome shaped canopy that efficiently intercepted sunlight in both the upper and lower canopy. The reduction in boll size in the upper canopy is reflective of variable radiation during the later stages of boll setting. This variable radiation also corresponds with the smaller bolls in the lower canopy of the mid-September sowing.

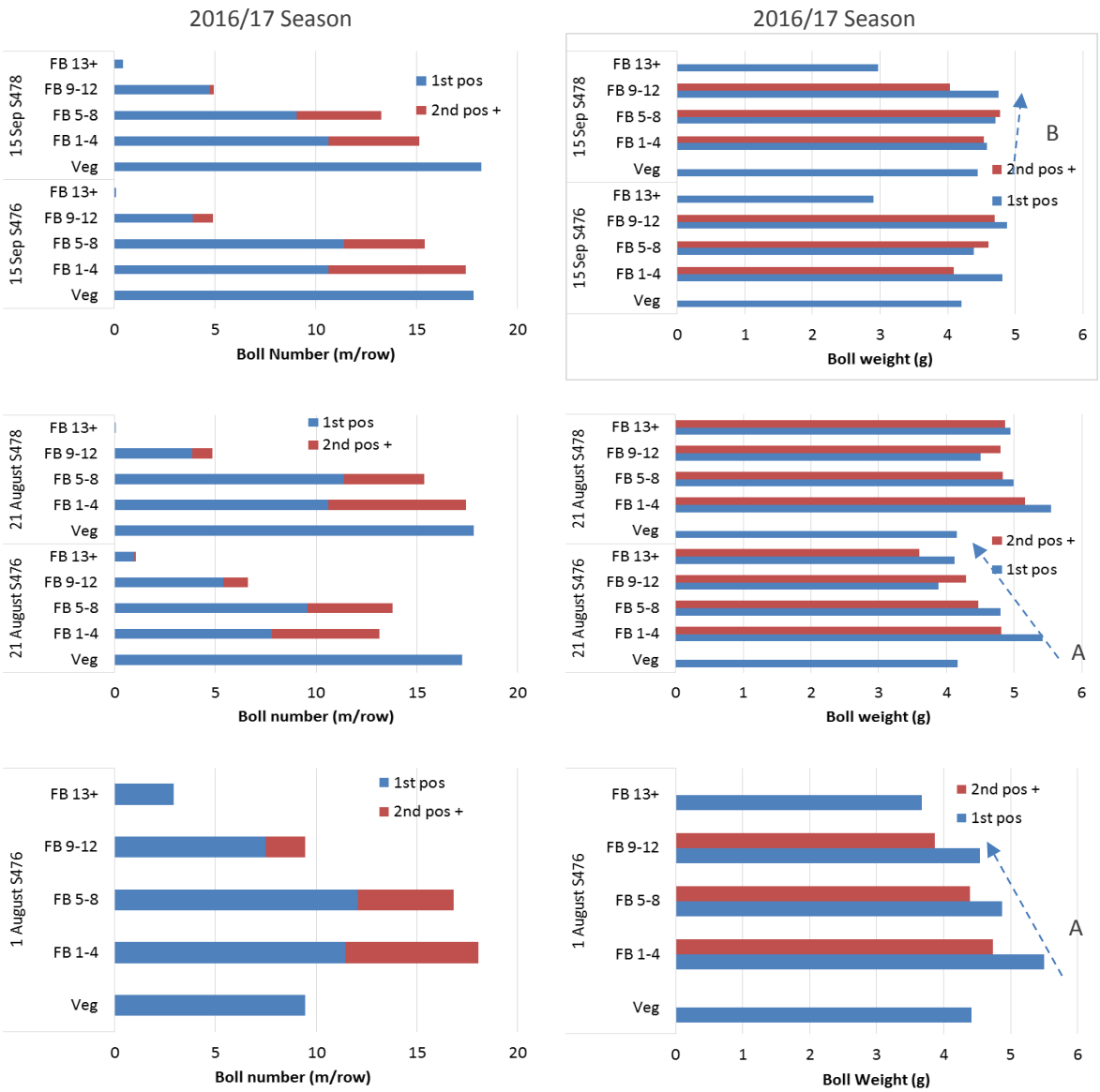


Figure 33. Boll numbers (left) and boll size (right) for different fruiting branch cohorts.
Note that the spread of bolls between the different fruiting branch cohorts are similar across each planting date and that the lower canopy bolls were larger for the August sowings **(A)** compared to the mid-September sown treatments **(B)** where the boll sizes were smaller. This is indicative of better radiation received by these treatments and different canopy shape.

*Box mapping yield data for each of the sowing dates. Veg = Vegetative branches, FB represents fruiting branches with 1-4 being the first 4 fruiting branches counting from the base of the plant. Blue represents first position bolls and red bolls on positions 2 or further out.

Photo 19. A typical example of August sown crop with the leaves removed as part of the partitioning process. August sowings were characterised by even overall boll set with large bolls to the top of the plant. This is early August sown variety Sicot 746BRF taken at FOB.

Crop evapotranspiration assessment in reponse to planting date

The relative crop water use of the August and mid-September sowing dates were calculated for the 2014, 2015 and 2016 seasons. The calculation of daily crop evapotranspiration (ETc) i.e. soil evap + crop transpiration was made by Daily ETc= Kc*ETo. Where

Kc = crop factor

ETo = potential ET calculated by met station.

Kc = 1.2719*LI-0.0779, LI= light interception as a fraction e.g. 0.5

When crop light interception was below 70% (LI < 0.7) (canopy is not fully closed) the contribution of the soil surface evaporation was included. Therefore if an irrigation or 15 mm or more of rain had occurred Kc = 1 for the next 2 days.

Daily ETo values were taken from the on-site meteorological station. Water usage for each planting date was then assessed by calculating the sum of evapotranspiration (∑ETc) for each planting date throughout the season for the period between crop emergence and leaf drop from defoliation.

These calculations were also validated by taking a number of gravimetric soil water measurements during the season from the early August and mid-September planting date treatments. These measurements were made by taking soil core samples from the hill and furrow to a depth where possible to 1.2 metres. Soil removed from these cores was split into 0-10, 10-30, 30-60, 60-90 and 90-120 cm intervals. These measurements were made just prior to emergence, first flower, cut out, first open boll and just prior to picking. Core samples were taken just prior to irrigation events. The upper drained field limit was determined by soil cores 2 days after an irrigation event around the crop stage of first flower and cut out.

These samples were immediately weighed and returned the laboratory for drying in a hot oven at 100°C for 4 days. From the change in soil weight and utilising soil bulk density values from a nearby field with a very similar soil type (Lance Pendergast pers com 2016), volumetric water was calculated as follows:

Gravimetric water % = ((wet weight –dry weight)÷wet weight)*100

Volumetric water % = (Bulk density * gravimetric %)

Volumetric Water (mm) = (Volumetric water% * (soil core cm÷10)

The calculated values for soil moisture changes recorded through volumetric soil sampling were used to cross-check the calculated ETc values calculated for each relatable time period. The soil core measurements were found to give similar measurements of the calculated ETc values suggesting that the ETc calculations did provide a realistic measure of crop water usage during each season.

The ETc calculations suggest that the August sowings were generally more water use efficient than the relative September sowings in each season (Figure 34). Across the three seasons the August sowings realised an annual saving of 0.9 ML of water per hectare compared to the mid-September sowing. This was generally due to the August sowings completing most of the boll filling during a cooler period of the year compared to the mid-September sowings.

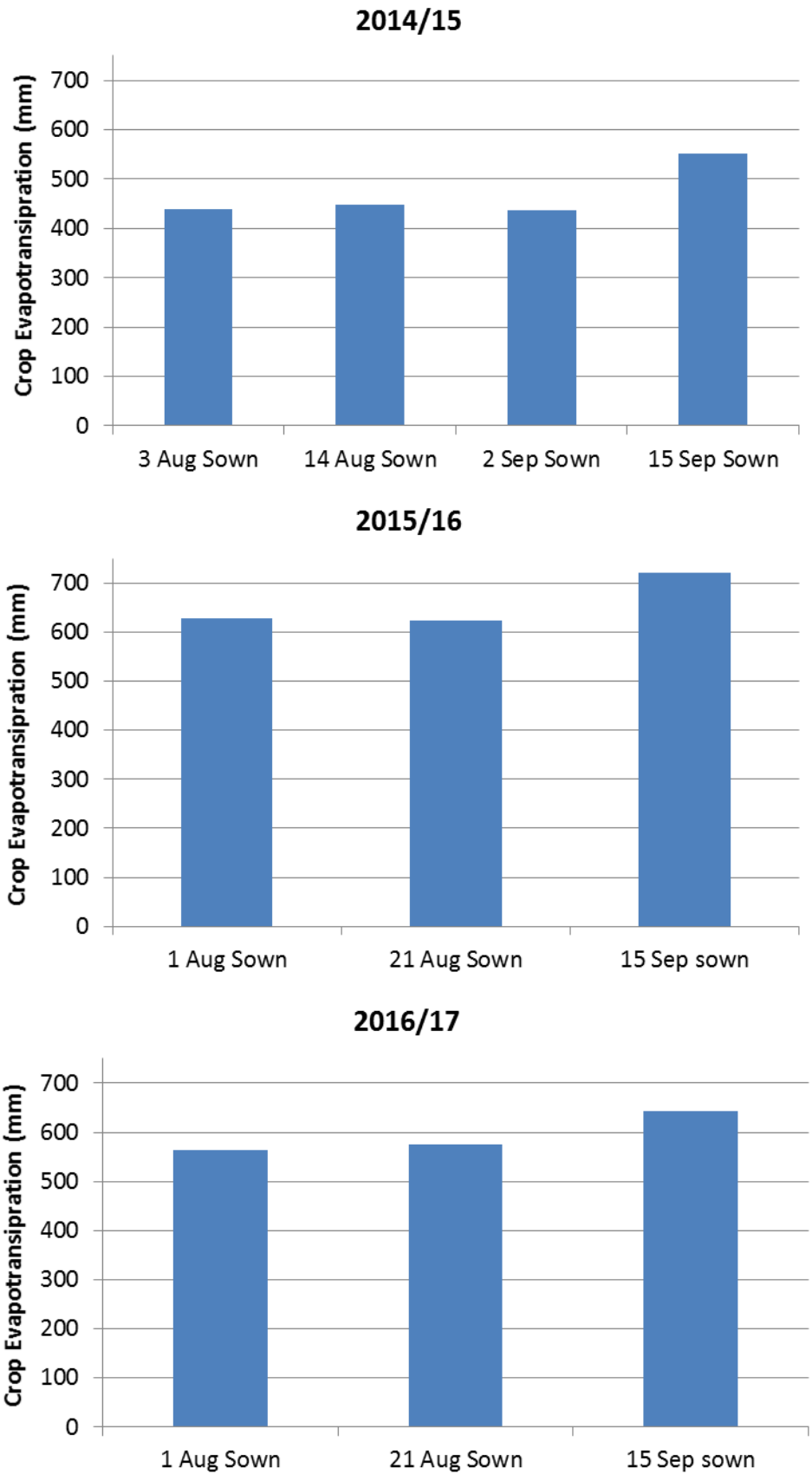


Figure 34. Calculated seasonal crop water usage ∑ETc for the 2014/15, 2015/16, 2016/17 season sowing date treatments dates. ∑ETc was calculated for the period between emergence and leaf drop from defoliation.

Commercial crop benchmarking

A series of commercial crops planted during August and December were benchmarked to provide validation data for future modelling so that the potential impacts of the Bollgard® 3 sowing window could be assessed. In 2015/16 a commercial planting of 17 ha was undertaken on 1 August as part of the Monsanto/AVPMA permit (that allowed for up to 30 ha of Bollgard II® to be sown early each season) at 'Argoon' near Comet. During 2016/17 a number of both early sown (August) and late sown (December) crops were benchmarked with the commercial release of Bollgard® 3 varieties and extension of the planting window.

The crops were benchmarked by keeping a record of key agronomic activities (fertiliser, planting, irrigation, defoliation and picked yield and quality) as well as measures being made of crop biomass accumulation and light interception using the same methodology as for the main experiment. Crop biomass was assessed by taking four representative samples of 1 m^2 from each crop at the key growth stages of first square, first flower, four weeks after first flower, first open boll and crop maturity (just prior to defoliation).

The data collected from these crops was provided to Dr Steve Yeates and Mr David Johnston (CSIRO) for the purpose of calibrating the Ozcot model for central Queensland conditions.

Early sown crop benchmarking

The 17 ha field at 'Argoon' planted on 1 August produced a nearly identical yield to the 1 August sown treatment at 'Orana' (Figure 35). Interestingly this field was unable to be picked on time due to the unavailability of picking equipment that had been deployed elsewhere to pick a Bollgard® 3 seed crop. As a result the field was subject to a major rainfall event receiving over 205 mm during a 10 consecutive day rainfall event. At the end of this period the crop yield was still very high although lint colour was severely degraded (51 colour). The high yield provided a buffer against the discount penalty. Similar discounds were applied to cotton picked from the same farm that had been sown in September but with a much lower yield.

During 2016/17 the performance of the early sown benchmark crops was pleasing with final yields that were similar to the yields observed at the 'Orana' trial site. Measurements of crop biomass development also showed that each crop irrespective of location and the actual date sown in August grew in a very uniform and regular way similar to what was observed at 'Orana' (Figure 36).

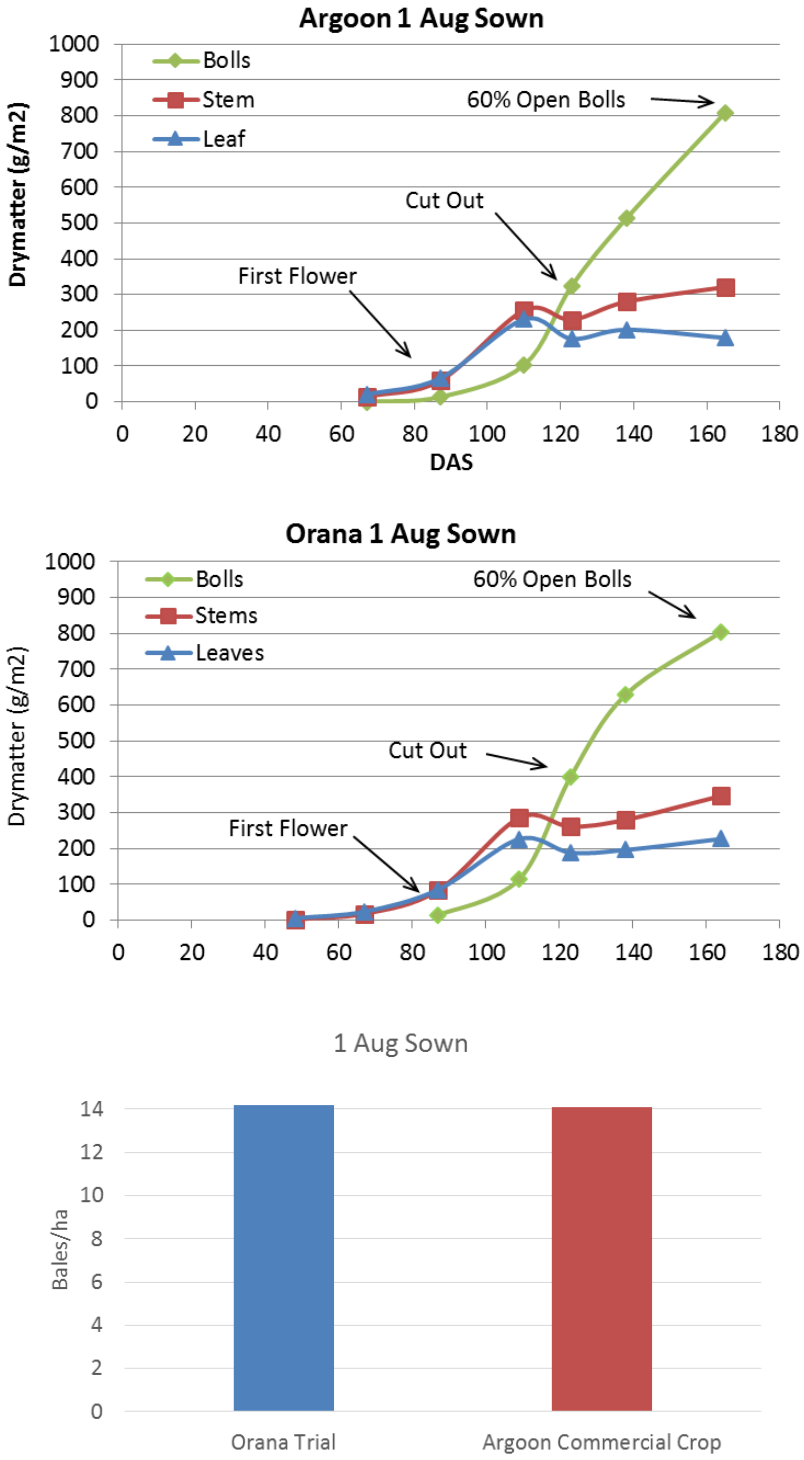
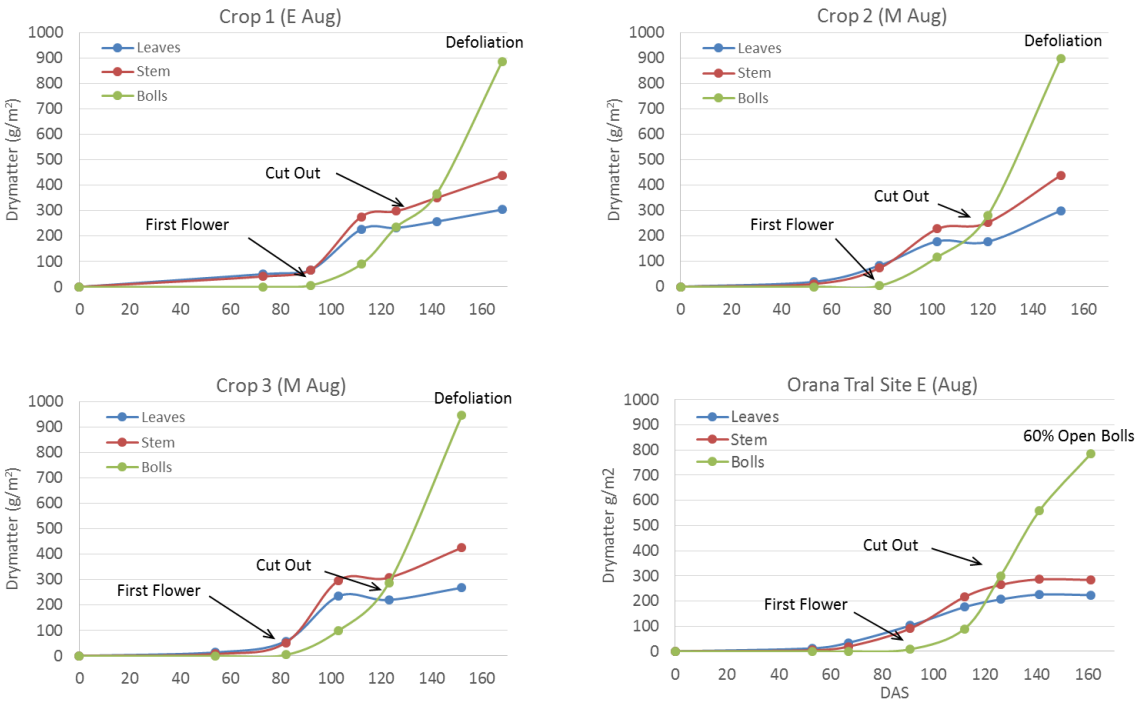


Figure 35. Dry matter accumulation and crop yield for the commercial benchmark crop at 'Argoon' (sown 1 August 2015) compared with 1 August 2015 sown treatment at 'Orana'.

Each crop showed a remarkably similar patter of biomass accumulation. Yields were basically identical at both sites at 14.1 b/ha. Interestingly the 'Argoon' crop receieved 205 mm over 10 days prior to picking compared to the 'Orana' site that was picked prior to this rain event.



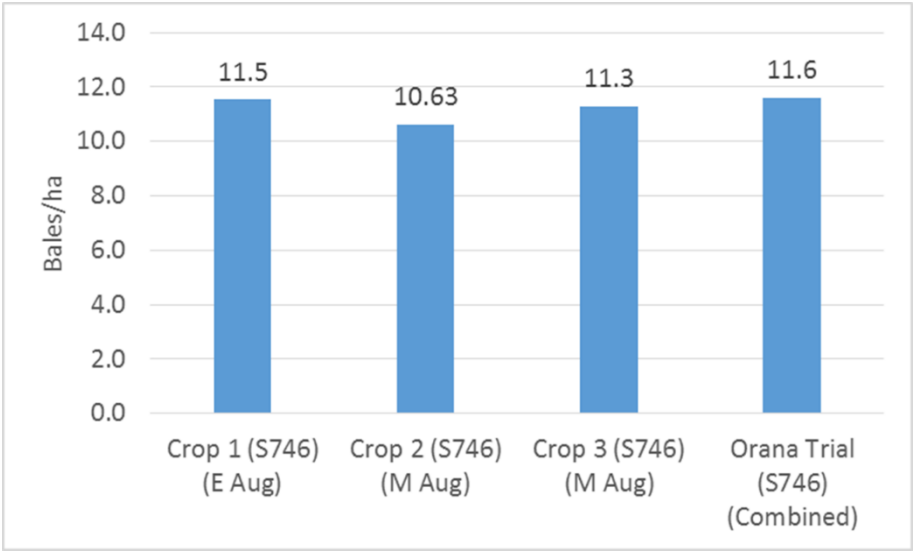


Figure 36. Dry matter accumulation and crop yields for three commercial crops that were benchmarked for yield and biomass during the 2016/17 season together with data from the early August 'Orana' trial treatment.

Each crop showed a remarkably similar patter of biomass accumulation. Yields were similar across all sites. Crop 2 had a lower yield than the other sites, which was due to a significant area of the field (30%) being affected by sodicity. Biomass samples from this field were taken from the larger non-sodic field area but yield was picked from the entire field.

Late sown crop benchmarking

The benchmarking of late sown crops provided some significant insights into the potential for late sown cotton to interact with the variable weather conditions likely to be encountered from late December onwards. The four crops benchmarked achieved varied yield results (Figure 37) and it is instructive to overlay the biomass data with ambient weather conditions that occurred relative to the days after sowing of each crop (Figure 38 and Figure 39).

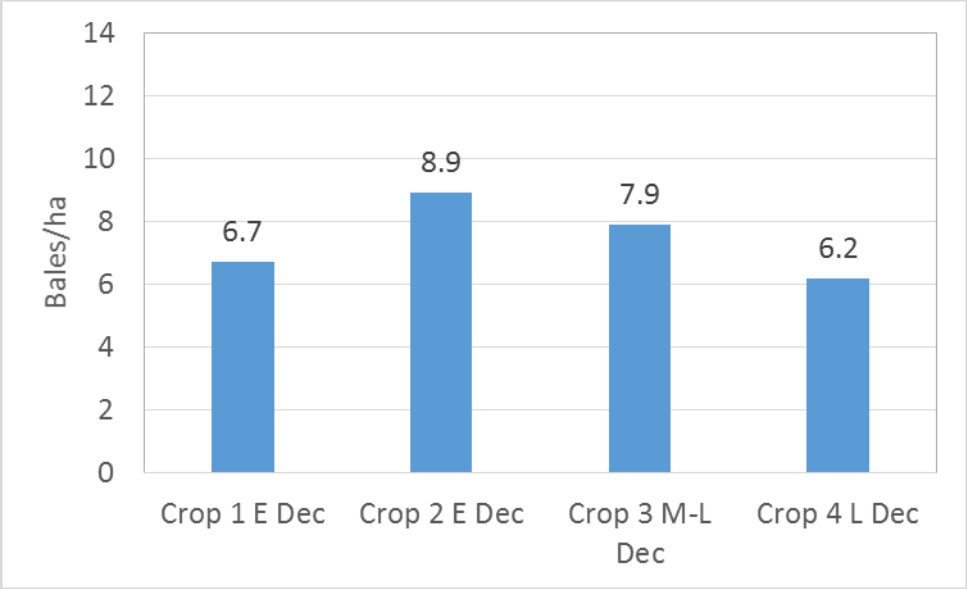


Figure 37. Picked yields from the 4 December sown benchmark crops.

In general terms, these crops were subject to a period of very hot weather that was relatively cloud free for the squaring and boll-setting stages before being subjected to a significant period of cloudy weather associated with Tropical Cyclone Debbie that affected the Queensland coast line during late March/early April 2017. It is important to recognise that the December-sown crops were affected in two ways by the weather. The hot and relatively sunny weather during December and January resulted in very rapid canopy growth. These plants did not partition assimilates to reproductive growth effectively resulting in significant shedding of squares and bolls during late January and February (Photo 22-Photo 24). Along with a tendency for rank growth, the hot conditions caused parrot-beaked bolls due to high temperature disruption of pollination (Photo 20-Photo 22). All crops had suffered significant losses in yield potential well before the advent of TC Debbie, which coincided with boll opening leading to boll rot losses.

The climate-related difficulties encountered by these benchmarked late sown crops are instructive as January and February were clear and sunny months but the boll losses caused by high temperatures highlighted the difficulty that can be encountered with filling bolls during the January and February period under CQ conditions when conditions are dry. The second constraint underscored by the benchmarking of these crops is that the ability to compensate for bolls losses by encouraging crops to be 'grown on' is curtailed by rapidly reducing available radiation and temperatures from the end of March (Equinox) onwards. There is therefore little opportunity to overcome weather-related setbacks for crops sown in December.

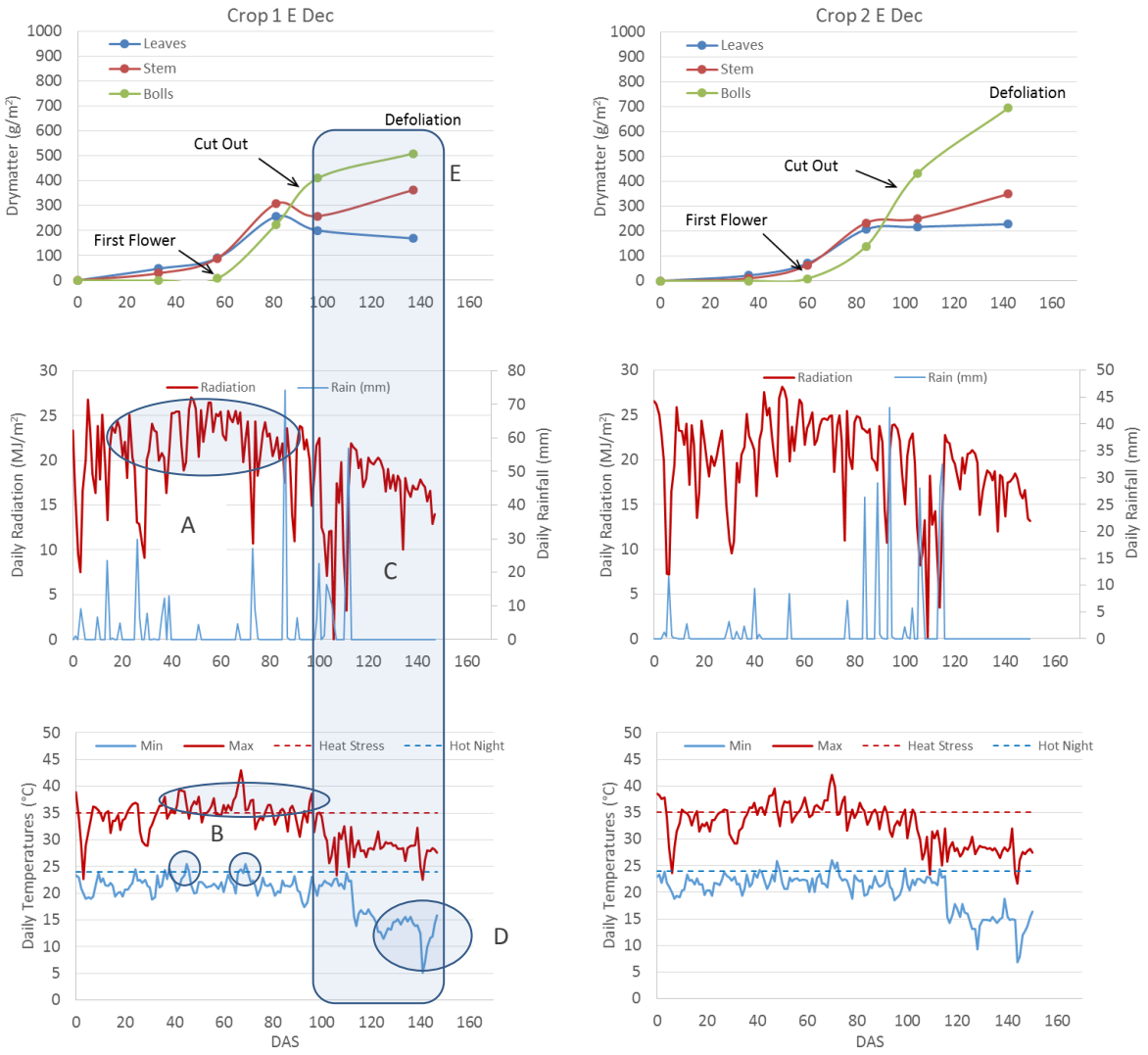


Figure 38. Overlay of crop biomass (top), ambient radiation (middle) and daily temperature and rainfall (bottom) plotted against Days After Sowing (DAS) for the two early December sown crops 2016/17.

Key points are:

2. Both crops received excellent radiation during the squaring and the first half of flowering **(A)**. Temperatures during this period were very hot during the day with some hot nights **(B)**.
3. Cloud and rainfall associated with TC Debbie coincided with the second half of boll filling **(C)** and had a major impact on boll dry matter accumulation **(E)**.
4. Radiation **(C)** and temperatures **(D)** during the last stages boll filling **(E)** were rapidly becoming unfavourable with cool nights and declining radiation dur to diurnal variation.

The second crop was managed better with nitrogen and irrigation and had set a higher proportion of bolls prior to TC Debbie and as such fared much better with a higher overall boll count due to lower levels of mid-season shedding of earlier fruit.

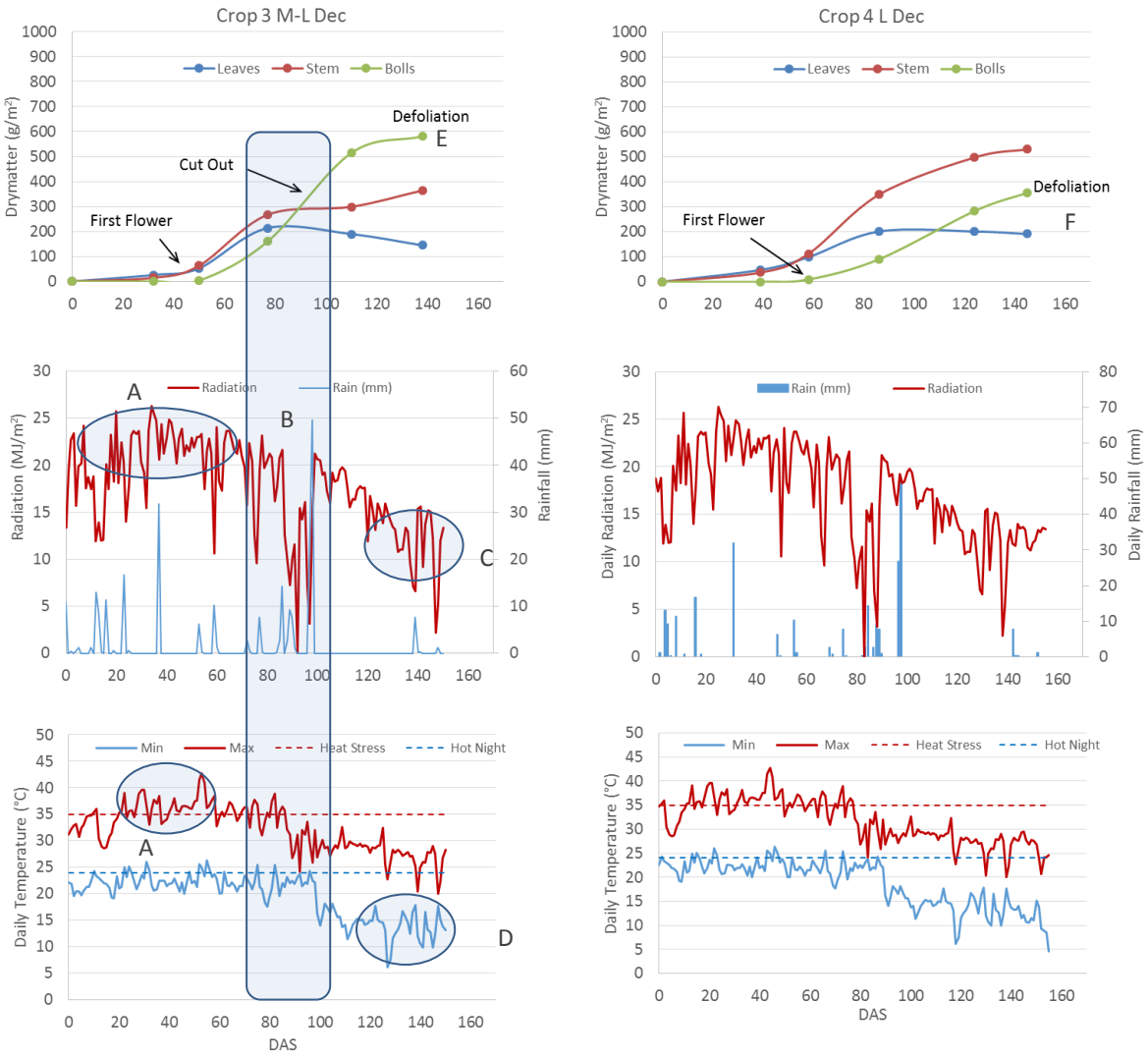


Figure 39. Overlay of crop biomass (top), ambient radiation (middle) and daily temperature and rainfall (bottom) plotted against Days After Sowing (DAS) for a mid-December and very late December sown crop 2016/17.

Key points are:

1. Both crops received excellent radiation during the squaring and up until the commencement of flowering **(A)** combined with hot temperatures.
2. Radiation then declined due to cloudy weather from TC Debbie **(B)** this had a major overlap with flowering and boll filling for these two later crops.
3. After TC Debbie radiation **(C)** and temperatures **(D)** decline rapidly preventing compensation **(E)**.

This is particularly apparent in the late December sowing that experiences poor weather throughout flowering and it continues to produce new fruiting sites until May but keeps losing these (together with leaves) due to shedding (*Alternaria* was affecting leaves). This is why the stem fraction keeps increasing but the leaves stay constant **(F)** as lower leaves that are lost are being replaced by upper canopy growth.

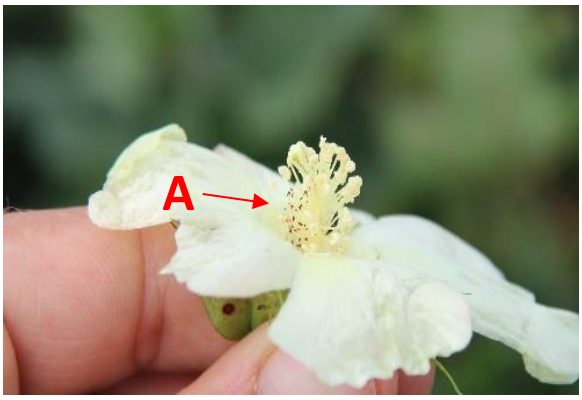


Photo 20. Hot temperatures have destroyed the anthers on this flower (A).

Photo 21. This small misshapen boll is the result of unfavourably hot conditions during flowering and early boll filling.

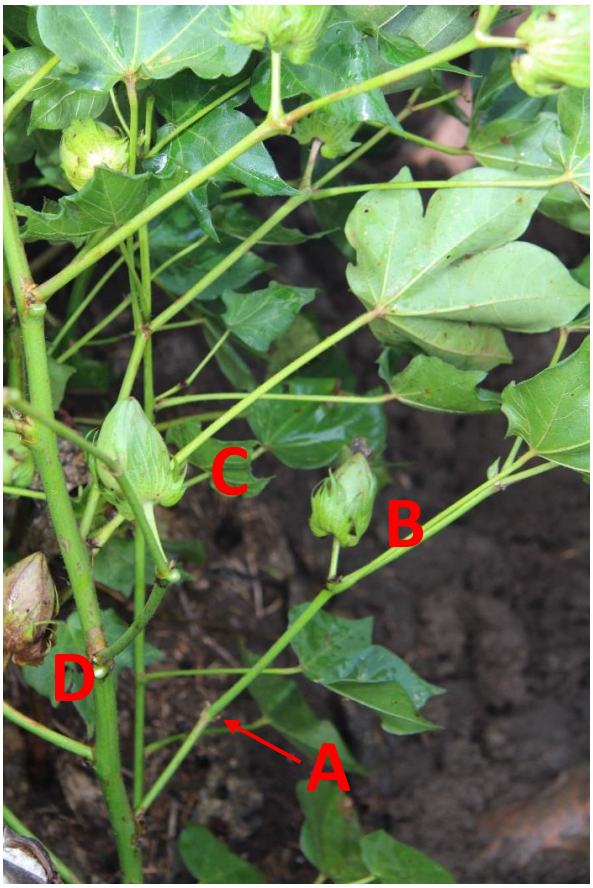


Photo 22. Showing pattern of disruption to bolls setting. Position A was aborted due to weather. Position B has set as a compensatory but due to poor conditions has reduced size. Boll C is parrot beaked due hot weather and boll D is suffering from boll rot as it opens during wet weather from ex TC Debbie.

Photo 23 An example of fruit retention at cut-out on a mid-December sown crop. Many positions were aborted during hot weather. The stems are elongated due to conditions favouring rank growth.

Photo 24. Abortion of recently set bolls due to unfavourable weather conditions on a crop planted at the end of December. Also notice that the leaves are large and the canopy is dark and closed. This canopy is not conducive to efficient light interception by the lower sections and with the rain from ex TC Debbie is predisposed to a higher incidence of boll rots.

Boll rot research

Written by Linda Smith & Paul Grundy

Background

Annual disease surveys have indicated a higher incidence of boll rots occur on the Central Highlands compared to other regions in most seasons. Losses have been observed to be as high as 40% when conditions are favourable, although on average seasonal incidence typically varies between 0.2-5% and is generally associated with wetter seasons. Of particular concern is the high level of tight lock resulting in yield loss. 'Tight lock' of cotton is described by Hillocks (1992) as the condition where the boll is able to open normally but one or more locks remain compact and fail to fluff out due to fungal or bacterial infection. The consistency of the seed cotton mass is such that harvesting equipment is not able to extract the fibre from the locules or it is knocked to the ground, giving the appearance of poor harvesting procedures. Tight lock is found in most humid regions of the US cotton belt and seriously affects yield, with losses ranging from 20-70% (Beltwide Cotton Conferences, 2007).

Tight lock is associated with rainfall, high rates of nitrogen fertilisation, high plant density, high temperature, and humidity during the growing season. Other possible causes for tight lock have been reported including thrips, stink bug damage and boll rot.

A study by Srivastava *et al.* (2010) confirmed that *Fusarium verticillioides* is a causal agent of a type of tight lock, identified as Fusarium tight lock, and that infection can occur through flowers. Infection of seeds occurred at an early stage of development, which may be the primary cause of symptoms.

Flower thrips (*Franklinella* spp.) also have an apparent role in the development of tight lock. Mailhot *et al.* (2007) reported that thrips were associated with increased tight lock severity and reducing thrips numbers reduced tight lock. Thrips were hypothesised to damage cotton flowers or serve as vectors of pathogens. Farrar and Davis (1991) also reported that controlling thrips with insecticides was an effective way to manage corn ear rot also caused by *F. verticillioides*.

Research conducted overseas has indicated that tight lock is associated with numerous pathogens, however *Fusarium verticilloides* has been shown to be a significant contributor to tight lock. This research aimed to determine whether *F. verticilloides* was the primary cause of tight lock in cotton bolls that develop from cotton flowers inoculated with the pathogen. A second experiment aimed to test whether the application of fungicide during flowering would have any impact on reducing the incidence of later tight locking.

Infection pathways during flowering

Methodology

The experiment aimed to test infection pathways and environmental interactions for *Fusarium verticilloides*. In particular, to test whether infection processes around pollination were the primary cause of tight locking symptoms observed later in the season.

To investigate the potential pathways of infection the following treatments using tagged flowers in the field were devised to manipulate conditions during pollination:

- T1 (Control). Unprotected flowers
- T2. *Fusarium*-inoculated unprotected flowers
- T3. Fully protected flowers
- T4. Fully protected but *Fusarium*-inoculated flowers

Innoculated treatments introduced *Fusarium verticilloides* at pollination. Flowers were either left open to the air allowing access by pollinators, or covered to exclude pathogens and pollinators.

The trial was conducted in Emerald at Field 4 of 'Kerry Downs' (Bradley & Renee Anderson). The cotton crop was grown with standard commercial planting, fertilising and irrigation procedures and equipment. The treatments were allocated to a randomized block design with three replicates. The experiment commenced on 26 November 2014 and cohorts of flowers were manipulated each week over a 4 week period. Plots were measured and marked out with conduit and treatments marked using coloured flagging tape. The following diagram shows the trial design and consecutive treatment timing (Figure 40).

	Rep 1				Rep 2				Rep 3			
60m	2	2	2	2	1	1	1	1	4	4	4	4
45m	3	3	3	3	4	4	4	4	2	2	2	2
30m	4	4	4	4	3	3	3	3	1	1	1	1
15m	1	1	1	1	2	2	2	2	3	3	3	3
Week	1	2	3	4	1	2	3	4	1	2	3	4
Head Ditch												

Figure 40. Trial design for tight lock experiment treatments. Flowers were manipulated at week 1 (Pink) 26/11/14, week 2 (Yellow) 1/12/14, week 3 (Blue) 8/12/2014 & week 4 (Green) 15/12/2014

An isolate of *Fusarium verticilloides* collected from maize and stored at Brisbane's Eco-Sciences Precinct Herbarium was obtained from Dr Dean Beasley for tight lock studies on cotton. The fungal isolate was subcultured onto ¼ strength PDA/Streptomycin and grown for 5 days at room temperature. A spore suspension containing approximately 10^4 cfu/ml was prepared by scraping fungal growth from growth media into sterile distilled water, counting spores using a haemocytometer and adjusting accordingly with sterile distilled water. A preliminary glasshouse bioassay under controlled environmental conditions of 30°C and 80% humidity, previously determined that this isolate when inoculated onto the stigma of cotton flowers on day 1 of opening, had the potential to cause tight lock.

Buds at the early candle stage were located, tagged and if required, protected with a paper bag to prevent insects accessing flower when it opened the following day. Bags remained in place until 2 days after flowering. A spore suspension of *F. verticilloides* was prepared containing approximately 10^4 cfu/ml. Bags were opened briefly during flower opening, to allow relevant flowers to be inoculated with *F. verticilloides*. Bolls were then followed until boll opening. Plots were checked for insects and additional hand spraying conducted as necessary to minimise sucking pest interactions.

Thirty candle stage flowers per treatment were tagged at each of the four different time periods (120 per treatment replicate) (see treatments in Figure 40) to capture exposure to different environmental conditions. Tagged bolls were harvested in March 2015 and bolls rated 1 to 4 based on a visual appearance where: 1= Healthy, fluffy locules; 2= slight tight lock, no discolouration; 3= slight tight lock, some discolouration; and 4= severe tight lock (see Photo 25).


Photo 25. Healthy, fluffy locules, rating 1 (left) and severe tight locked locules, rating 4 (right).

Seed from tight locked bolls that were rated a '4' were hand de-linted, counted and weighed. Seed was surface-sterilised and plated onto growth media to recover any seed-borne fungi. The process for plating the seed and conducting fungal identification was as follows:

Seed plating

1. Sterilise scalpel and tweezers with 90% Ethanol and Bunsen burner
2. Sterilise seed in 0.6% bleach (Hypo -10) for 2 minutes
3. Seeds placed to dry for approximately 1 minute on sterile filter paper in sterile working area
4. Cut seed longitudinally with scalpel, holding in place with scalpel
5. Plate on ¼ PDA with streptomycin
6. Plate all seeds from 1 locule/envelope on a plate, placing each successive seed clockwise from the preceding seed.
4. Label plate ensuring to mark the 1st seed placed on the plate from the underneath

Incubate 3-7 days and if possible conduct preliminary taxonomic ID using microscope (before any refrigeration).

Further morphological identification was conducted by

1. Sub isolates to fresh ¼ PDA/S (discard extraction plate)
2. Incubate 3-7 days
3. Conduct morphological identification using microscope
4. If novel isolate single spore isolate.
5. Store SS isolate after ID

The protocol for material stored in the fridge was

1. Incubate at room temperature for 2 days if possible
2. Collect mycelium (note on spreadsheet mycelium harvested)
3. Subculture entire seed to new PDA plate 2-4 seeds per plate (discard old plate)
4. Incubate at room temperature for 5-12 days
5. Conduct taxonomic identification (ID) if possible on fungi.
6. Sub to ¼ PDA/s if novel isolate
7. Single spore (SS) 5-12 days later
8. Store SS isolate in collection
9. Harvest mycelium for DNA extraction
10. Microscopic ID and photos
11. Update spreadsheet with COTT collection number
12. Discard SS plate
13. Discard seed subbed plates

Results

Week 1 was the only time period in which severe tight locking was observed (Figure 41). A significant rainfall event occurred during week 1 (40 mm over 2 days, evening storms) compared to other weeks where no rainfall events were recorded during flowering. During this period, protected flowers produced bolls with less severe tight lock symptoms (Figure 41). This suggests that the infection processes around pollination may be the primary cause of later tight locking symptoms.

The higher incidence of more severe tight lock after the rainfall even suggests that environmental conditions during pollination are likely to have a significant impact on the level of infection and subsequent tight lock symptoms.

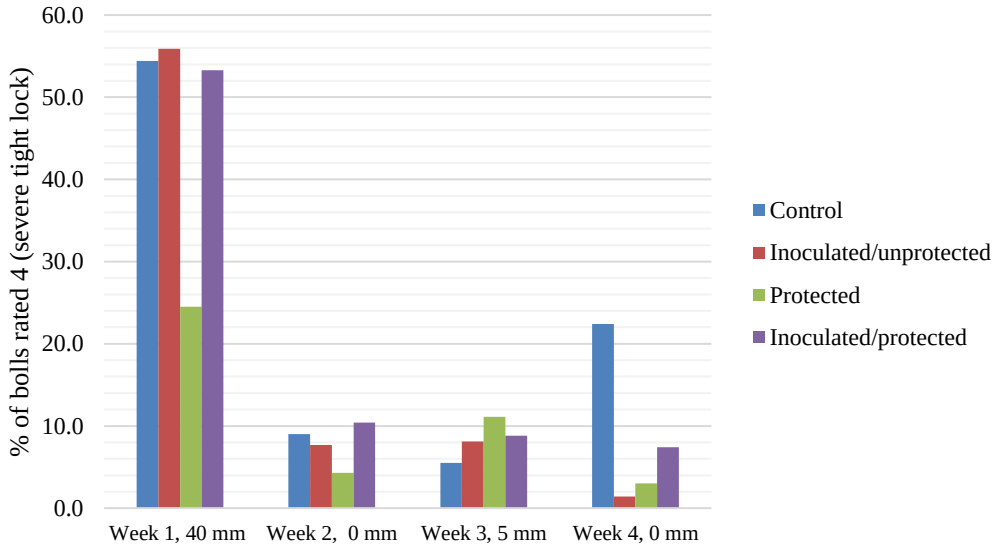


Figure 41. Effect of fungal inoculation of flowers, flower protection and the environmental conditions on percentage of bolls with severe tight locking under field conditions in Emerald, Qld.

The fungi isolated from surface-sterilised seed taken from the severely tight locked bolls is listed in Table 4. Results indicate there could be a number of fungi involved in tight lock, but Koch's postulates will need to be conducted to determine causal agents. The high level of *Alternaria* spp. that was present (36.27%) is interesting given that this fungus is not usually considered an issue in cotton in New South Wales or Queensland, even though it causes a leaf spot disease. The most common *Fusarium* species isolated from seed was *F. semitectum* (12.75%), *F. verticilloides* (11.61%) and *F. proliferatum* (11.5%).

Table 4. The range of fungal species isolated from bolls with tight locking symptoms

Fungal species	Count	Percent
Total *Fusarium* spp.	**572**	**59.27**
Alternaria spp.	350	36.27
F. semitectum	123	12.75
F. verticilloides	112	11.61
F. proliferatum	111	11.50
F. pseudocircinatum	53	5.49
F. oxysporum	39	4.04
Helminthosporium	28	2.90
F. fujikuroi	26	2.69
F. nygamai	26	2.69
F. chlamydosporum	24	2.49
F. rosum	11	1.14
F. brevicatenulatum	9	0.93
F. scirpi	9	0.93
Verticillium sp	9	0.93
F. nisikadoi	8	0.83
F. udum	6	0.62
Cladosporium	4	0.41
F. circinatum	3	0.31
F. compactum	3	0.31
F. polyphialidicum	3	0.31
F. sterilihyphosum	3	0.31
Aspergillus	2	0.21
F. sporotroichiodes	2	0.21
F. beomiforme	1	0.10

The most prevalent genus previously reported to be associated with tight lock is *Fusarium*. Other genera include *Aspergillus*, *Cheatomium*, *Pestalotia, Cunninghamella*, *Nigrospora*, *Phoma, Xanthomonas and Alternaria*, as well as *Glomerella gossypii* and *Colletotrichum capsici. Fusarium* species include *F. oxysporum*; *F. roseum and F. verticilloides.* Of the *Fusarium* isolates recovered from severely tight locked bolls in a study by Srivastava *et al*. (2010), 85% were *F. verticilloides*. Additionally, these researchers observed that seed number and seed weight significantly reduced as the degree of visible tight lock symptoms became more severe.

To determine if a similar relationship could be determined in this trial, bolls from Treatment 4 (inoculated and bagged flowers) from week 1 were examined for effect of tight lock severity on seed weight, number of locules and seeds per locule. Due to the time required to remove seed

by hand from each locule separately, only one replicate of a treatment and time was selected. Mean seed weight declined with symptom severity which agrees with Srivastava *et al*. (2010), however there was no reduction in seeds per locule in severely affected locules compared to healthy bolls. Interestingly bolls with greater number of locules were more susceptible to tight lock (Table 5).

Table 5. Effect of tight lock severity on mean seed weight, mean number of locules per boll and mean number of seeds per locule in bolls collected from Replicate 1, Treatment 4 (inoculated and bagged flowers) in Week 1 cohort (T4 R1 Pink)

Visual rating of bolls for tight lock	Mean seed weight (g)	Mean number of locules per boll	Mean number of seeds per locule
1	0.10	4.07	6.68
2	0.10	4.00	6.90
3	0.10	4.43	6.91
4	0.09	4.55	6.68

Where 1= Healthy, fluffy locules; 2= slight tight lock, no discolouration; 3= slight tight lock, some discolouration; and 4= Severe tight lock

Impact of fungicides on the incidence of tight locking

Methodology

A simple pilot experiment was implemented at 'Orana' (Cowral Agriculture) during the 2015/16 season to investigate the potential to utilise fungicides applied at flowering to reduce the incidence of tight locking at harvest. Two products were examined during this experiment: Prosaro® 420SC (active ingredients prothioconazole 210 g/L and tebuconazole 210 g/L) and the plant activator Bion®. The treatments were:

1. Control (no fungicides applied)
2. Prosaro® 420SC applied at (300 mL/ha) during first flower (20/11/15)
3. Prosaro® 420SC applied at (300 mL/ha) at crop cut-out (23/12/15)
4. Prosaro® 420SC applied at (300 mL/ha) during early first flower (20/11/15) and cut-out (23/12/15)
5. Bion® applied at (10 g/ha) during first flower (20/11/15) and cut-out (23/12/15)

Plots were marked out within an area of commercial crop that had been grown using standard planting, fertilising and irrigation practices and equipment. The plots were 10 m long by two rows wide with four replicates of each treatment. The treatments were assigned to the plots randomly within each block.

The fungicides were applied to the crop at the respective crop stages using a pump pack hand-held sprayer calibrated to apply 100 L/ha spray volume with a two nozzle boom (50 cm apart) equipped with 0.015 flat fan nozzles.

The plots were grown out to maturity as part of the overall field and treatment impacts were assessed just prior to picking. A three metre section of crop row within each plot was randomly selected and all of the bolls assessed as being tight locked or unaffected. This was done in two places within each treatment plot.

Rainfall was recorded at the trial site during the experiment and its timing and amount relative to first flower (FF), cut-out (CO) and the crop being fully defoliated (Figure 42).

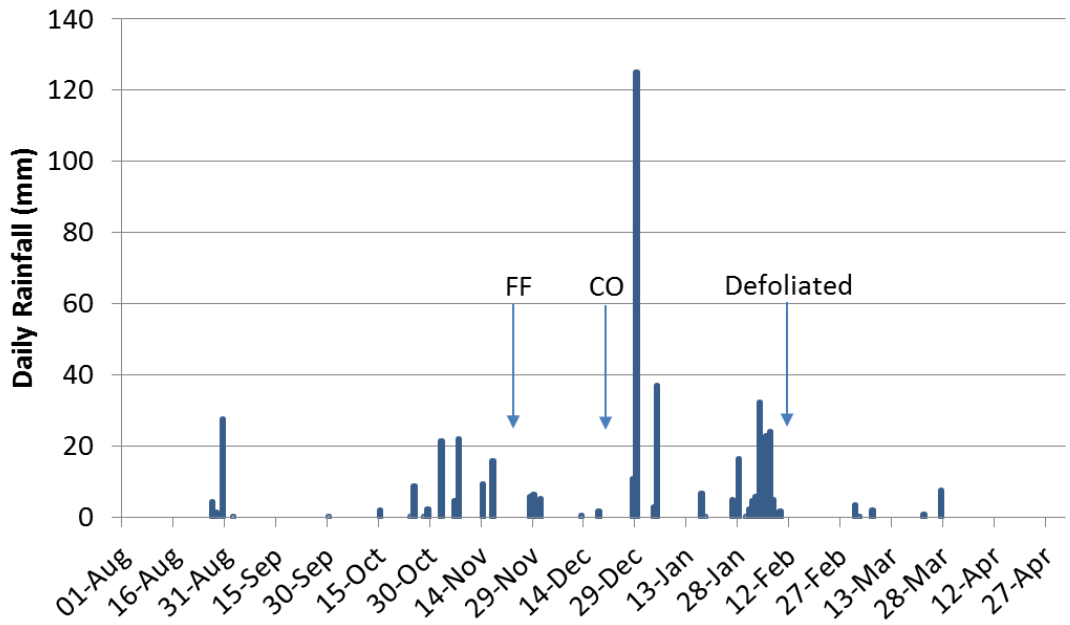


Figure 42. Rainfall received at the trial site during the experiment. Crop stages first flower, cut-out and full defoliation are indicated on the figure. Treatments were applied either at FF, CO, or both.

Due to the lack of treatment differences in the percentage of tight locking observed, bolls were collected from the first replicate of the Prosaro® applied at first flower (T2) and control plots, and returned to the laboratory to identify the species of fungi responsible for the tight locking symptoms. Table 6 details the characteristics of the bolls collected. The seed was removed from these bolls, surface sterilised and plated onto growth media to isolate seed-borne fungi. Isolates were subcultured, stored and tentative identification was conducted using morphological characteristics.

Table 6. Details of bolls collected for isolation of seed-borne fungi.

Treatment	Number of seed/locule	Seed weight (g)
T1	8	0.660
T1	9	0.722
T1	9	0.721
T1	9	0.709
T1	9	0.626
T1	9	0.797
T2	9	0.740
T2	9	0.703
T2	5	0.519
T2	9	0.729
T2	7	0.635

Results

The application of Prosaro® or BION® applied as a foliar spray did not cause any significant (P<0.05) reductions in the proportion of tight locking compared to the untreated control (Figure 43).

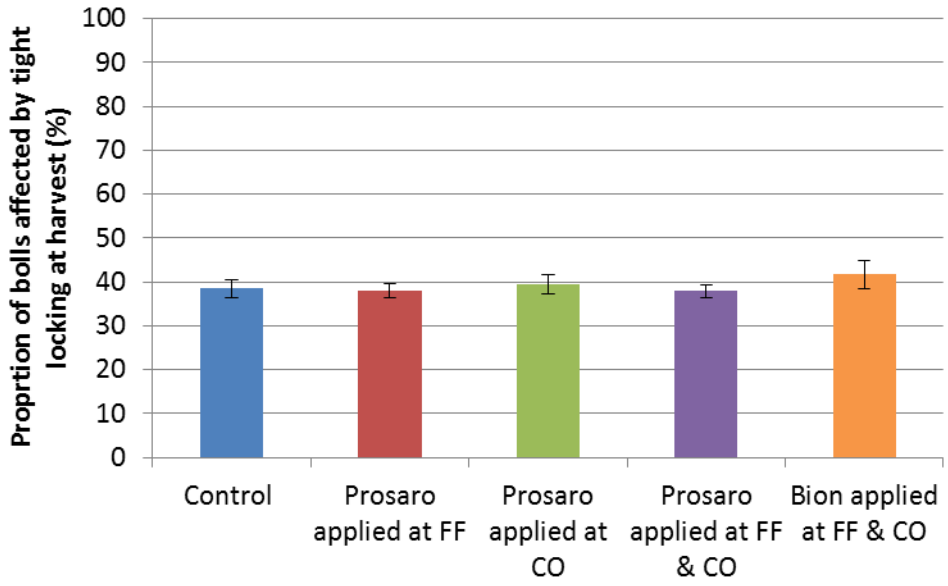


Figure 43. The percentage of bolls recorded as affected by tight locking in response to the application of Persaro® 420SC and Bion® at either first flower (FF) or cut-out (CO) or both time periods.

Despite the lack of treatment differences observed in the field for the incidence of tight locked bolls, an examination of the type of pathogens recorded in the Prosaro® applied during early flowering treatment would appear to have changed the proportional spectrum of fungal species compared with the untreated control (Table 7). The Prosaro® treatment had a reduced proportion of *Alternaria* spp present but increased level of *Fusarium* spp. compared to the control treatment (Figure 44). It is possible that the proportion of isolates belonging to a particular genus or species were altered following application of fungal treatments. **Note** that only a small sample of bolls from one replicate was examined.

Table 7. Number of isolates recovered from cotton seed belonging to various genera of fungi following foliar application of Prosaro® at early flowering compared to the untreated Control.

Morphological identification	Number of isolates	
	T1 Control	T2 Prosaro® early flowering
Fusarium spp.	13	32
Alternaria	16	4
Monilinia	18	4
F. solani	3	0
F. verticiloides	5	2
F. dlamini	3	2
F. proliferatum (may be *F. verticilloides)*	0	23
F. sporotroichiades	1	1
F. semitectum	0	4
F. oxysporum	1	0

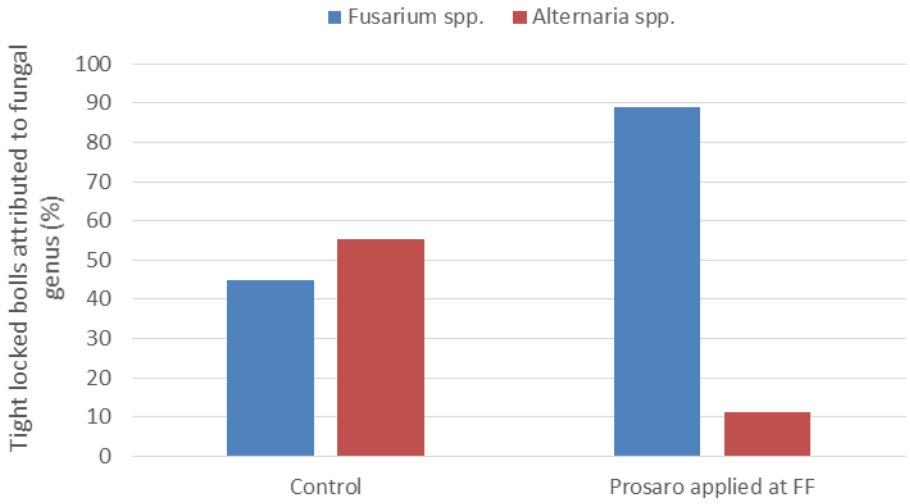


Figure 44. The proportion of *Fusarium* spp. vs *Alternaria* spp. for the control and Prosaro® 420SC applied at first flower treatment. Despite the overall level of tight locked bolls being the same, the application of Presaro would appear to have changed the relative proportion of contributing fungal species.

Discussion

The primary purpose of the flower manipulation experiment was to investigate whether the process of pollination provided a potential infection pathway for pathogens such as *F. verticillioides* that may result in tight locking at boll maturity. The results suggested that the pollination period is a potential stage whereby pathogen spores gain entry to the developing boll but the data also suggest that environmental conditions during pollination have to be conducive to enable infection-causing disease.

The flowers that were treated during the first week of the experiment coincided with two rain events (rain occurred during the two evenings when the flowers were covered by bags). This cohort of flowers went on to develop a high incidence of tight locking compared to the remaining three weeks of flowers that experienced dry conditions during pollination. Additionally, flowers that were protected in Week 1 produced bolls with less severe tight lock symptoms. This indicates that when flowers first open they may be vulnerable to inoculation/infection with fungi that cause tight lock, however environmental conditions need to be conducive for disease progression, as suggested by the literature.

The results from the laboratory assays suggested that *F. verticillioides* was not the predominant pathogen associated with tight lock. Fungal isolations from surface sterilised seed in tight locked bolls show there are numerous other fungi that may have contributed to the tight lock symptoms. While 59% of the species recorded were from the *Fusarium* genera, 36% were *Alternaria* spp., which have also been reported to be associated with tight lock. It may be that this fungus is far more important than previously considered with regard to disease impact in Central Queensland.

Fusarium graminearum, other *Fusarium* species and fungi from genera *Alternaria, Aspergillus, Penicillium* etc., colonize wheat kernels and induced significant losses in a study by Balaž *et al*. 2011. In their research, Prosaro® foliar fungicide provided efficient protection of wheat from *Alternaria* spp. and *Fusarium graminearum*. It was for this reason that Prosaro® was tested against for its potential to be used against tight locking given the likely presence of both *Alternaria* spp. and *Fusarium* spp.. While Prosaro® failed to provide any significant reductions in the incidence of tight locking compared to the control treatment, an assessment of the fungal species present in the bolls collected from the plot treated with Prosaro® at first flower strongly

suggests that the fungicide reduced the incidence of *Alternaria* spp.. However, the reduction of *Alternaria* was offset by a corresponding increase in *Fusarium* spp. resulting in the same overall level of disease symptoms.

The two field experiments suggest that the causes for tight locking are complex with a range of causal species and infection depending on weather conditions at particular points in time. The diversity of fungal species was surprising and presents a challenge for contemplating any form of fungicidal control strategy as there few chemicals that would be effective across the range of species recorded. Reducing the population of one fungal species may allow the increase of another due to reduced competition for that niche environment. In this situation, it would be expected that Prosaro® would also reduce *Fusarium* spp., however this would be dependent on fungicide application prior to time of pathogen infection.

Tight locking is likely to remain a challenge in the CQ environment. The best management approach might be one that reduces flower exposure to humid conditions that are likely to coincide with rain events and also limits boll opening under wet conditions. The August sowing methodology largely confines flowering to November (a drier time of year) and completes boll opening by mid to late January, halving the period of crop exposure to monsoonal conditions compared to planting at the traditional time of mid-September to the end of October.

Symphyla sampling and research

Symphylids potentially causing damage to young cotton crops has been a concern since they were first detected in the Dawson Valley by cotton consultant Mr Damian Erbacher during 2008. The pest status of this organism for cotton has been unclear although a pot trial conducted by Murray and Hall (2009) pointed towards this organism having the capacity to cause the symptoms that were observed on cotton in the Dawson region.

Determining the pest status of symphylids has been difficult because damage symptoms have been inconsistent between fields, farms and seasons. Initial outbreaks of damage were curiously isolated primarily to two farms in the Dawson Valley with adjoining fields having either no obvious damage symptoms or much less damage despite the presence of the organism in soil samples in less affected areas. The cotton crops that were planted were more or less contiguous in the irrigation area being sown at a similar time on the same soil types and row configuration systems. Aerial photos taken at the time show this anomaly (Photo 26).

Photo 26. Aerial view of field with suspected symphylan damage (P. French).

To further investigate the pest status of this organism, collections of symphylids were made from the Dawson Valley, Darling Downs and Moree regions during October 2013 in an attempt to establish a laboratory colony so that basic density-controlled experiments could be conducted with this cryptic pest. However, these efforts were unsuccessful despite repeat collections and seeking rearing methodologies from previous researchers (D Murray and overseas authors).

Given the inability to rear symphyllids, it was concluded that an alternative approach would be to sample a large number of fields where symphylids were reported and attempt to correlate abundance with crop symptoms. To enable these comparisons to be made, it was necessary to have a consistent method to numerically quantify symphylid abundance at each sample site. Marie-Alphonsine *et al.* (2011) reported a simple bait trap method used to sample symphylids in pineapple fields in New Caledonia. The authors used was a 250 mL black PVC conical pot (9 cm high; 11 cm wide at the top and 8 cm wide at the bottom) containing 76 holes 13 mm in diameter in the sides and bottom. The method described was to dig a hole 15 cm deep in the field, the pot was placed in the hole and then filled by 1/3 with the excavated soil. 2.5 cm cubes of potato were placed onto the soil in the pot which was then backfilled with the remaining soil so that it was fully covered. The sample pots were recovered 3-5 days later and returned to the laboratory where the soil was tipped out of each pot into a tray for examination for symphylids.

A search for the same style of pot was not successful in Australia. However, several types of "net pots" commonly used for orchid culture were purchased and a small experiment was conducted to test the relative capture efficacy of three differently designed pots. A field with high numbers of symphylids was identified in the Nandi area of the Darling Downs. The three different pot styles were buried and baited with potato using the described method above, left in place for four days and then recovered and returned to the laboratory. Fifteen of each pot type were tested, randomly assigned along a zig zag transect through the field. The different pot types are shown in Photo 27.

Photo 27. The three different net pots tested for symphyla trapping. From left to right is the large net pot, small diamond pot and small net pot.

This test identified that the small net pot was the most efficient and effective trap for sampling symphylans. Effective in terms of capturing large numbers (Figure 45) and efficiency being defined by the amount of soil contained in the pot that had to be sorted through after the traps

were recovered relative to symphylid abundance (Figure 46). A simple comparison was also made to compare potato as a trap bait with soaked grain (wheat seed) in the small net pots. This test showed that grain baits were not as attractive to symphylids as potato (Figure 47). A comparison of grain baits and potato for other soil pests found that potato was just as attractive as grain baits (Figure 48) and could therefore be used as an 'easy to prepare' alternative to pre-soaked grain.

Photo 28. Recovery of a small net pot that had been baited with potato.

Photo 29. Symphyla that have been attracted to the potato bait within a small net pot. Note the difference between the two symphylids in the centre of the photo compared with the dipluran at the top right hand side of the image. Diplurans were frequent 'bycatch' during sampling.

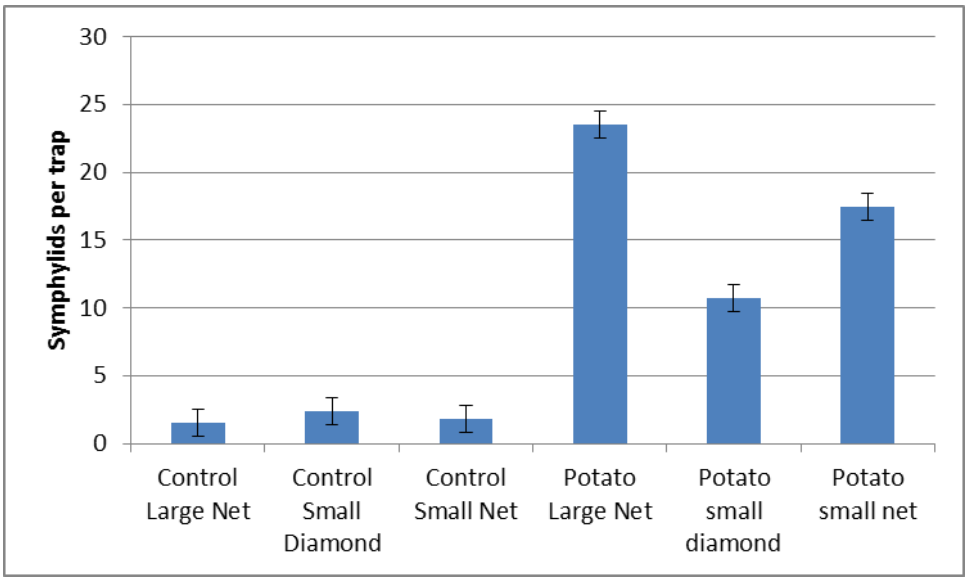


Figure 45. A comparison of "air pot" types for capture sympylids in the field. The data displayed is the mean trap catch of the three pot types both unbaited (soil only) and with potato baits.

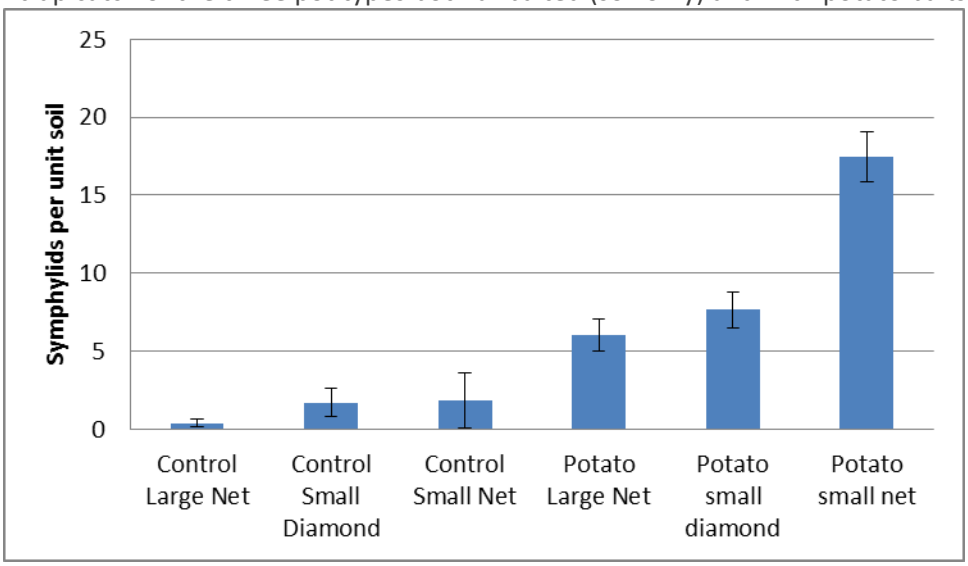


Figure 46. Symphylid abundance expressed as an average per unit volume of soil held in each pot type. The small net pot was the most efficient capturing the highest number of symphyllids per unit of sampled soil contained in the trap.

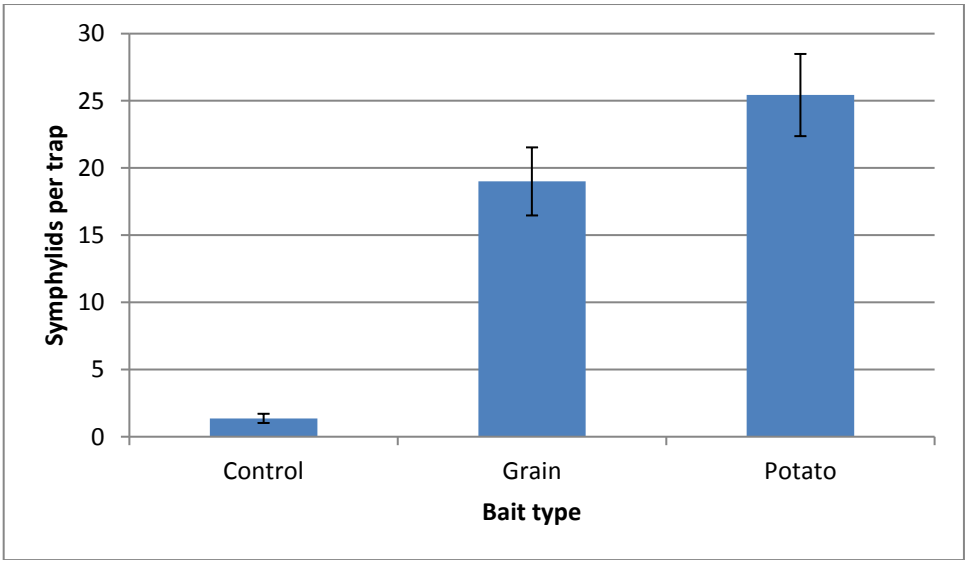


Figure 47. Symphyllids captured in the small net pot utilising potato and soaked (germinating) wheat as a bait.

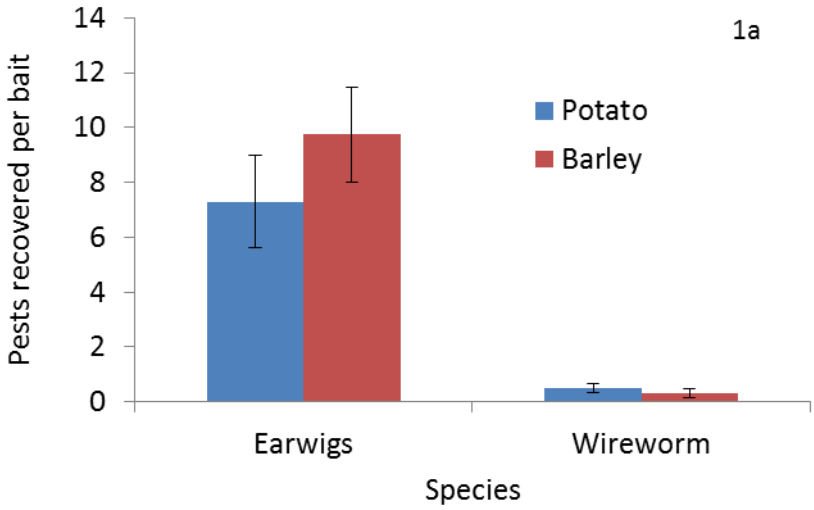


Figure 48. Comparison of attractiveness of potato and soaked grain baits to common soil pests.

With an established method for sampling symphylids and general soil pests determined, fields thought to have symphylid problems were targeted for sampling between 2014 and 2016. In each case sampling was conducted in areas where cotton showed seedling damage symptoms (plant death, retardation, patchy emergence/stand) as well as in adjacent areas that were symptom free. This sometimes entailed sampling other areas in the same field or adjacent fields provided the sowing date was similar.

Symphylids were sampled at Theodore and the Darling Downs in 2014, Goondiwindi and Theodore in 2015 and Theodore in 2016. A large number of fields in total (>30) were sampled for symphyla and the health and vigour of the crops visually assessed in an attempt to correlate the presence of symphyla with signs of early season crop damage. Sampling was conducted by placing small net pots baited with potato in a transect through each field area (generally 5-10 m between each trap and eight traps per sample site). The traps were typically left for 4-5 days prior to being recovered for assessment.

The results of this sampling are collectively presented in Figure 49. Sampling from these fields suggested that symphylids acting alone are unlikely to be a significant factor in causing seedling retardation or death. This was confirmed by sampling from several fields where significant populations of symphyla were trapped with little apparent impact on crop establishment or seedling vigour being visually evident at the time of sampling. For the fields that had poor establishment and retarded seedling growth, symphylids were often present, however, sampling also indicated the presence of a range of other insect pests. A mean of the fields with good and poor establishment showed that symphylla were present at similar levels (2.8 per trap) but for the poor fields earwigs were present at 3.2 insects and wireworm larvae at 0.8 per trap. Wireworm were mostly absent in the fields with good plant stands and earwigs present at much lower densities (average 0.6 per trap). The other factor that needs to be considered were field conditions and incidence of disease at the time of sampling. A number of fields exhibiting establishment issues were very dry with seedling plants struggling under poor conditions from both a soil moisture and ambient temperature perspective. Black root rot was also present in a number of problem Darling Downs fields during 2014 (Linda Smith pers com).

The sampling conducted over three seasons suggests that the impact of symphyla is unclear. What the sampling does suggest is that the causes for the seedling mortality and retardation that were observed were more likely due to a complex interaction between a number of soil organisms, disease pathogens and typically unfavourable field conditions. It is unclear whether

or not symphyla alone are a pest organism or whether they may just add to negative field factors that collectively can cause plant stand issues.

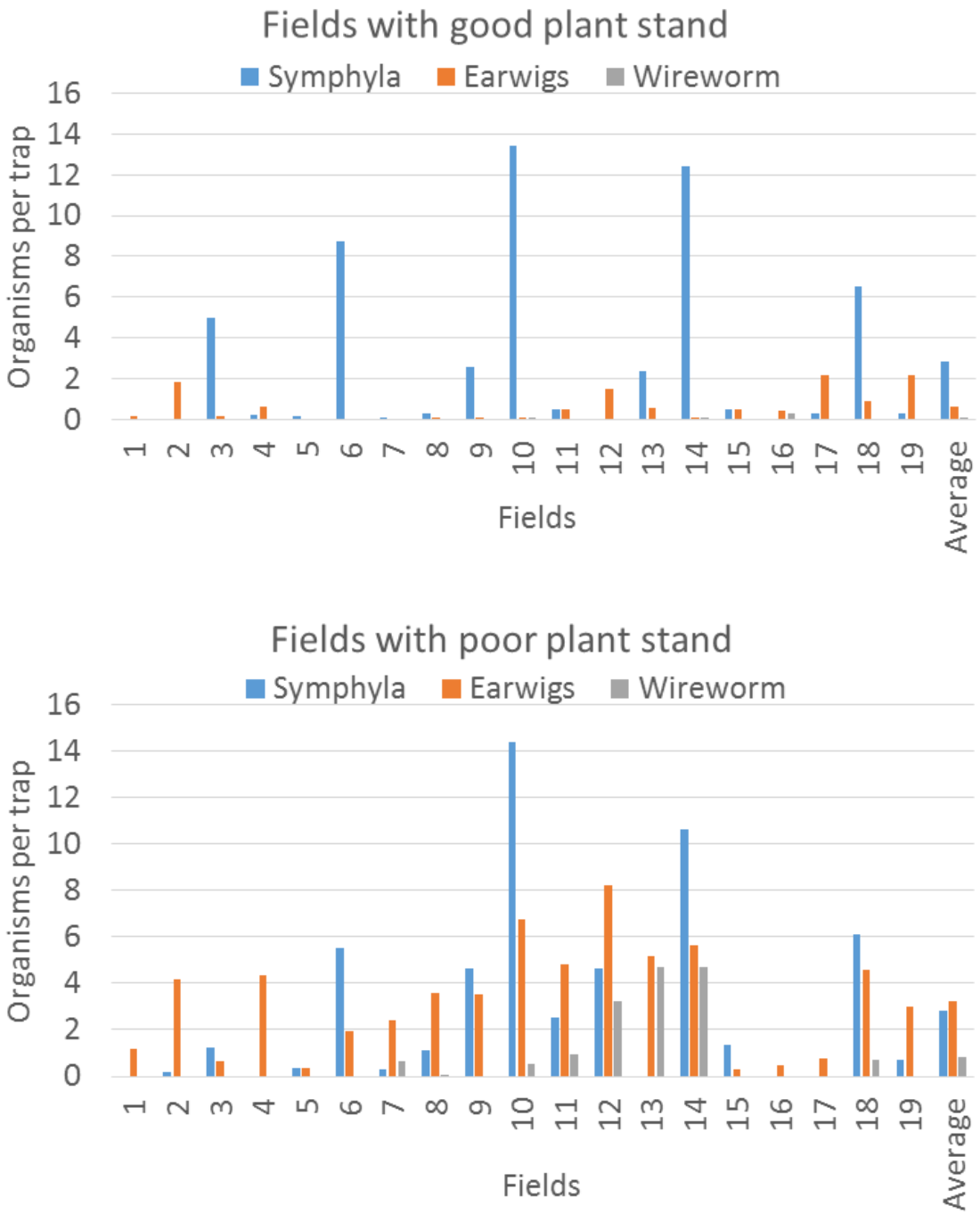


Figure 49. Depicting soil organism trap data from fields with a good plant stand (top) vs fields with a poor plant stand (stunting and/or seedling death causing an uneven stand). The sample sites for the good plant stand sites were either from fields adjacent to problem areas planted at the same time or samples from within the same field but collected from field areas where plants were healthy and growing vigorously.

Previous DAF research with symphylids

Given the ambiguity around the pest status of symphyla, the results of some pot trials conducted during 2009 by Dr David Murray and Ms Zara Hall will be reviewed here to seek additional context regarding symphyla impacts and to have this research work placed on the cotton reporting record.

Dr Murray and Ms Hall conducted two pot trials during 2009 after the initial recorded incidences of crop damage that were associated with high abundance of symphylids in the Dawson Valley. These experiments confirmed that symphylids could cause plant retardation and negatively affect seedling root system development. The conclusion from these pot trials supported the hypothesis that sympylids could have been a causal agent for the type of damage observed in fields at Theodore during the 2008 season.

However, reviewing these studies in light of the more recent survey data presented here provides a different context for these experiments that only had the primary aim of determining whether or not symphyla could cause damage. For these experiments symphyla were collected from cotton fields at Theodore, Qld in 2009 and placed into moist peat moss and sustained on a diet of lettuce leaves at 27°C.

For the first pot trial a mix of 50% peat: 50% potting mix was used to fill 150 mm pots. A filter paper was placed into the bottom of each container to prevent symphyla escaping or moving between pots through the drainage holes. Single cotton seeds (Sicot 70 BRF treated with Dynasty™) were planted in each pot and the pot watered and allowed to drain. Large symphylids (4 mm length) were then added to the pots with the following treatment replicate regime:

Treatments	**Replicates**
0 Symphyla (control)	32
5 Symphyla	20
10 Symphyla	20
20 Symphyla	20

The pots were placed into a controlled temperature room using a randomised design and left to emerge. Assessments were made of seedling emergence and dry weight biomass (root and canopy) was sampled destructively on half of the replicates at 2 weeks and the remaining half at 4 weeks after sowing (Photo 31). The pot contents were also searched for remaining symphilids when destructive sampling was undertaken.

Photo 30. Cotton seedlings 22 days after sowing showing visual difference between a control and symphyla treatment.

Photo 31. Plants removed from the pots and washed of soil before being dried for dry matter accumulation assessment.

There were no differences observed for seedling emergence. The total dry weight of roots and shoots only showed a significant difference between the control and the highest treatment of 20 symphyla per 150 mm pot at the first sampling dates (2 weeks) (F pr 0.056). However, there were no significant differences between the lower treatments of 5 and 10 symphylids per pot and the control. By the second assessment date (4 weeks after sowing) there were no significant treatments between any of treatments for total dry weight (F pr 0.237) indicating that plants had compensated for early growth delays.

Above ground biomass was not significantly different between any of the treatments (F pr 0.083), whereas the root system biomass was significantly different for the highest symphyla treatment, 20 symphyla per pot (F pr 0.021) but not for the 5 and 10 symphyla per pot.

At the conclusion of this trial a second more basic experiment was conducted utilising the surviving symphylids from the first experiment. Surviving symphylids were split between 10 pots (37 symphylids per pot) that was set up in the same way as the first experiment with a single cotton seed. Following emergence, the plants were sampled and photographed as the treatment impact was very clear and significant at (P<0.001) (Photo 32Photo 33).

Photo 32. Cotton seedlings exposed to 37 symphylla per pot during germination

Photo 33. Cotton seedlings free from symphyla during germination (control).

The impact of the symphylids on emerging cotton was very clear in the second experiment. However, to context these results, 37 symphyllids contained in a small pot with a single cotton seedling host equates to a very high pest density relative to field conditions. In the first experiment, lower numbers of symphyla at 5 and 10 per pot had no significant impact and 20 per pot was only just significant. Whilst these experiments demonstrated that symphyla feeding can cause root system damage, the number of symphylans per pot needed to be in very high densities to cause significant seedling damage or mortality.

A generalisation from this earlier study and the field surveys are that symphyla would appear to be an unlikely candidate to solely cause cotton establishment issues and that the potential pest impact would depend on having high symphylan densities, unfavourable field conditions and possibly the presence of other causal agents.

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Project outcomes and Industry impact

Early sowing research

The sowing date research in relation to long term climatic trends in CQ has provided a new option (August sowing) for growers to better manage and mitigate climatic risks. Prior to the commencement of this project parts of the CQ cotton industry had lost confidence in the regions ability to reliably grow high yielding and quality cotton.

August sowing has been demonstrated over four seasons to provide significant advantages in the CQ environment as a mechanism for limiting unfavourable crop outcomes due to monsoon-related weather events. August sowing does not eliminate these problems but compared to the previous status quo scenario of planting between mid-September and late October, August sowing reduces the risk of rainfall or heat stress causing boll losses.

An independent impact analysis of this project by Agtrans Research was commissioned by DAF to examine the benefits of the early sowing research. The analysis concluded that the likely benefit of the project to the CQ industry would be $20.24 million in present value terms providing a project benefit cost ratio of 17:1. This estimate of return was based on the assumptions listed below.

During the life of the project the August sowings averaged a yield of over 11 bales per ha compared with the long term average for Emerald of just above 8 bales per ha, representing a potential average yield increase of 37.5%. However, the report utilises a conservative estimate of 20% increase in yield with only a 50% probability of impact (50% grower adoption) taking up to 3 years to achieve (2021). Assumptions were then made on the likelihood of lint quality discounts and reduction in crop losses associated with deleterious weather events. The various assumptions, time frames and rates of adoption used to calculate the benefit of this project are given in Table 8.

Table 8. Summary of Assumptions for DAQ1401 Impact Assessment

Variable	Assumption	Source
Benefit 1: Increased average yields		
Average area of irrigated cotton – Central Highlands (10-year average)	14,800 ha	Based on date obtained from The Australian Cottongrower, 2010, 2011, 2012, 2013, 2014, 2015 & 2016
Average yield for irrigated cotton – Central Highlands (10-year average)	8.0 bales/ha	
Average price of cotton lint (5-year average)	$480/bale	Based on data obtained from the Australian Grown Cotton Sustainability Report, 2014
First year of impact	2018	Agtrans Research based on project DAQ1401 being completed 30 June 2017
Maximum adoption	50% of Central Highlands irrigated crop area	Agtrans Research[(a)]
Time to maximum adoption	3 years	
Average yield improvement	20%	Agtrans Research (based on yield data obtained during the commercial scale trials for DAQ1401)
Risk Factors		
Probability of output	100%	Agtrans Research
Probability of usage	100%	
Probability of impact	50%	Agtrans Research (based on published interviews with trial participants and researchers)

Benefit 2: Reduced crop losses in years with severe weather events		
Average area of irrigated cotton – Central Highlands (10-year average)	14,800 ha	Based on date obtained from The Australian Cottongrower, 2010, 2011, 2012, 2013, 2014, 2015 & 2016
Average yield for irrigated cotton – Central Highlands (10-year average)	8.0 bales/ha	
Average price of cotton lint (5-year average)	$480/bale	Based on data obtained from the Australian Grown Cotton Sustainability Report, 2014
First year of impact	2018	Agtrans Research based on project DAQ1401 being completed 30 June 2017
Maximum adoption	50% of Central Highlands irrigated crop area	Agtrans Research[(a)]
Time to maximum adoption	3 years	
Frequency of severe weather events occurring from mid-February	10% (1 year in 10)	
Production losses for crops sown at traditional times in years with severe weather events	50%	Agtrans Research based on reports of crop losses due to flooding (e.g. ABC Rural, 2011)
Production losses (reduced) for growers who adopt early sowing in years with severe weather events	Nil	Agtrans Research[(a)]
Risk Factors		
Probability of output	100%	Agtrans Research
Probability of usage	100%	
Probability of impact	50%	
Benefit 3: Reduced incidence of quality discounts		
Average area of irrigated cotton – Central Highlands (10-year average)	14,800 ha	Based on date obtained from The Australian Cottongrower, 2010, 2011, 2012, 2013, 2014, 2015 & 2016
Average yield for irrigated cotton – Central Highlands (10-year average)	8.0 bales/ha	
Average price of cotton lint (5-year average)	$480/bale	Based on data obtained from the Australian Grown Cotton Sustainability Report, 2014
First year of impact	2018	Agtrans Research based on project DAQ1401 being completed 30 June 2017
Maximum adoption	50% of Central Highlands irrigated crop area	Agtrans Research[(a)]
Time to maximum adoption	3 years	
Frequency of variable weather conditions (e.g. wetter-than-average or hotter/more humid) years	40% (2 year in 5)	
Average quality discounts on cotton lint for the Central Highlands in wet years for crops planted at traditional times	$40/bale	CRDC, 2015
Quality discount for cotton lint for the Central Highlands in wetter/more humid years for crops planted early	Nil	Agtrans Research[(a)]
Risk Factors		
Probability of outputs	100%	Agtrans Research
Probability of usage	100%	
Probability of impact	50%	
COUNTERFACTUAL: RD&E into agronomic practices for Bollgard 3® (including early sowing) would have happened anyway.		
Cost of RD&E into agronomic practices for Bollgard 3® in Central Queensland	$1.08 million over four years	Based on total investment in DAQ1401 from 2014 to 2017 in real dollar terms

First year of investment/RD&E	2018/19	Agtrans Research (based on first commercial release of Bollgard 3® for the 2016/17 season)
First year of impact	2024/25	Based on six years for data collection and development of an updated resistance management plan for Bollgard 3® from 2018/19
All other variables held constant.	Benefits 1, 2, and 3 delayed eight years.	Agtrans Research
Additional Costs: Adoption of August sowing incurs some addition costs compared to planting during the traditional sowing window for the Central Highlands.		
Average, expected additional crop management costs from increased seeding rates and additional seed treatments.	$140 per hectare	Paul Grundy
Probability of incurring additional cost	50%	Agtrans Research[(a)] based on the potential for offsetting water savings depending on the season and prevailing management practices

Agtrans estimates based on consultation with project PI Paul Grundy

The analysis identified three sources of benefits and attributed a value to each of these factors. Table 9 shows the relative contributions to the present value of benefits (PVB) from each source. As the additional costs required to achieve the benefits (i.e. expected additional costs for higher seeding rates and additional seed treatments) could not be apportioned between the three benefits, the contributions to the PVB are based on the proportion of each benefit from the total gross benefits (undiscounted). The benefit 'increased average yields' is the largest contributor to total benefits by a significant margin.

Table 9. Contribution to total benefits from each source

Source of Benefits	Contribution to PVB ($m)	Share of benefits (%)
Increase average cotton yields for the Central Highlands (Benefit 1)	14.29	70.6
Reduced crop losses from severe weather events (Benefit 2)	3.57	17.6
Reduced incidence of quality discounts due to variable weather conditions (Benefit 3)	2.38	11.8
Total	**20.24**	**100.0**

The investment in project DAQ1401 has given growers confidence that planting cotton crops early in the Central Highlands is a good tactic that enables early flowering of cotton crops in spring, bringing forward the time at which crops mature thus reducing exposure of boll filling crops to periods of variable weather conditions. This will provide benefits to the Queensland Central Highland cotton industry.

The R&D undertaken in project DAQ1401 was focussed on cotton sown in the Central Highlands in Queensland. However, the research findings also may be applicable to the Dawson-Callide region in CQ but to a lesser extent. The potential benefits for the Dawson-Callide cotton region were excluded from the analysis undertaken by Agtrans and therefore are likely an underestimate of the total value of the potential impacts for Central Queensland.

Sensitivity analyses carried out on key variables used in the valuation of impacts indicate that, even using extremely conservative assumptions for the maximum level of adoption or the average yield improvement, results remain positive.

Impact of crop benchmarking

The crop benchmarking has been valuable for the local industry as it has provided detailed explanation of why crops planted during August and December have performed differently. Importantly, these differences were attributable to key weather and management factors and the benchmarking provided a very direct comparison between commercial crop outcomes and weather interactions. The crop benchmarking has provided people with a better understanding of the linkages between certain weather events and crop growth and development, providing a basis for how agronomic management tactics may or may not be able to be deployed to ameliorate particular responses.

Impact of boll rot research

The impact of the roll rot research has been to reinforce the complexity associated with outbreaks of these diseases. The research conducted in this project demonstrated that flower pollination was a potential pathway for future tight locking of bolls although the development of disease symptoms was dependent on ambient weather conditions at the time. Similarly the fungicide trial demonstrated that the pathogens that might be responsible for tight locking are abundant and varied and that the control of one group of pathogens may only create an opportunity for another pathogen genera to thrive resulting in a similar incidence of tight lock disease.

The complexity identified by this research suggests that interventions such as the use of a fungicide is unlikely to provide significant benefits. Growing the crop at a time of season when conditions are less conducive to disease outbreak remains the most appropriate tactic for reducing the incidence of boll rots in CQ. Early sowing reduces the period of a crop's exposure to the chance of extended monsoon-related wet weather events and therefore at this time is most credible approach for reducing the overall prevalence of these diseases.

Impact of symphyla research

The impact of the symphyla research has been to highlight the importance of soil pests generally as something to should be considered by all growers and agronomists before cotton is sown. Investigation of the potential causes of poor plant stands highlighted the presence of soil pests (of which crop managers are generally unaware). The pest status of symphyla remains somewhat unknown but the crop survey data in this project suggests that symphyla in isolation are unlikely to cause establishment issues unless the numbers are very high. It may well be that symphyla may exacerbate the damage caused by other soil pests or disease organisms.

Take home messages from DAQ1401

The take home messages from DAQ1401 are:

- CQ is geographically and climatically distinct from all of Australia's other cotton-producing regions and therefore will benefit from a crop production strategy tailored to the constraints and opportunities of this environment. The direct deployment of tactics from temperate regions without consideration of local factors should be avoided.
- August sowing is a tactic that can reduce climate-related cotton production risks in CQ. Earlier sowing reduces the period of crop exposure to variable monsoon-related weather conditions that occur from late December until the end of February. Although this tactic does not avoid the possibility of wet picking, compared to the previous status quo of planting between mid-September and late-October, August sowing reduces wet weather picking risks by approximately 50%.
- When sowing in August, growers need to exercise care and ensure that the practices used are of a very high standard. August-sown crops are more susceptible to seedling loss due to cold or disease and therefore growers should be mindful of weather/temperature outlooks, field conditions, and field disease history status. The use of appropriate seed dressings and higher planting rates is recommended.
- Planting in very early August compared to mid-August provided no significant yield advantages over the four years of trials and only marginal gains in picking maturity (4-7 days). Growers need to balance the increased establishment risks with planting very early August against the minor gains in maturity. It would be advisable that growers do not commence planting before 10 August.
- August sowing brings forward the boll setting and filling period into a time of year (November and December) when radiation is more consistent, temperatures less extreme and extended periods of rainfall unlikely. The result is a crop that is easier to manage agronomically and partitions biomass very efficiently into bolls (as opposed to stems and leaf).
- August-sown crops cut out in early December before the summer solstice. The continuing lengthening of days after cut-out provides a buffer against the increasing likelihood of cloudy weather from late December onwards.
- August-sown crops have provided a significant 23% yield advantage (2.2 b/ha pa) compared to mid-September sown crops over a four year period. This is the result of August-sown crops mostly fulfilling their yield potential without major disruption from weather events. *September-sown crops failed to fulfil their yield potential in each of the four years of the research project due to deleterious weather events (cloud, rainfall or heat waves)*.
- The yield potential of August-sown crops is dependent on implementing early season management that encourages vegetative expansion during the period leading up to first flower. Tactics include lower deficit irrigation scheduling, earlier side-dressing of nitrogen, and more relaxed early season square retention targets. Failure to achieve sufficient canopy biomass by first flower can result in a compact plant that cuts out prematurely due to the rapid onset of boll demand.
- Boll rots are a complex problem for CQ growers with the increased incidence of tight locking potentially due to the presence of a broad range of causal organisms combined with a more favourable environment (higher humidity and rainfall). There are no silver bullets for boll rots due to the range of competing causal pathogens and the increased likelihood of rainfall during the boll setting and filling period compared to southern

climates. Early sowing may provide some relief from the severity or frequency of boll rots or tight lock due to the reduced exposure to monsoon conditions during February when disease outbreak is most prevalent.

- The pest status of symphyla is unclear but it is unlikely that this organism alone is responsible for the crop establishment damage sometimes reported by growers and consultants. In fields that presented with poor crop establishment, symphyla were found to be present along with other recognised soil insects and seedling diseases. Often symphyla were found to be just as abundant in areas or adjacent fields where no visible symptoms were evident. Whilst it is possible that symphyla might contribute to establishment difficulties (root feeding may increase disease incidence or a reduced rate of plant development may extend the period of susceptibility to other soil pests) this animal is unlikely to be a sole causal agent.

Extension opportunities

The outcomes of this project have been well extended through a series of field walks and two specific half day grower workshops that have aimed to bring all of the information together. Learnings gained through the conduct of the experimental project have subsequently been reinforced through CQ newsletters put together in conjunction with Ruth Redfern and Sharna Holman and branded under CottonInfo. The content of these newsletters has addressed various considerations for early or late sowing in CQ from a sowing, irrigation, insect and nutrition management perspective.

The results from this project have also been presented at the Association of Australian Cotton Scientists conference in Canberra during September 2017.

It is anticipated that the key findings of this work with regard to cotton production and climate in CQ will be collated into a grower booklet at the end of the 2018 season when a further season of continuing benchmarking of central Queensland crops is complete. This booklet will surmise previous sowing date research, the climate analysis, trial results, agronomic management advice in a format that growers should find easy to use and apply.

The main requirement for further research is the continued benchmarking of commercial crops planted at different times through the Bollgard® 3 planting window. This additional data will be invaluable for validation of future OZCOT modelling for CQ. Reliable modelling to calculate the relative performance of different sowing dates over much longer time periods using historical weather records would be of significant benefit to the CQ industry.

List the publications arising from the research project and/or a publication plan.

The only project-specific publications arising from this work to date are articles in Spotlight and Australian Cotton Grower Magazine. It is anticipated that the planting date research will be submitted as manuscripts for publication in a scientific journal within the next 18 months.

The following articles have been published in the Australian Cotton Grower.

Grundy P, Yeates S, Iker J, Spargo G & Holman S. 2017. Bollgard 3 flexibility bears early fruit in Emerald. *The Australian Cottongrower* Feb/Mar. Greenmount Press Toowoomba. Aug/Sep. Greenmount Press Toowoomba 22-26.

Grundy P, Yeates S, Iker J, Spargo G & Roughley N. 2014. Biodegradable film for earlier boll filling. *The Australian Cottongrower* Apr/May Greenmount Press Toowoomba 16-22.

Grundy P & Quade A. 2014. Planting cotton – have you baited for soil pests first? *The Australian Cottongrower* Aug/Sep. Greenmount Press Toowoomba 22-26.

Have you developed any online resources and what is the website address?

No.

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- **Mr Jamie Iker** (Spackman Iker Ag Consulting) was responsible for the day to day checking of the trial field area and making recommendations for insect management and general crop agronomy as well as collecting some of the in crop measurements (Photo 36). Jamie spent many, many hours on the phone discussing the trial with the project leader and his commitment and focus over four seasons is commendable and appreciated.
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- **Dr Stephen Yeates** made a major contribution to this research with his insightful climatic analysis and willingness to make site visits throughout the project to examine the trial plots and participate in grower workshops. The experience and knowledge that he has brought to this project is a significant factor in the project's success.
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Photo 34. Carlo and Gail with one of the last modules picked from the experiment. Carlo's good humour has been a mainstay of the four year experiment at Orana.

Photo 35. 'Elation' - Gail and Sharna collecting the last biomass samples from the four year experiment.

Photo 36. Jamie Iker looking pleased with the development of an early August sowing treatment.

Part 4 – Final Report Executive Summary

Central Queensland is geographically and climatically distinct from Australia's other cotton production regions and as such presents both opportunities and challenges for cotton production and the farming system. This project examined the Emerald climate to identify opportunities that might enable the production of more consistent cotton yields and quality in what can be a highly variable climate.

The climatic analysis identified that spring and early summer is the most optimal period for boll growth and maturation. However, to unlock this potential requires unseasonal winter sowing that is 4 to 6 weeks earlier than the traditional mid-September planting time. Consequently our research investigated: (i) how much earlier can cotton be sown whilst maintaining reliable crop establishment, (ii) what benefits could accrue with earlier sowing both in terms of yield and quality and (iii) how should agronomic management be varied to optimise crop performance when sown early.

Data collected over 4 years has demonstrated that August sowing offers the potential to grow reliably higher yields compared to the traditional spring planting window with an average improvement of 2.2 b/ha per annum (23%) with no additional outlay except extra seed costs at planting. Earlier sown crops have proven to be easier to manage, as boll setting is confined to more favourable spring and early summer conditions. A measured benefit has been an average saving of 0.9 ML/ha pa over three years for the irrigation water required.

The other surprising outcome from this research has been the reliably poorer yields achieved from the mid-September sown cotton treatments over four years. Every season the yield potential of September sown cotton was compromised by deleterious weather conditions (e.g. cloud, heat waves or rainfall) highlighting the inherent limitations that have been associated with the traditional Bollgard II® mid-September to late October planting window.

August sowing does not negate the risk of wet weather at picking but compared to the traditional mid-September to late October sowing window the level of crop exposure is significantly reduced and the increased yield potential offers a sizable buffer against lint quality downgrades if they occur.

This research has been conducted in partnership with growers and consultants at a commercial scale without forsaking scientific rigour. The experiments were also fully utilised for extension purposes so that growers could experience research results in real time. The outcome has been rapid adoption of August sowing by CQ growers with 70% of the Central Highlands crop planted in August for the 2017/18 season just months after the completion of this research project.

The project also examined the pest status of symphylids a soil dwelling organism that had been considered to cause crop establishment problems in some seasons in CQ. Survey data suggests that this organism alone is an unlikely causal agent for crop establishment problems with damaged fields found to have a complex of other contributing soil pests and pathogens present.

Experiments to better understand boll rots were also conducted during the project. This research suggests that some of the causal pathogens for tight locking may gain entry to the boll during the pollination process although the development of disease is still dependent on favourable (wet) conditions during flowering and boll opening. A wide array of pathogens were identified from tight locked bolls with the abundant presence of *Alternaria* spp. suggesting that this group of pathogens (typically associated with leaf disease) might also be significant in the incidence of tight lock disease in CQ.