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Part 1 - Summary Details

Please use your TAB key to complete Parts 1 & 2.

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Part 3 – Final Report

Background

Outline the background to the project.

This project was developed in response to the commercial release of Bollgard® 3 varieties which hold promise for underpinning an expansion of the dryland cotton industry. Changes to the Resistance Management Plan (RMP) for Bollgard® 3 (with the relaxation of planting windows and pupae busting requirements) offer the potential for greater flexibility for how growers might utilise cotton within the dryland farming system.

The proposed 5 year project commenced with a series of workshops to engage with dryland growers from across the northern region to better understand the strengths and limitations of the overall farming system and dryland cotton's place within it for the purpose of identifying opportunities where RD&E could make an impact. These workshops were used as the basis for a broad review of the topics and issues raised by growers and agronomists to determine the extent of existing gaps and the potential for new research. At the same time, a number of pilot studies were also proposed to examine potential tactics that may help provide solutions for two long term priority issues - crop establishment under dry conditions and zero-tillage crop destruction. Based on the findings of the grower workshops and RD&E review, a plan would be put forward for stakeholder consideration for the remaining 4 years of the project which would focus on identified gaps.

A key conclusion of the review was that the greatest need for RD&E centred around the Gwydir plains, the upper and lower Namoi and Liverpool Plains regions and that as a Queensland-based organisation, DAF was not geographically well placed to deliver these field based activities. Project activities were therefore concluded early in year 2 so that a reworked project based around the findings of the review could be considered going forward.

This report will detail the following activities

- Dryland grower engagement workshops
- RD&E review
- Preliminary testing water injection and the moisture attracting product SE14
- Preliminary testing of Aquatil for zero-tillage end of season cotton crop destruction

Objectives

List the project objectives and the extent to which these have been achieved, with reference to the Milestones and Performance indicators.

1. **Review existing knowledge and practices for dryland cotton and farming systems. Conduct focus group meetings with dryland grower groups to establish challenges and opportunities of BG3 and identify the RD&E gaps.**

   This objective was fully achieved. 5 grower workshops were held during year 1 of the project at Quirindi, Moree, Boggabri, Goondiwindi and Dalby. These workshops identified key grower questions and gaps and was followed by a comprehensive review of previous research and relevant literature to identify RD&E gaps and needs.

2. **Establish a dryland cotton grower reference/advisory group for the purpose of regular project review and engagement.**
   This milestone was partly achieved through regular involvement with the Dryland Cotton Grower Association. Project members attended the majority of DCRA meetings and planning events in 2016 and 2017 to provide updates of project activities and gather feedback.

3. **Engagement with other RD&E stakeholders.**
   This milestone was partly achieved. The project team had active engagement with other RD&E stakeholders throughout the planning and review stages of the project including CSD, CRDC, DCRA, CottonInfo and various agronomists. Input from these sources helped frame the topics covered by the RD&E review.

4. **Update research objectives for dryland components (2) and systems research (3) based on industry developments and grower reference group feedback.**

   This milestone was partly achieved. The review document has provided a comprehensive background which will help inform future RD&E investment and activity.
5. **Investigate novel commercial technologies that may partly ameliorate abiotic or biotic factors effecting establishment.**
   This milestone was partly achieved. Preliminary experiments were conducted with the moisture attractant project SE14 (Sacoa Pty Ltd). Ultimately the results from these experiments were inconclusive but suggest a limited capacity for the use water injection or SE14 to overcome marginal planting conditions. The review document provided subsequent insights regarding the complexity of establishment problems and potential efficacy of various solutions.

6. **Investigate alternate tactics for increasing seed germination and establishment in marginal planting soil moisture conditions.**
   Partly achieved as outlined for milestone 5.0.

7. **Conduct DE exercised around known best practices for seedling establishment in conjunction with CottonInfo.**
   Partly achieved. A grower field walk was conducted with Geoff Hunter of CottonInfo to view treatment impacts of the first SE14 trial on the Liverpool Plains December 2016.

8. **Test effectiveness of minimal tillage crop destruction tactics for dryland crops post picking in conjunction with Nufarm Australia.**
   Partly achieved. Preliminary experiments were conducted to examine the potential of AquaTill for zero-tillage end of season crop destruction during 2017. Product choice was informed from previous work with Nufarm Australia for the control of large ratoon cotton.

Methods, Results & Conclusions

For ease of reporting this section will be presented as 3 discrete sections. These sections are:

a) RD&E Review & Grower Workshops
b) Testing of SE14 for improving seedling establishment
c) Testing of AquaTill for end of season cotton crop destruction

Review of Dryland Cotton Farming Systems Opportunities for Research and Extension

Executive Summary

A review of dryland farming systems with regard to cotton production was undertaken with the purpose of identifying research and extension needs. The introduction of Bollgard 3 and the revised Resistance Management Plan (RMP) provided an impetus for considering how this new technology might be of benefit for dryland cotton production and the broader farming system.

The review process commenced with a series of professionally-facilitated workshops involving 40 growers from across five major dryland cotton producing regions (Liverpool Plains, Upper Namoi, Gwydir, Macintyre and Darling Downs). The purposes of the workshops was to seek grower opinions and advice on the following topics:

- Characterisation of each regions farming system, soil types and typical crop sequences
- Opportunities or threats afforded by the revised RMP for Bollgard 3. What would planting flexibility, reduced refuges and changes to pupae busting requirements mean for either dryland cotton or the broader farming system?
- What are the strengths and weaknesses of growers' current farming system (not cotton-specific)? What is the most challenging or important aspect of these strengths and weaknesses? Why?
- How does dryland cotton either benefit or disadvantage the overall farming system? What are the greatest benefits or disadvantages of dryland cotton? Why?
- What is holding growers or their neighbouring growers back from growing more dryland cotton?
- Where do participants envisage dryland cotton production 20 years from now? What will have changed and what is likely to be the same?

Following grower feedback and advice on topics of interest or concern, a comprehensive review of the literature (publications, conference proceedings, final and technical reports) related to dryland cotton and the northern dryland farming systems was undertaken. Potential gaps for research and development that have not been adequately addressed by previous research include:

- Determining the systems effects that might arise from changes to pupae busting tillage for the dryland farming system. Unknowns include the techniques that might be employed over time and resulting impact on soil, weed, cotton crop destruction, crop disease and productivity of lead-out grain crop sequences.
- Investigation of crop destruction techniques (physical or chemical) that deliver timely, effective and, if required, development of AVPMA registration for crop destruction.
- Utilising modelling combined with structured research questions, experimentation and, most importantly, real life validation, as a tool for assessing and extrapolating treatment impacts. Conducting farming systems RD&E without complimentary modelling and validation only creates one-off district level trial results (for which the examples are many) with limited ability to create lasting impacts across regions and seasons. Potential applications for modelling might include:
    - Use of OZCOT to determine the likely seasonal frequency that cotton crops would mature prior to a set defoliation date to avoid pupae busting tillage.
    - Use of APSIM to determine the contribution that seasonal, soil type and geographic variations might have on the measured impacts of tillage on lead-out crop success or the impact of strip tillage on resultant seed bed condition.

    - Use of APSIM in combination with cereal cultivar information to investigate the limits for late sowing of winter cereals for the purposes of generating stubble cover, grain, or both across regions.
- Ensuring that weed management research is targeting species across the entire farming system and not just within particular commodities.

A range of other topics raised relating to crop establishment, row spacing, crop rotations, varieties and nutrition were also reviewed with minor recommendations being made within the body of the report regarding research potential.

A key finding of this review is that a significant body of previous research exists regarding dryland cotton and various aspects of the farming system, which appears to be under-utilised. Many of the questions raised by growers during the workshop process could potentially be answered with existing knowledge or extension of previous research outcomes. This highlighted an opportunity for the role that extension might play in supporting the dryland cotton industry.

Review Contents

Introduction

With a less restrictive Resistance Management Plan (RMP), Bollgard 3 would appear to offer new opportunities and potential challenges for dryland cotton production and the associated farming system. Reduced refuge and pupae busting requirements and increased sowing window flexibility have been broadly welcomed by the cotton industry as key elements that will help drive dryland cotton productivity gains and enable industry expansion. However, this may be a narrow view of cotton's place within dryland farming systems as it assumes that the planting window and pupae busting have been significant limitations influencing people's choice to grow dryland cotton.

Most growers described dryland cotton as either the pillar crop within their farming system or an opportunity crop featuring as a less frequent rotation (dependent on various factors such as commodity price, soil moisture, seasonal outlook etc). 'Pillar crops' are usually prioritised, and other crop rotation and operational choices are based on providing the best outcome for the pillar crop at each stage of the farming system. Profitability is typically the reason why many workshop participants nominated dryland cotton as having pillar crop status within their system. However, from a sustainability perspective it could be argued that less profitable crops such as winter cereals are also a pillar crop, as without cereal crop rotations and resulting stubble cover, the viability of dryland farming systems in the northern region would be in doubt. This dichotomy between a crops contribution to profitability and sustainability underscores a key challenge when thinking about the status of any particular crop within the dryland farming system.

Issues related to profitability, sustainability and seasonality are not static. The relationships between different factors maybe well-known, or poorly understood, or difficult to manage due to seasonal or financial factors. Crops come and go, each finding the soil in a particular state and leaving it in an altered state (McCown *et al.*, 1995). Therefore a key conundrum is weighing up the here and now against down-the-line consequences. This was demonstrated with crop rotation research (Hullegale *et al.*, 2002) where the impact of a seasonal cropping decision can span a period of years well after a crop is gone.

The purpose of this review is to examine the role of cotton in the dryland farming system and attempt to identify the opportunities and constraints associated with dryland cotton production. In doing so, we will attempt to take a broader view of cottons place within the northern region's dryland farming system.

The northern farming system

For the purpose of this review, we have engaged with growers from the production areas that span the Liverpool Plains where dryland cotton production is relatively recent, through the upper Namoi, Gwydir and Macintyre regions to the Darling Downs where dryland cotton has been an established cropping option since the early 1980s (CRDC 1997). Despite the focus on these particular regions, many of the topics considered will be relevant to other areas where we did not directly engage with growers such as the Macquarie, Central Queensland and the more arid western regions e.g. Walgett.

The dryland cotton production regions examined in this report are typified by flood plain soils with Vertosol characteristics of basaltic origin and a number of adjoining transitional soil types that differ in terms of structure, depth and sodicity. Soil water holding capacity is a key determinant for whether or not fields are suitable for dryland cotton production. Many growers indicated that 140 mm of plant available water content (PAWC) was a minimum criteria for prospective soil types. Seasonal rainfall and evaporative demands are the other key determinants for dryland cotton potential; the most favourable areas have a summer-dominant annual rainfall of at least 600 mm (CRDC 2002).

Bollgard 3 RMP changes: potential implications for cotton and the dryland system

The release of Bollgard 3 with the inclusion of a third *Bacillus thuringiensis* (Bt) toxin (Vip3a) was the catalyst for reviewing the Bt Resistance Management Plan (RMP) for Bollgard 2 that has centred around the tenets of a controlled planting window, the sowing of a purpose-planted refuge and end of season pupae busting.

For dryland cotton, the Bollgard 2 RMP stipulated:

- A defined planting window for all cotton (irrigated/dryland) in each region outside of which Bollgard cotton could not be sown
- Sowing of a 10% unsprayed conventional cotton refuge on the same row configuration as the main crop
- Implementation of tillage for the purpose of pupae busting as soon as practically possible after crop picking and before July 31. Tillage is to ensure complete disturbance across the entire field surface irrespective of row configuration and to a depth of 10 cm.

With the advent of Bollgard 3, the RMP was modified to:

- An open planting window 1 August to 31 December for all regions (Emerald to Griffith).
- Reduced requirement for the unsprayed refuge area sown to either 5% cotton or pigeon peas at 2.5% of the area sown to Bollgard cotton
- Reduced pupae busting requirements. For crops where defoliation is commenced prior to March 31st there is no requirement to pupae bust in all regions. Crops commencing defoliation after this time must be pupae busted but tillage can be restricted to 30 cm either side of the plant line as opposed to the entire field surface. Tillage depth remains at 10 cm.

From a dryland cotton perspective, each of these changes have the potential to impact the farming system and the production/profitability of dryland cotton. For example the longer planting window may enable growers in more northerly regions to take advantage of late November and December rainfall for planting that had previously been excluded by planting window restrictions. Reduced refuge requirements could increase farm productivity with less land area used for unsprayed lower-yielding cotton, and changes to pupae busting have the potential to enable cotton to be grown with less soil disturbance potentially increasing the appeal of cotton to traditional zero tillage grain farmers.

Revised planting window and dryland cotton

The implications of the wider planting window vary for growers across the industry. For regions increasingly further south of Moree, the ability to plant later until 31 December is of decreasing value as cool temperatures in autumn curtail season length. Planting in December might be used by some growers in these regions when faced with very specific circumstances that might counter end of season cold temperature risks.

For Goondiwindi and the Darling Downs, the extended planting window no longer ties growers to a closed window finishing in November that was shared with irrigators. This often generated conflict, particularly on the Darling Downs whereby irrigators could plant on pre-determined fixed dates whilst dryland growers could miss out on a planting opportunity if rain did not fall before mid to late November. The opportunity to plant through until December will provide some dryland growers with new planting opportunities in seasons where planting rains do not occur until late November. This will improve system productivity and profitability for growers who have already foregone a winter crop opportunity to provide a lead in fallow to plant cotton in some seasons.

Despite the increased flexibility for planting with Bollgard 3, most growers will try and plant cotton at the recognised optimal time for dryland cotton. Modelling conducted by Bange *et al.* (ACPG 2016) as well as hard-won experience has demonstrated that for nearly all regions this period is October and early November. Planting at this time balances the risk of cold temperatures with an increased probability of in-crop summer rainfall occurring during crop flowering.

The region for which the Bollgard 3 planting window could make a very large difference is Central Queensland (CQ). This region has had a restrictive 6 week planting window with Bollgard 2 and the timing of this window has always been selected to span mid-September to the end of October for the needs of irrigated growers. This has largely excluded dryland cotton from being grown between Emerald and Theodore as spring is typically dry in CQ and planting opportunities scarce in September and October. With rainfall peaking in January and February a much better time to plant is December. The new Bollgard 3 window will provide for the first time, the opportunity for growers between Emerald and Theodore to plant dryland cotton during December.

Ultimately, the wider Bollgard 3 planting window allows growers greater scope to take advantage of rainfall over a longer period of time which will be useful in some seasons. It is likely though in most seasons that growers will continue with their existing sowing time practices due to typical seasonal constraints.

Revised refuge options and dryland cotton

When the changes to the RMP regarding refuge options were discussed with growers, most viewed the changes as being no more than a small gain in production efficiency in terms of not having to commit as much land area to less productive unsprayed cotton. Very few growers indicated that they would be interested in growing pigeon peas as a refuge (primarily due to weed management being simpler with roundup ready cotton). A couple of larger growers did indicate that they might try pigeon peas, particularly the new variety Sunrise™ to test whether or not it might be a suitable dryland legume for their system.

Revised pupae busting requirements and dryland cotton

The changes to pupae busting with Bollgard 3 were rated by workshop participants as has having the greatest implications for cotton production and the dryland farming system. On that basis, pupae busting will be examined in detail as the interactions between pupae busting, the cotton crop and the system have the potential to be complex.

History of pupae busting for dryland cotton

Pupae busting was first introduced in the mid-1980s as a tactic to curtail insecticide resistance by destroying *Helicoverpa armigera* pupae that might be carrying resistance alleles. The pupae typically diapause in the soil during winter, and pupae busting was obligatory for non-transgenic cotton with a high level of acceptance by industry—such was the threat of conventional insecticide resistance. The inability to reliably control *Helicoverpa* larvae during the 1990s with conventional chemistry caused many growers in hot climates such as Central Queensland, to abandon dryland cotton due to an inability to control insecticide expenditure (Marshall pers com 2017). This problem was redressed by the release of Bollgard 2 technology providing growers with a platform for *Helicoverpa* control that could be budgeted. However, for some growers the requirements of the Bollgard 2 RMP created new impediments for production with the narrow six week planting window in CQ largely excluding cotton as an option for dryland cropping and the mandatory enforcement of pupae busting as part of the Technology User Agreements (TUAs) being a deterrent for others.

Pupae busting requirements have been subject of criticism and concern, particularly from dryland growers. Specific concerns raised by growers have included:

- Difficulties complying with pupae busting when soil conditions are often very dry at the end of a dryland cotton crop and therefore not suited to tillage (hard on equipment and results in large soil clods)
- The practicality of enacting tillage across entire field surface when skip row configurations (that may only cover 50% of the field surface) have been used
- The requirement to pupae bust irrespective of pupae abundance or the timing of crop maturity in relation to whether or not pupating *Helicoverpa* are likely to enter diapause. In low rainfall years many dryland crops finish well before diapause induction and therefore pupae busting would be ineffective from a pest management perspective.
- Tillage-related loss of cover and soil moisture makes the next crop more difficult to establish.
- Tillage exposes soil to increased short term erosion risks.

In response to these questions a review of pupae busting practices was undertaken by Tann & Braunack (2016) and a number of recommendations made for pupae busting with the release of Bollgard 3. These were:

- Soil disturbance to be limited to 30 cm either side of the plant row. This created a workable compromise to target tillage to where the majority of pupae are likely to occur relative to the plant line.
- Pupae busting not be conducted on fields where defoliation starts prior to 31 March as the likelihood of pupating *Helicoverpa* larvae having entered diapause at that time of year in all regions is very low.
- Soil disturbance to a depth of 10 cm still remains a key objective when pupae busting is undertaken.

These changes were considered and endorsed by Transgenic & Insecticide Management Strategies (TIMS) committee in 2015 and enacted with the registration of Bollgard 3.

Compared with the extended planting window for dryland cotton, the ability to avoid or substantially reduce pupae busting tillage is likely to have greater system impacts for dryland cotton growers. When asked specifically about this measure and implications of the changes, growers who attended one of the five workshops offered responses which were then categorised as having a positive, negative or unknown impact for the dryland farming systems. These responses are given in Table 1.

Table 1 Implications of the ability to reduce pupae busting tillage from dryland growers' perspectives

Positive	Negative	Uncertain
Potential to improve soil structure Increased stubble and moisture retention Increased opportunity to double crop (as soil surface is not disturbed) and achieve faster stubble cover Avoid tillage when field conditions are unsuitable e.g. too dry or too wet Opportunity to retain cotton stubble on the surface Monetary savings on equipment operation and maintenance Improved moisture infiltration due to minimal disturbance and retention of deep cracks from the surface.	Lost opportunity to incorporate nutrients such as P and K or animal manures Lost opportunity to remove large weeds that have survived herbicide exposure and may be resistant No reliable mechanism to ensure 100% effective crop destruction without tillage Lost opportunity to deep rip to alleviate compaction and/or renovate tramlines Managing a cotton crop for an earlier 31 March maturity (e.g. narrower row spacing or cut-out pix) to avoid pupae busting may result in yield or quality penalty Ratoon cotton is likely to be a greatly increased phenomena in the farming system and presents both as a weed and hygiene threat Subsequent crops such as sorghum anecdotally perform better after cotton and pupae busting (nutrition requirements are less) Retention of remanent cereal stubble on the surface after cotton may increase cereal disease carry over	Uncertainty around surface infiltration of moisture after dryland cotton without tillage (cotton can leave the ground somewhat waxy and water repellent) Impacts on weeds and seed bank: incorporation may advantage some species and disadvantage others; species spectrum might change Efficacy of minimum tillage crop destruction tactics on flat unfurrowed country e.g. root cutters, puller mulchers and herbicides likely to give variable results Pupae busting may not make a discernible difference to following crop success as the underlying profile will be dry from cotton and therefore if the difference is just a planting opportunity it may not translate into a returnable crop Efficacy of pupae busting when tillage is undertaken with new guidelines Resultant changes to the status of certain pests and diseases if growers use a herbicide approach for ratoon management that could create an interim seasonal bridge for cotton pests due to slow mode of action. Whether or not alternative crop destruction strategies can be successful across a range of crop destruction scenarios

In the context of dryland cotton systems pupae busting tillage and crop destruction clearly overlap with crop destruction being a typical outcome from the tillage operation. With the changes to the Bollgard 3 RMP and opportunity to avoid pupae busting tillage we will examine the issues of tillage and the system and crop destruction separately.

Implications of removing occasional tillage (pupae busting) on soil characteristics and system factors

The inclusion of dryland cotton within the northern dryland farming system has inadvertently forced growers from zero tillage (ZT) to a form of minimum tillage (MT) due to pupae busting requirements. When growers were asked about the impact of pupae busting tillage within their farming system responses were varied. Some growers viewed pupae busting as a significantly disruptive systems event that was deleterious to soil moisture, structure and stubble cover and therefore subsequent grain crops, and incompatible with zero tillage objectives. For other growers that perhaps regard dryland cotton as a system pillar crop, views on pupae busting were more circumspect and considered it an opportunity to incorporate nutrients (synthetic or manures), remove surviving weeds, and ameliorate surface compaction/wheel ruts (refer to Table 1).

In the northern region 65% of cropping land was estimated to be ZT or MT in 2010 with many growers considering it as standard practice (Llewellyn *et al.*, 2012). However, the increased adoption of ZT or MT practices, particularly where tillage is actively avoided has seen the emergence of several issues: (i) build-up of soil and stubble-borne diseases; (ii) build-up of herbicide-resistant weeds; (iii) enrichment of shallow surface soils accompanied by depletion of subsoil layers due to a combination of fertiliser placement and residue return (nutrient enrichment); (iv) build-up of soil insects, combined with limitations to managing pests such as *Helicoverpa* that have a below-ground pupal stage; and (v) concerns about the viability of herbicides that ZT systems depend on (Thomas *et al.*, 2007).

It is difficult to predict the implications of removing pupae busting tillage for the broader system where it has been practiced as part of dryland cotton crop rotations for 25-30 years. It may be that the tillage associated with pupae busting after dryland cotton has been ameliorating some of the adverse outcomes of MT or ZT listed above. Recent research that examined the impacts of having ***introduced*** strategic tillage at long term ZT farming sites might provide insights as to the possible impacts that occasional pupae busting tillage may have been having on the system. Dang *et. al.* (2015) conducted a series of experiments where tillage (tine and/or disc to depths of 0.15-0.2m) were enacted at a range of sites from Wee Waa to Biloela where no form of tillage had taken place for 7 to 44 years. Measurements were taken of resultant impacts on weeds, soil bulk density, soil water, microbial mass, soil organic carbon and ensuing crop yield. The impetus for conducting these experiments was due to the responses provided by 55 growers and advisors in the north-eastern region of Australia that had indicated certain diseases (cereal crown rot & yellow leaf spot) and weeds (feathertop Rhodes, fleabane and glyphosate-resistant barnyard grass) were more prevalent in zero tillage systems compared to farms where some forms of tillage were regularly used (Argent *et al.*, 2013). Continuous zero tillage had also been considered to lead to the stratification of nutrients and carbon at the soil surface (Dang *et al.* 2015ab). What was not clear from the published records of this work and survey was the extent to which tillage was being deployed by the growers who drew comparisons between zero tillage and systems that engaged some tillage operations.

The experiments found that one time tillage using minimal soil inversion such as chisel ploughing (a commonly deployed method for pupae busting) did not cause significant changes to soil bulk density, organic carbon and microbial activity although all factors did trend negatively at each site (Dang *et al.*, 2014 Liu *et al.*, 2016). The impact of tillage on weeds was variable with a decrease at most sites in the density of fleabane, turnip and wild oats several months after the tillage event. Twelve months later weed densities remained lower except at one site (soil type: Brown Sodosol) where significant increases in weed densities were recorded. Crop productivity (wheat) following the tillage was unaffected across all sites although the experiment was conducted during a period of increased rainfall throughout the northern region with all sites receiving between 95-205 mm of rain post-tillage. This rainfall is likely to have offset the tillage-induced soil surface moisture losses (tillage treatment moisture losses were not significant although trended downward) at each of the sites.

Comparisons with pupae busting?

When contemplating how this work might compare with pupae busting, it is important to consider that in each case the implemented tillage treatments occurred after a summer fallow where stored moisture in the subsoil would have been high. This combined with good rainfall post-tillage may have contributed to the lack of tillage treatment impacts, particularly in regard to soil surface moisture dynamics and subsequent crop productivity.

The potential to utilise strategic tillage as an adjunct to zero tillage systems in the northern region was subsequently reviewed by a number of discipline specialists (weeds, nutrition, soil science and soil health) and published (Dang *et al.*, 2015ab).

An overall conclusion was that the timing of a tillage event is likely to have a significant bearing on its potential system impacts. In a winter crop reliant on stored water, a tillage event conducted close to sowing resulting in soil water loss from the seeding zone (Crawford *et al.*, 2015) is likely to reduce planting opportunity or contribute to poor crop establishment. Tillage immediately after the harvest of the previous crop may result in incorporation or accelerated decomposition of crop residues, thereby resulting in a greater loss of soil cover. Both of these scenarios are possible with pupae busting after dryland cotton.

An analysis of historical climate data (1960–2013) for six sites across the northern region (Wee Waa to Biloela) showed that the probability of receiving 100 mm of rain between March and May (three months before sowing of winter crops) is only 40–55% as compared to 90–95% between January and May (five months before sowing of winter crops) (Dang *et al.*, 2015a). For growers having to implement pupae busting as part of the Bollgard 3 RMP, tillage after April has mediocre odds of coinciding with subsequent rainfall that would allow immediate winter cereal sowing. Given this constraint it would make sense for growers implementing pupae busting operations to ensure that the tillage is multi-purpose by targeting herbicide-resistant weeds (McLean *et al.*, 2012) and taking the opportunity to place fertiliser deeper in the profile (Bell *et al.*, 2012).

Soil conditions at the time of tillage also have a significant bearing on treatment impacts. Tillage performed at higher than the optimum soil water content can produce large clods resulting in structural damage. On the other hand, tillage performed at lower than the optimum soil water content requires excessive energy and can also produce large clods (Dexter and Bird, 2001).

Trying to draw parallels between this tillage work and the potential impacts of pupae busting tillage on the farming system highlights some key points. Unlike the experiments reported here, tillage for pupae busting is a post-harvest event that must be completed within a set timeframe (as soon as practical between harvest and 31 July), limiting the opportunity to optimise the tillage timing to soil conditions. Pupae busting tillage also occurs at a time of year when most of the northern region district's rainfall events are reducing in frequency and volume.

Ceasing pupae busting is more likely to allow a winter cereal to be sown (with 30-40 mm of rainfall being received post-picking) compared to a freshly ploughed field. However, as the underlying soil is likely to be very dry from the cotton crop, this establishment opportunity would only result in useful stubble or yield if significant follow-up rainfall was received. There is likely to be an earlier crossover point for cereal crop success when comparing tilled and non-tilled fields but this would depend on soil type, field factors, rainfall timing, rainfall amounts and other seasonal conditions.

The impacts of pupae busting on weed management will be addressed in the weeds section of this review but could be expected to vary depending on the weed type, seed fall and timing of germinating rainfall. However, on the whole it could be expected that in many instances pupae busting tillage has been having minimal longer term effects on the farming system beyond the immediate impacts on soil moisture and ability to rapidly replant a cereal crop. Many of the soil types on which dryland cotton is grown are capable of self-repair post tillage with subsequent wetting and drying cycles. It could be expected that in some years the influence of pupae busting tillage is minimal and for others it may have an extended influence depending on seasonality.

Crop destruction in the absence of pupae busting tillage

A fundamental challenge for growers undertaking a minimum tillage approach in the absence of pupae busting with cotton will be to achieve 100% effective crop destruction in a timely and efficient manner. At the workshops many growers expressed uncertainty as to the efficacy of different methods that might be used. Generally, all participants agreed that timely crop destruction was important from both a farm hygiene and moisture conservation perspective.

Table 2 Potential methods for enacting minimal tillage crop destruction

Method	Stage of development	Challenges	Opportunities
Stump spraying	Various on-farm tests	Variable results depending on deployment, crop status, herbicide selection and rates; no registrations	Could provide effective kill during mulching operation and stop all regrowth immediately
Spraying regrowth	Various on-farm tests	Variable results depending on regrowth; herbicide selection and rates undefined; no registrations; have to allow significant regrowth before herbicides translocate and become effective	Minimal opportunity as a crop destruction method
High pressure water herbicide injection	Pilot research trials	Effective ground/plant engagement; herbicide selection and rates undefined; registration for a novel application technique; OH&S considerations; volume of water required	Could be highly effective at enabling plant death within weeks of mulching, thus eliminating green bridge
High pressure water root cutting	Pilot research trials	Ground/plant engagement; engineering design; water volumes required	Could give immediate crop destruction if engineering and water volume constraints are overcome
Puller mulcher	Commercially available but typically deployed on irrigated crops on hills	Plant pulling efficacy can depend on soil conditions; developing configurations for dryland row spacings; could displace soil clods out of the plant line causing future tramline issues	Can mulch and destroy a crop in a single pass
Root cutting	Commercially available	Efficacy can vary depending on set up and ground conditions; more difficult on unfurrowed ground or if there are stones	Can effectively destroy the crop leaving few ratoons; soil disturbance is limited
Zonal tillage	Commercially under development	Efficacy should be very high as it directly undercuts the plant line; Tillage disturbance is limited to a band either side of plant line	Could fulfil pupae busting requirements whilst minimising disturbance to inter-row areas

Achieving effective and timely crop destruction is a central tenet of integrated pest management (IPM) and a requirement of the Bollgard 3 RMP and therefore any new technique used for crop destruction must meet this criteria. With the exception of root cutting and puller mulching nearly all of the other potential methods outlined (table 2) are either untested on a commercial scale or lack appropriate chemical registrations.

Can effective crop destruction be achieved without tillage?

Crop destruction tactics that avoid the need for tillage have been attempted by many growers and researchers over the last 25 years with mixed success. Tactics have included stump spraying during mulching operations or spraying regrowing ratoon cotton many months after mulching. Another tactic has been to utilise pulling or root cutting. Marshall & Walker (1995) examined tactics for crop destruction utilising herbicides on regrowth. A large number of products were tested of which Tilmaster (Glyphosate) was found to be the most effective achieving 80% control. Herbicide efficacy was dependent on having adequate regrowth leaf area to ensure uptake and a rating system was developed so that growers could assess whether or not sufficient regrowth was present to achieve a good kill. However, 80% control would have fallen well short of the Bollgard 3 requirement of 100% crop destruction by 31 July.

The advent of roundup ready Flex® technology rendered glyphosate ineffective for volunteer and ratoon cotton control. Growers at the dryland workshops reported mixed success with applying various Group I herbicides to the freshly cut stump as part of the crop mulching operation. Growers reported this tactic as providing a variable response with 100% control in some seasons and poor control in others. It was speculated that the variability was linked to plant vigour and soil moisture status at the time of mulching. Crops that had endured a particularly hard dry finish were found to be less responsive to herbicide application. Ensuring accurate alignment of the applied product to the cut stump during mulching also required regular attention with nozzle blockages or trash residue build-up interfering with application efficacy.

Growers at the workshops reported having mixed success with root cutting or stalk pulling in dryland systems. The primary limitation reported with these techniques is the influence that field conditions can have on efficacy. Root cutting can be difficult to enact with 100% efficacy on sloping undulating ground across a parallelogram whilst ensuring accurate engagement with the base of plants on flat ground (compared to hills and furrows). If surface soil had been scraped away to moisture seek during the planting process, root cutting was found to be more difficult due to the cotyledon nodes being well below the surrounding soil surface. Stones within fields also presented challenges.

Growers who had tested puller/lifter (either ground or PTO driven) style crop removal techniques had found that efficacy varied depending on field conditions and the type of season that a crop had experienced. Dryland cotton root systems are more broadly anchored in the soil profile compared to higher density irrigated plants growing on a hill and can therefore be more difficult to remove. Cotton grown on skip rows tend to exacerbate the situation with roots anchored even more broadly across the soil profile. A common complaint was that these methods left a small percentage of plants intact creating follow-up control issues.

The other option suggested by growers was to simply mulch or slash the crop post picking and utilise regular applications of group I herbicides on regrowing ratoon cotton until 100% efficacy is achieved. The intent of this strategy would be to plant a cereal crop during which antagonistic herbicides would be used. This would then be followed by further application of Group I herbicides as either a directed spray on the previous cotton plant line or through the use of optical boom technology in the ensuing stubble fallow. A limitation of this approach is the need for ratoon regrowth to gain sufficient size that applied herbicides successfully translocate and are effective. Recent trials looking at control measures for ratoon cotton showed that 3-4 applications were required as the rate of regrowth between plants within the plant line was staggered with new plants regrowing after subsequent rainfall events during summer (Holman & Grundy 2017). Growers have also indicated that rotating with chickpeas might provide an avenue for controlling ratoon cotton with the use of the residual herbicide isoxaflutole as part of the chickpea weed management program. The efficacy of this for ratoon control is unknown but either the repeat use of Group I herbicides or isoxaflutole use is unlikely to provide timely enough control to fulfil the requirements of the Bollgard 3 TUA stipulating complete crop destruction is to occur by 31 July.

Mechanisms for managing dryland cotton to ensure March defoliation

For growers to be able to avoid pupae busting tillage, they need to ensure crop maturity and commencement of defoliation prior to 31 March. Some growers at the workshops indicated a willingness to manage dryland cotton so as to ensure that this maturity timeframe is achieved.

Due to plant indeterminacy the main mechanisms for manipulating dryland cotton maturity would be to

- ensure that planting is timely and avoid late sowing
- utilise a row spacing that ensures the timely depletion of soil moisture to encourage earlier cut-out

- apply high rates of mepiquat chloride to cause a cessation of vegetative expansion at a pre-determined date (e.g. cut-out pix application).

Due to the cotton plant's indeterminacy and likely variability between seasonal conditions, sowing earlier in the planting window may not ensure defoliation prior to 31 March. Modelling by the CSIRO for a range of regions (Australian Cotton Production Manual 2017) suggests a limit to the earliness with which crops might be planted; the optimum period identified for most regions is October, which balances the risks of early season cold shocks with the risk of hot dry weather during peak flowering, and avoids cool late autumn conditions at the season's end. Generally, sowing dryland cotton crops earlier than this optimal timeframe is unlikely to be a tool for manipulating maturity although late planting (mid-November onwards) should definitely be avoided if March maturity is a key objective.

Decreased row spacing to ensure a more rapid depletion of soil moisture could be a tactic used to encourage earlier maturity compared to a wider spacing in the same field and season. However, potential gains from earlier maturity (e.g. not having to pupae bust) need to be offset with the increased risk of poor lint quality arising from moisture stress during boll filling. Experiments examining row spacing and fibre quality have shown variable results (Marshall *et. al.* 1994; Goyne 2000) with quality downgrades linked to narrower row spacing in some years but not others. In general terms, narrower row spacing was unlikely to be associated with quality discounts when yields were high, which typically reflect seasons with good in-crop rainfall. In years of low in-crop rainfall, quality discounts were much higher from solid plantings compared with skip row configurations (Goyne 2000). This concurs with long term data from CSD variety trials that demonstrate skip row configurations having a much lower incidence of fibre quality downgrades compared to solid plant configurations (CSD Website). Amongst skip row configurations, a viable option maybe to adjust the size of the skip to assist with earliness but ultimately using row spacing as a device for manipulating defoliation maturity will be imprecise and risks lint quality discounts.

Application of mepiquat chloride (MC) to induce cut-out by at a set date may be the most reliable tactic for ensuring a timely defoliation by March 31. However, cut-out rates of MC when applied to a plant with abundant soil moisture and nutrition may simply produce adventitious fruiting sites (back fruiting) thus reducing potential earliness gains. It is also questionable given the significant setup costs of a dryland cotton crop (long fallow lead in and planting difficulty/expense) that a grower experiencing a season with good in-crop rainfall would choose to truncate flowering, reducing yield potential with cut-out MC. Whilst pupae busting could be avoided and a proportion of soil moisture conserved at depth, the benefits for a following winter cereal crop may not be realised unless planting rain occurs after picking. Prematurely cutting-out cotton for this objective would run counter to the comments made by many growers in the workshops that the standout benefit of cotton compared to all other summer crops is that it is the most profitable option when the season runs with you and has the capacity to turn abundant soil moisture into yield.

Of the maturity management options reviewed, the avoidance of late planting and strategic MC application in certain circumstances are likely to be the tactics growers would adopt to avoid pupae busting tillage. Application of MC to expedite the maturity of a crop that was already likely to be close to coinciding with 31 March would be a compromise that many growers would consider. MC is regularly used in this way for irrigated cotton production where meaningful trade-offs are made by crop managers between the value of timely crop maturity for picking efficiency verses the probable yield contribution from a small percentage of lingering immature bolls.

Summation – Implications of changed pupae busting requirements for the system, crop destruction and dryland crop management

The specific implications of removing pupae busting from the dryland cotton farming system are unclear. Potential improvements in factors such as surface soil moisture retention, winter cereal planting opportunities and the retention of cotton trash on the surface need to be offset with potential unknowns such as changes to nutrient stratification, the weed seed bank, and surface compaction.

Measuring the possible flow-on implications from removing pupae busting tillage from the farming system is multifaceted and not likely to be answered with simplistic comparisons of soil, system productivity and biotic factors. Research treatment structures can become rapidly complex depending on lead out crop rotations selected, seasonal variability and soil type. Measurements might include soil structural characteristics, moisture and organic carbon along with biotic factors such as disease and weed measures, nutrient cycling and crop growth/productivity measures. Accounting for seasonality is the other significant challenge when understanding tillage changes within the broader systems context.

Combining such experiments with modelling and validation with a program like APSIM (Agricultural Production Systems sIMulator) could enable conclusions to be tested across a range of geographic locations, soil types and historical climate records. Experimentation or modelling alone would be unlikely to provide answers regarding the impacts of removing pupae busting tillage from the farming system. For example, the research conducted by Dang *et al.*, (2014) on strategic tillage is ultimately limited in scope due to the study being conducted over just two seasons that were wetter than average. A longer period of work to span greater seasonal variability combined with modelling would provide more comprehensive answers.

The removal of tillage from dryland cotton production will depend on achieving reliable crop maturity prior to 31 March and having a successful minimal disturbance crop destruction technique. The trade-offs between the prospective benefits of avoiding tillage and the potential reduction in cotton yield potential when managing for 31 March maturity during a season when soil moisture is not limiting is unclear. The literature and grower experiences suggest that at the current time there are no guaranteed herbicide-based tactics that would fulfil the 31 July crop destruction deadline. Very recent pilot trials with high pressure water and herbicide directed at the plant base have shown potential to give very rapid and effective control of cotton plants post-mulching. Further development of these types of technology will require engineering design refinement to ensure reliable commercial agricultural performance as well as requiring the registration of herbicides.

Currently there are no herbicides registered for the purpose of cotton crop destruction for any of the delivery mechanisms under consideration. Registration would require comprehensive testing across many crop sites and seasons to identify appropriate herbicides, application methodologies, and efficacy for a range of scenarios. Importantly, such research must be conducted with the support of the companies that hold the registration rights of active ingredients otherwise registration and label changes cannot proceed. The standard of control of any herbicide tactics would need to be very high (virtually 100%) so as to fulfil the Bollgard 3 RMP requirements of 100% crop destruction by 31 July. Whilst potential options exist, the barriers for the commercialisation of an herbicide-based technique that delivers ***effective, rapid & reliable*** crop destruction are significant and easily underestimated by people looking for a simple solution. Moreover, the addition of dicamba tolerance traits in future cotton varieties may make any herbicide-based strategies that rely on phenoxy (group I) products redundant within five years.

Modelling with OZCOT (expertise for which is currently held in-house by CSIRO) could be a useful tool for determining the likely frequency that crops would naturally mature prior to 31 March across the main production regions, thus indicating the potential scale of zero tillage technique adoption within the industry. This could then be balanced against the likelihood of the commercial marketplace developing novel zero tillage crop destruction options (new engineering or herbicides) for the dryland sector to determine where RD&E investment could or should be made in this space.

Research conducted to examine the impacts of removing an occasional tillage event from the dryland farming system and separating this effect from the impact of the cotton crop itself would require detailed measurement over many years. In the interim there is significant risk that the emergence of new technologies, a future increase in resistance allele frequencies within *Helicoverpa* spp or a significant failure rate for zero tillage crop destruction methodologies could result in a strengthening of the RMP pupae busting requirements thus negating the questions raised in this area.

An alternative is that the industry may settle for zonal tillage—a compromise between zero/minimal tillage and conventional pupae busting tillage approaches. Several agricultural equipment manufacturers have recognised the potential market for implements that can enact zonal tillage, with a blade plough concept that destroys the crop by undercutting the plant row whilst also fulfilling pupae busting requirements by providing soil disturbance to 30 cm either side of the plant line. On a skip row configuration this would leave a proportion of the field surface untilled. Should such equipment become proven commercially in the next 2-5 years for reliable crop destruction and pupae busting, it is conceivable that growers would adopt such an approach irrespective of what research data may say about comparisons between zero and conventional pupae busting tillage. Consequently it may be premature to embark on a long term study to determine the impacts of changes in pupae busting practices at this early stage of Bollgard 3 adoption where the likely practices are uncertain.

Integrated management of summer weeds

A common concern raised during the grower workshops was the sustainability of weed control in dryland cotton systems, particularly with regard to summer grasses and the threats posed by glyphosate resistance. The species of concern varied between regions but the general issues raised (weed types, difficulties with control in other system crops and over reliance on glyphosate) were similar. An increased prevalence of summer grasses as a weed within dryland cotton, stubble fallows and summer sorghum has been observed. Roundup ready technology has provided advantages for the management of grass weed species during summer compared to sorghum where few options exist. However, from an integrated weed management perspective, dryland cotton offers little more than a cash flow generating alternative to a summer stubble fallow as both options have very high reliance on glyphosate application.

Growers generally agreed that the spectrum of weed species had changed within the broader farming system; that grass weeds were of most concern and that an inability to effectively manage these species in sorghum crops had influenced people towards growing cotton. Growers did not necessary reflect that these same weeds were becoming difficult to control in cotton but had become more prevalent generally in the farming system.

The species of weeds nominated by growers differed between regions. At Quirindi, a sorghum off type commonly referred to as 'shatter cane' and barnyard grass were of major concern for the Liverpool Plains farming system. Shatter cane in particular had reached a point in some fields where it was threatening sorghum production. Growing of dryland cotton was seen as helpful as shatter cane was very susceptible to glyphosate although growers mentioned that this species quickly re-asserted itself as a dominant weed if sorghum was regrown due to the high proportion of seeds capable of prolonged dormancy in the seed bank.

On the Darling Downs growers raised concerns about barnyard and feathertop Rhodes grasses and a species of urochloa that were becoming prevalent within sorghum and summer fallows. Pulse and winter cereal crops rotations were seen as providing opportunities for rotating chemistry as cotton's heavy reliance on glyphosate makes it very similar in weed control terms to a summer fallow.

For the Gwydir, cotton was seen as a profitable way of achieving the same weed management objectives as a summer long fallow with cereal stubble in place. However, compared to cereal stubble, cotton provides some competition within the row and dries the profile out making it more difficult for summer-germinating weeds to survive. Pupae busting tillage was seen as a useful way to remove resistant weeds such as feathertop Rhodes grass. Again, grass weeds dominated the discussion from a general systems perspective with specific mention made of phalaris, barnyard grass, feathertop Rhodes grass and rye grasses.

In the Upper Namoi growers reported problems with windmill grass, barnyard grass and fleabane. Sow thistle was also seen as an increasing problem. Controlling these weeds within the fallow leading up to cotton was also becoming more difficult with the standard approach being glyphosate-dependent.

In the Goondiwindi area feathertop Rhodes grass and barnyard grass were the key concerns in the broader farming system. Cotton was again being used in a way that does not significantly differ from a summer fallow, being heavily dependent on glyphosate, which is cost effective but acknowledged as having longer term consequences.

Growers also generally nominated broadleaf weeds such as sow thistle and fleabane as being of concern but not to the same extent as the grasses which was a reflection of grasses being difficult to control in general throughout the other crop rotations in the system.

In summary, concerns about weed management being sustainable was a recurring theme that emerged at all grower workshops. Over-reliance on glyphosate for weed management and the increasing prevalence of grass weeds in the systems were the main concerns.

Weed trends in the dryland system and transgenic cotton

A review, by Walker *et. al.* (2010) of weed control practices since the introduction of herbicide-tolerant cotton in Australia confirmed major changes have taken place in how weeds are managed in dryland cotton, which in turn has changed the flora and infestation levels of weed populations.

Prior to the introduction of glyphosate-tolerant varieties, weed management in dryland cotton was achieved through the use of residual herbicides applied pre-plant and/or at planting followed by in crop emergent knockdown and residual herbicides applied with shielded sprayers or directed layby applications. These herbicide tactics were also complimented by inter-row tillage and very occasionally manual chipping. Growers relied on an extensive number of herbicides from 11 modes of action groups (Charles 1991; Charles, *et. al.* 2004).

A scoping study on weeds in dryland cotton cropping systems (Taylor & Walker 2003) found that in general terms weed management in dryland cotton systems was complex. A variety of herbicides that might be used in rotational crops have the potential to damage cotton and equally some cotton herbicides imposed long plant-back restrictions for following winter and summer cereals. Managing weeds and associated herbicide risks added significant complexity for growers when integrating cotton and grains together within the farming system (Marshall *et al.*, 1996). These challenges are demonstrated in the Table 3 (an excerpt from the weed management section of the Dryland Cotton Production Guideline 2nd Edition) showing the minimum re-cropping intervals for various herbicides that were commonly used for weed management at the time.

Table 3 Minimum re-cropping intervals (months) after various herbicides used for cotton

Crop	**trifluralin**	**pendamethalin**	**metolachlor**	**prometryn**	**fluometuron**	**diuron**	**Zoliar®**	**Staple®**
Winter cereals	12	6	6	12	6	12	12	5
Chickpeas	0	0	6	12	6	12	12	-
Faba beans	0	0	6	12	6	12	12	-
Maize	12	0	0	12	6	12	12	22
Mungbeans	0	0	6	12	6	12	12	11
Sorghum	12	12	0*	12	6	12	12	22

*concept treated sorghum seed

A survey of weed control practices utilised by dryland cotton growers was undertaken during 2001/02. The survey found that the weed spectrum was diverse with 41 species represented as common weeds in dryland cotton crops (Taylor & Walker 2003). The majority of growers surveyed reported that they did not achieve consistent control of bladder ketmia, liverseed grass and barnyard grass in summer fallows, cotton and sorghum. Sow thistle was also reported as a problem at any time of year within the farming system. At the time fleabane was noted as a difficult to control weed but not considered to be common. In terms of factors affecting farming system decisions, weed control was given the second highest priority for growers making crop rotation choices (soil moisture management considerations ranked first).

An economic analysis of the cost of weeds within the system was undertaken as part of the study. The costs associated with weeds in dryland cotton were high ($345/ha) compared to sorghum at the time ($152/ha). As a variable cost, the impact of weeds was a significant factor affecting the profitability of dryland cotton.

Research and development issues raised at the time were prescient of the issues that would be reported by growers in 2016/17. Key themes were: emerging weeds such as fleabane and summer grasses, over reliance on glyphosate for weed control (in fallows), need for growers to better understand biology of key species and how that relates to control and the general imbalance between weed control costs for cotton verses other parts of the system (Taylor & Walker 2003).

When contrasted against a review only eight years later (Walker *et. al.* 2010), the changes to weed flora and management in dryland cotton were both profound and inevitable. Key changes included fleabane becoming a common difficult to control weed along with increasing prevalence of sow thistle and grasses. Concerns expressed by growers regarding the over-reliance on glyphosate only worsened with the introduction of roundup ready Flex® technology. Between these studies, the general approach to weed management had shifted away from pre-emptive use of residual pre-emergent herbicides to tactics that control the seedling stage of weeds and any survivors of glyphosate applications. The change in weed spectrum would appear to reflect an increased usage of glyphosate and decreased usage of tillage across the whole farming system providing competitive advantage to species that have multiple emergence events during the year, can germinate from the soil surface, and have a tolerance for or detected resistance to glyphosate. These trends were reported by Werth (2008) (Table 4).

Table 4 Characteristics of key weeds of dryland cotton (Werth 2008)

Species	Emergence habit	Zone from which emergence is successful	Persistence of seed	Other comments
Liverseed grass	One major flush per year	Greater from 5 cm than 2 cm	Limited at surface but increases with depth	Preventing seed set in fallows greatly reduces in crop occurrence
Fleabane	Multiple flushes Autumn to spring	All emergence from surface (2 cm)	Limited at surface with limited increases at depth	Emergence decreased with tillage particularly chisel and disc plough
Sowthistle	Multiple flushes any time of year	All emergence from surface (2 cm)	Limited persistence at surface	
Bladder ketmia	Multiple flushes	Emergence greater from depth (5 cm) than surface.	Seed persistence increase significantly with depth	52% of seed survived 3 years at 10 cm depth
Barnyard grass	Several flushes per year	Soil surface (2 cm)	Limited at surface but increases with depth	Tillage increased emergence and reduces persistence

The weediness trends identified in 2008 were found to have continued in subsequent work reported by Werth (2011). Weeds such as bladder ketmia, peach vine and barnyard grass have remained in the top ten weed species throughout all surveys pre- and post-roundup ready Flex® technology. However fleabane had shifted from number 14 in 1996 to number 1 in 2010 and sow thistle from 13th 1992 to 2nd in 2010 (Werth 2011). The shifts that have occurred are due to glyphosate tolerance (peach vine) or being favoured by minimum tillage systems (barnyard grass and sow thistle), or both (fleabane).

During the 2010/11 survey, the increased prevalence of a range of summer grasses was also noted including feathertop Rhodes and summer grass (Werth 2011). This trend has continued with growers reporting these species as key weeds of concern in 2016/17.

Werth (2011) singled out fleabane, sow thistle, barnyard grass and feathertop Rhodes grass as being of particular concern for risk of developing or already possessing glyphosate resistance and therefore becoming the dominants weeds of the dryland cotton farming system. It was proposed that control efforts should be refined to minimise the impact of these species.

What might Bollgard 3 mean for integrated weed management?

The changes observed in flora and weed prevalence since the introduction of glyphosate-tolerant cotton is likely to continue. It may be possible that the impact of weeds will worsen with changes to the Bollgard 3 RMP that will see further reductions in system tillage that may have previously disadvantaged surface germinating weeds such as fleabane, sow thistle and some grasses. Nearly all of the weed species to emerge as major weeds of not only dryland cotton but of the broader farming system have been favoured by reduced tillage and produce mostly wind-borne seed.

At the same time glyphosate technology has provided tremendous advantages for the ***integration*** of dryland cotton with grains in the farming system. The shift away from pre-emergent residual herbicides has simplified the lead out of cotton back into grains by eliminating many of the prolonged plant-back issues for cereals following cotton that were commonplace a decade ago. It is ironic that evolving changes in weed flora species and prevalence threaten these gains with a likely outcome being the increased need to revert back to greater reliance on residual herbicides. A likely reduction in tillage may only serve to hasten this process by potentially advantaging the weed species that currently threaten the system the most.

The introduction of glufosinate and dicamba-tolerant varieties due within the next 5 years are likely to stem some of the trends and changes observed as well as reduce the evolution of glyphosate resistance. However, for the emerging problem of grass species glufosinate is not considered to be a strong knockdown which was reflected in the previous weed registrations for Liberty Link® cotton, and dicamba is only effective for broadleaf weeds with concerns already emerging for group I resistance for sow thistle (Spotlight Winter 2017).

Summation – Challenges for weed management and the dryland cotton farming system

The continued ability to be able to cost-effectively manage weeds is arguably the biggest challenge facing the northern regions farming system and dryland cotton production. Weed management for dryland cotton has never been easier or more cost effective than since the introduction of Roundup Ready Flex™ technology. However, it is widely recognised by growers that glyphosate resistance is an impending problem that will require higher levels of herbicide and management inputs in the future.

Potential changes associated with pupae busting tillage is the only factor that may impact on weeds when viewed from a Bollgard 3 perspective. While it is difficult to predict the changes that may occur with reduced tillage, a reasonable conclusion would be the continued or accelerated dominance of weed species favoured by minimum tillage systems (such as fleabane, sow thistle and various grasses).

The likely return of residual herbicides used as either pre-emergent sprays or layby applications may see a return of the difficulties with establishing cereal crops post-picking experienced a decade ago. Whether this will be further complicated by the potential removal of tillage from the system remains to be seen.

Clearly there will be a greater need for co-ordination between weed researchers working in both cotton and grains as the key weed species occur across all crops within the farming system.

A review of the literature regarding recent weed research shows that the industry is well served by a number of projects focused on both weed resistance management and the integrated management of specific weed species. However, a common feature of outcomes reported from such research is a tendency towards developing solutions in isolation that have the potential to be inconsistent with other important components of the farming system.

A recent series of scenarios on weed management in Spotlight Winter edition 2017 examined cover crops and the use of modelling to determine the costs of resistant barnyard grass. Broader systems issues such as the implications of these treatments on moisture and nutrient management or cereal diseases were not mentioned, and the modelling presented appeared optimistic in its assumptions of soil moisture and crop growth. Similarly, other articles referred to the need to adopt a broader range of herbicide tactics within dryland cotton crops as part of a strategy to combat glyphosate resistance; it was unclear whether considerations are being given to the impacts of those herbicides on subsequent crop rotations, or if management strategies being developed for particular weed species are taking into account all of the crops and fallows within the farming system to best exploit opportunities for control. This is critical given that cotton might only feature within the same field every 2-5 years.

This example is included not for the purpose of being critical of recent research, but rather to highlight (i) the multifaceted nature of dryland production systems, (ii) the benefit of using powerful validated modelling systems such as APSIM to better test assumptions, and (iii) the need for solutions that consider each crop rotation stage, and are not just cotton-centric.

A reasonable assessment of the challenges presented by weeds within the farming system from cotton production perspective would suggest that the ease with which weeds have been largely managed during the last 12 years may in time look to be an aberration rather than the norm. Successful weed management in dryland cotton is likely to again gravitate towards greater use of residuals and secondary modes-of-action products. Importantly, weed management will have to be considered well beyond dryland cotton, to seek and identify opportunities to target weed species such as sow thistle, fleabane and various grasses that also present significant threats to grain cropping rotations. Currently much of the emphasis of weed advice for cotton production systems typically relates to the cotton crop itself and fallow periods either side rather than the other grain crop rotations that represents a significant proportion of the system.

Weed management may also benefit from having a regular industry forum (WEEDCOM) for the purpose of facilitating information exchange between researchers, stakeholders and end users. The industry has been well served by other regular forums such as FUSCOM, REFCOM and researcher-led IPM forums that have been excellent sounding boards for reviewing research, testing ideas and ensuring that new solutions are likely to meet market needs.

The system and dryland cotton

Unlike irrigated cotton production where the highest gross margins can be attained with continuous cotton, successful dryland cotton production is co-dependent on integration with other grain crops. However, dryland cotton systems do enjoy a significant advantage over irrigated systems in that seedling diseases occur at much lower frequencies due to these longer term non-cotton crop periods.

During industry expansion in the early 1980s, continuous dryland cotton was commercially grown for a period of time. However, back to back cotton in a dryland system was found to be an unsustainable cropping strategy due to VAM problems, low water use efficiency and runoff related soil losses (CRDC 1997; Hulugalle 2002). In long term crop rotation experiments, the inclusion of grain crops was found to be essential to the sustainable production of dryland cotton. Therefore, it could be legitimately argued that dryland cotton production should be viewed through the prism of the grains farming system, which with its existing cereal and legume options can be sustainable in its own right with or without cotton.

From a systems sustainability and production scale perspective, winter cereals (mainly wheat) are the pillar crop of the northern dryland farming system. When all of the potential cropping options are considered, winter cereals play a vital role in respect to maintaining soil structure, recycling leached nutrients and producing lasting stubble cover that protects the soil and improves rainfall infiltration (Hulugalle 2002). However, the wheat production system is challenged by weeds and diseases that are better managed by having dicotyledon crop rotations; the options being various legumes, canola and cotton. Of these options canola and faba beans have a limited climatic range in the northern region (Moree is a typical northern limit) and summer legumes such as mungbeans are still viewed as risky despite significant improvement to the cultivars and commodity prices offered in recent years. This may explain in part the popularity of dryland cotton in the Darling Downs where faba beans and canola are rarely seen and mungbeans remain a price-driven opportunity crop.

For dryland grains systems, the inclusion of cotton as a rotation crop offers significant advantages coupled with a number of challenges. In regions where dryland cotton has been grown over many decades (Darling Downs, East Moree and Upper Namoi) many growers take a set crop sequence approach. Crop sequence choices are primarily driven by the need to capture and take best advantage of rainfall. This in turn places significant emphasis on the maintenance of stubble cover that slows down water movement at the soil surface, assisting infiltration and storage of rainfall moisture, an essential prerequisite for all cropping.

Growers opting to utilise cotton as part of their cropping sequence view its inclusion either as a pillar crop that underpins farm profitability around which other rotations are grown primarily to ensure system sustainability, or as a less frequent (either opportunistically or low frequency purpose planned) rotation crop that adds profitability but also provides key system benefits. These benefits might include the provision of a disease break or the ability to utilise glyphosate and group A herbicides as alternative to what occurs in sorghum. Cotton also has the ability to make use of moisture at depth during summer even in soil types where sodicity is a factor as well as accessing leached bands of nitrogen.

At the dryland cotton workshops, growers reported the following typical[1] crop sequences where cotton was a planned feature:

Liverpool Plains

Cotton – Long Fallow (LF)[2] - wheat – sorghum – wheat/barley – LF - Cotton[3]

Gunnedah

Cotton – LF – durum wheat - (canola – wheat) – LF – Cotton[3]

Cotton – LF – wheat – LF – Sorghum – LF – wheat – LF Cotton[3]

Boggabri/Mullaley

Harder setting red soils

Cotton – Durum – Canola – Durum – Cotton or

Cotton – Sorghum – Canola – Durum - Cotton

Vertosols

Cotton – Durum – Cotton

Cotton – Barley – Faba Beans – Durum – Cotton

Moree

Eastern areas

Cotton – Wheat/chickpea – LF – Cotton

Cotton – LF – Wheat – Cotton

Western areas

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[1] Sequences listed are generalisations and in practice vary depending on circumstances and individual farm parameters such as soil type, slope and seasonality.

[2] LF refers to a period of 12 months (summer and winter)

[3] Winter cereal will be sown straight after cotton if conditions allow

Cotton – LF – Chickpea – Wheat – Cotton^3

Cotton – LF – Wheat – Chickpea – Wheat – Cotton^3

Goondiwindi

Cotton – Wheat – Chickpea – Wheat – Cotton

Darling Downs

Jimbour/Bongeen/Jondaryan (280-320 mm PAWC soils)

Cotton – Wheat or Millet – LF – Cotton

Cotton – Wheat – LF – Sorghum – Sorghum – Cotton

Brigalow soils (250 mm PAWC)

Cotton – wheat/chickpea – LF – Sorghum/Cotton (depending on commodity price)

Box Soils <200 mm PAWC

Cotton – Sorghum – Sorghum/Mungbeans – Cotton

Cotton – Wheat – Wheat/Chickpeas – LF – Cotton

PAWC= plant available water capacity. The choice to plant sorghum or cotton as the summer crop is largely driven by commodity price on the Darling Downs.

Key aspects of crop sequences used by dryland cotton growers

The key farming systems advantages cited by growers for including cotton as a crop rotation was the opportunity to:

- break cereal disease organism lifecycles (non-host for nematodes and fungi)
- target problematic grass weeds with glyphosate or group A herbicides
- make use of deep-stored soil profile moisture and leached nitrogen.

In nearly every circumstance growers utilise a winter cereal crop followed by a long fallow (summer and winter) as a lead into cotton. The primary reasons for this are that cereals create significant and long lasting stubble cover that offers protection to the soil, improving infiltration and moisture accumulation. The build-up soil moisture reserves so that the profile has at least 140 mm or more of stored moisture is seen as a pre-requisite for planting dryland cotton.

Remaining stubble cover after the cotton is planted provides a degree of protection for seedling cotton against sand blasting and insect attack as well as lowering soil loss from the skipped inter-row areas (Hennegeler *et al.*, 2000; Cleary 2008).

In some circumstances growers may rotate out of sorghum into cotton if sufficient soil moisture reserves can be accumulated from autumn and winter rainfall. Whilst a viable rotation in some circumstances, spring-sown sorghum does not provide the same level of stubble cover as winter cereals, and allelopathic affects have been observed from time to time (Maas *et al.*, 2012). Growers cited using a winter legume such as chickpeas followed by a fallow as having undesirable lead in circumstances due to a lack of stubble cover and potential disease issues.

A second key factor cited by growers across all regions was the desire to re-establish some form of crop cover as soon as practically possible after cotton crop destruction. Typically cereal crops are either dry sown or sown after planting rain. If neither of these occur a summer grain sorghum or millet cover crop may be sown instead. In some areas transitioning to a winter cereal directly after cotton is not possible due to a lack of profile moisture or planting rain to re-wet the surface after completion of pupae busting. Failure to quickly establish soil cover after cotton leaves soil exposed to erosion and reduced rainfall infiltration and storage.

The inability in some seasons or regions to reliably establish a winter cereal straight after dryland cotton was cited by growers as the most significant systems constraint for including cotton as a crop rotation, particularly for growers where cotton appears once every 3-5 years. The inability to establish a winter cereal was seen as a key systems risk from a soil cover perspective especially for growers on undulating country. Most growers would prefer that an established cereal be taken through to grain harvest, as a cereal crop that succeeds in producing grain has longer lasting stubble as well as providing a return on planting. Two outcomes that were viewed as a failure for cereals after cotton was the inability to plant or the failure of the planted cereal to tiller and produce seed heads due to cotton-induced soil moisture constraints.

Some growers had experimented with summer millet as a follow up option for achieving ground cover if a winter cereal could not be established. Generally millet was an unpopular choice, viewed as being difficult to establish and problematic to manage (for further details see 'What would enable better crop sequencing?' section).

What does previous research say about cotton and grain rotations?

Studies of crop sequencing and rotation strategies around cotton have primarily focused on the down the line impacts of different crop sequences on a future cotton crop. A replicated dryland cotton crop rotation study was conducted at Warra on the Darling Downs between 1993 and 2001. This experiment was complimented by simpler shorter term experiments conducted in CQ and Wee Waa with similar treatment objectives. The treatments implemented at the Warra site are given in Table 5.

A number of key conclusions were drawn from these studies, the principles of which supported what growers reported at the dryland workshops. Firstly back-to-back dryland cotton with fallow periods suffered from VAM and nitrogen cycling problems and had lower water use efficiency due to reduced rainfall infiltration, that increased runoff and soil loss risk (Marshall 1998). Cotton rotated with cereals (either summer sorghum or winter wheat/barley) were found to be the most optimal sequences from a water use efficiency, VAM and nutrient recycling perspective. Sowing a cereal crop immediately after cotton was found to produce reliable stubble cover but had limited grain yield potential. The sowing of a winter cereal straight after cotton picking was dependent on good autumn rainfall to ensure crop establishment and yield potential. In terms of system profitability, cotton double-cropped with a winter cereal or rotated with sorghum were found to be the most profitable over the eight year period. Interestingly the inclusion of chickpea lowered profitability due to the higher incidence of crop diseases, reduced soil water storage efficiencies and a commodity price at the time that ranged between $300-350/tonne. Today, it is possible with the much higher commodity prices and improvements in cotton cultivar fusarium tolerances that these trade-offs might have changed although inefficiencies linked to soil cover and moisture infiltration would remain.

Table 5 Crop sequence treatments from the dryland farming systems trial at the Darling Downs Warra site 1993, to 2001

Season	**1 Continuous cotton**	**2 Cotton/summer cereal**	**3 Cotton & double cropped winter cereal**	**4 Cotton/ winter legume**	**5 Cotton/winter cereal**
Summer 1992/93	Cotton	Cotton	Cotton	Cotton	Cotton
Winter 93	Fallow	Fallow	Barley	Barley	Fallow
Summer 93/94	Fallow	Sorghum	Fallow	Fallow	Fallow
Winter 94	Fallow	Fallow	Fallow	Chickpea	Wheat
Summer 94/95	Cotton	Cotton	Cotton	Fallow	Fallow
Winter 95	Fallow	Fallow	Wheat	Fallow	Fallow
Summer 95/96	Fallow	Sorghum	Fallow	Cotton	Cotton
Winter 96	Fallow	Fallow	Fallow	Wheat	Wheat
Summer 96/97	Cotton	Cotton	Cotton	Fallow	Fallow
Winter 97	Fallow	Fallow	Wheat	Chickpea	Fallow
Summer 97/98	Fallow	Sorghum	Fallow	Fallow	Cotton
Winter 98	Fallow	Fallow	Fallow	Fallow	Wheat
Summer 98/99	Cotton	Cotton	Cotton	Cotton	Fallow
Winter 99	Fallow	Fallow	Wheat	Chickpea	Fallow
Summer 99/00	Fallow	Sorghum	Fallow	Fallow	Cotton
Winter 00	Fallow	Fallow	Fallow	Wheat	Fallow
Summer 00/01	Cotton	Cotton	Cotton	Fallow	Fallow

The challenges and opportunities of the different crop sequences tested during the eight years is well demonstrated in the following table showing the systems trade-offs for each approach as identified at the time.

Table 6 Possible rotation options for dryland cotton and tradeoffs[1]

S	W	S	W	S	W	S	W	S	Soil H_2O	Surface Cover	Disease	VAM	Nitrogen
1 Cotton	Fallow	Fallow	Fallow	Cotton	Fallow	Fallow	Fallow	Cotton	+	--	++	--	+
2 Cotton	Fallow	Fallow	Winter cereal	Fallow	Fallow	Cotton	Fallow	Fallow	++	+	++	+	+
3 Cotton	Fallow	Sorghum late	Fallow	Fallow	Fallow	Cotton	Fallow	Sorghum late	++	+	++	++	+
4 Cotton	Winter cereal	Fallow	Winter legume	Fallow	Fallow	Cotton	Winter cereal	Fallow	+	-	+	++	+
5 Cotton	Winter cereal	Fallow	Fallow	Cotton	Winter Cereal	Fallow	Fallow	Cotton	++	+	++	+	+
6 Cotton	Fallow	Sorghum early	Fallow	Cotton	Fallow	Sorghum early	Fallow	Cotton	-	++	++	++	-

[1] Dryland Cotton Production Guideline (3rd Ed)

Most of the rotation options listed in Table 6 from the long term farming systems trial conducted in 1990s have similarity with the crop sequences given by growers at the dryland workshops. Option 1 was not practiced by any growers who attended the workshops and nearly all growers expressed a preference for double cropping from cotton straight back to a winter cereal when circumstances allow. A few growers were also using deep sown chickpeas during the last two seasons as a lead out option although this was primarily due to the high commodity price and perceived advantage that the use of the herbicide isoxaflutole would provide cotton volunteer control.

Research conducted by Hulugalle (1999) and Hulugalle *et. al.* (2002; 2005) examined a number of soil sustainability characteristics at the Warra and Emerald dryland sites together with a number of irrigated crop rotation study sites.

The overall conclusion from this research was that in nearly every respect wheat (winter cereals) represent the best rotation crop to follow cotton due to a range of bio-physical and economic reasons. When compared with legumes in particular, wheat was better at;

- ameliorating soil compaction
- providing soil structure improvements (that lasted several years beyond the cessation of dryland trial treatments)
- enabling nutrient recycling
- improving subsequent cotton crop root growth and cotton yield
- improving rainfall infiltration and soil moisture retention

Compared to legumes, winter cereals were also easier to manage with fewer weed, pest, disease and herbicide issues. Legumes were found to contribute positively to soil nitrogen but this gain was insufficient to offset the other benefits provided by wheat. Weed management in the fallow following legumes was also observed to be more problematic due to a lack of persistent stubble cover.

Compaction and the dryland farming system

Compaction associated with cotton production was raised by a number of workshop participants as an emerging issue for dryland farming system. The cause for these concerns primarily revolved around JD7760 pickers and the difficulties that are encountered with traversing controlled traffic fields (CTF) with the standard wheel spacings of these machines.

Many dryland growers indicated that the advent of the JD7760 had been very useful in terms of allowing greater contractor availability for picking cotton but these machines are rarely set up to fit CTF systems. A small number of these machines have been modified from the usual dual tyre design to run single wheels at a 3 m spacing, which works well for dedicated usage in CTF systems. However, there are few incentives for contractors to modify wheel spacings for this purpose.

This presents a conundrum for many dryland growers who rely on contract picking. If conditions are not completely dry at picking, the lack of furrows in dryland fields and the typical lack of tillage in these systems leaves the soil highly exposed to compaction both near the surface and at depth.

This was an issue that many growers recognised but could not see a viable means of developing workable solutions particularly where contract picking is used. Many growers rated soil compaction as a sleeper issue facing dryland systems and a significant impediment for the integration of cotton as a crop rotation within the broader farming system, particularly where cotton only features every 3-5 years.

Nutrition in dryland systems that include cotton

Growers outlined their general approach for nutrient management across the farming system during the workshops. Most viewed cotton to be an effective scavenger of nutrients making use of elements that had leached deeper into the profile compared to other crops such as wheat. Fertiliser additions (particularly nitrogen) are often applied to crops such as wheat that precede cotton at rates that were typically higher than necessary. The intention generally being to produce longer lasting stubble and residual nitrogen that has had time to convert to more stable forms and move deeper into the profile reducing denitrification risks. Many growers also placed a small amount of nitrogen blended with phosphorous and zinc near the seed during planting to serve as a crop starter, whilst others reported taking the opportunity to make an in-crop applications of nitrogen particularly in more reliable production areas such as the Darling Downs. Generally dryland cotton makes good use of mineralised nitrogen that builds up during the long fallow leading into cotton to fulfil the majority of the crops requirement The use of phosphorous and zinc in starter blends was seen to provide an advantage to establishing cotton as a root development stimulant that also insures against any reduced VAM affects associated with the long fallow lead in time.

Crop yield is closely related to root development with root growth and development being influenced by soil fertility, bulk density and moisture (Min *et al*., 2014). Dryland cotton is typically grown on Vertosols that are well structured, high moisture-holding medium clay soils, with moderate organic matter and nutrient status (SOILpak 1998, McKenzie *et al*., (2003). However, over the course of crop production the grain and fibre produced by crops removes many nutrients from the profile and during long fallows organic matter mineralisation exceeds the subsequent inputs from crop growth, leading to a general decline in the soil's ability to replenish nutrient reserves.

In the lead up to planting dryland cotton, growers often have long fallows to build profile moisture. The same can often occur for the subsequent crop and lead out from cotton. These fallows decrease risk of soil moisture related crop failure but come at the expense of soil carbon, nutrient decline and soil microbial diversity (Bell *et al*. 2006). Page *et al*, (2013) assessed carbon levels from three long term agronomic trial sites in Queensland and reported no till management was not capable of increasing soil organic carbon under the crop-fallow rotation system practised throughout Queensland. In no till systems, Mitchel and Entry (1998) found that when cotton was grown in rotation with other crops such as corn, wheat and legumes soil carbon levels were higher compared with crop monocultures. Growing crops closer together (reducing fallows) and rotating crop types based on root architectures was a sound approach for increasing soil carbon as well as maintaining soil structure and fertility.

During soil nutrition workshops conducted 2013-2017, broad-acre growers and advisors took part in nutrient budgeting exercises. The kilograms of nutrient removed in harvested products were subtracted from the kilograms of nutrient applied to their crops as fertiliser. Across most regions of Queensland and Northern NSW, calculations revealed most synthetic nutrients, with the exception of nitrogen, are supplied to crops at levels below what is exported from the field in seed, fibre and foliage (Klepper 2017).

Whilst this net removal of nutrients from the soil profile has been economic, broadly evidenced by the continued scale of cropping across the northern region, there will ultimately be long term fertility decline implications for immobile nutrients such as phosphorous and potassium. Whilst the addition of fertiliser can ameliorate this problem, crop response will depend heavily on the ability of the root system to access nutrient rich zones that are created by the resultant banding of nutrients from applied fertiliser. Bell (2014) investigated the efficiency at which cotton root systems were able to access banded phosphorous and potassium fertilisers in a series of field experiments. A key conclusion was that cotton was inefficient at accessing fertiliser bands and responded more effectively when nutrients were dispersed more uniformly throughout the soil volume where roots were actively growing. This research implies that cotton is likely to fulfil the majority of its potassium requirements by exploiting inherent soil profile reserves, and that when those reserves become depleted, the incorporation of synthetic fertilisers to depth will need to occur to overcome depletion in a meaningful way. Achieving this without tillage would be difficult. Therefore the reduction of pupae busting, an operation where many growers had indicated the opportunity to incorporate immobile nutrients may exacerbate fertility decline as there is limited opportunity for the redistribution of surface applied nutrient.

In summary, cotton grown in sequence with grains offers the advantages that come with its ability to forage for residual nutrient particularly at depths beyond the rooting zones of other species. However, the long fallows before and after cotton and the inefficiency of the root system for exploiting fertiliser bands may make it a more challenging crop to grow into the future. Developing more appropriate application strategies for immobile nutrients across different soil types and crop rotation sequences is an area that is likely to require future research. Opportunities may exist to better target nutrient application across the system utilising the varying attributes of different crops to access applied nutrient, remobilise and deposit it elsewhere within the soil profile that may subsequently benefit cotton. The current grower practice of fertilising grain crops with an intention of providing a future benefit for cotton would appear to be a sound management approach when the behaviour of the crop root system is considered. Going forward, the decline of immobile nutrients in the subsoil layers maybe a significant threat for maintaining cotton yield.

What would enable better crop sequencing?

Cotton is a difficult crop to include in dryland cropping sequences. It requires a longer fallow lead in than all other grain crops which can pose opportunity costs. Similarly, the lead out of cotton can significantly curtail the performance of the next crop sequence. In terms of systems contribution when compared to other broad leaf crops such as legumes, cotton would appear to provide few advantages beyond its ability to make use of moisture and nutrients deep in the soil profile and the ability to control weeds with over-the-top glyphosate application. Difficulties associated with cotton as a crop rotation arise from the lack of post-crop stubble, its potential to be a systems weed, and the general incompatibility between picking with the newer JD7760 machines and controlled traffic farming practices.

Profitability is therefore the most likely driver for why cotton is grown as a rotation in the farming system and given pillar crop status by some. In terms of profitability, cotton was nominated as the most reliable summer cropping option by many growers due to its indeterminate growth habit and ability to make best use of stored moisture and rainfall whenever it occurs. From the perspective of the other crops within the farming system, cotton represents a series of trade-offs and compromises. Ultimately within the dryland farming system, cotton cannot be successful without grains but due to the availability of legumes, grains can prosper without cotton.

A key issue raised by growers regarding crop sequencing is the difficulty encountered when rotating out of cotton back to a winter cereal. This was a significant issue for drier areas west of Moree and surrounding Goondiwindi. It was also put forward as a problem for the Liverpool Plains; by the time cotton is picked and pupae busted there is often insufficient time or planting moisture to sow a winter cereal. However, most growers who raised this issue had the expectation that a double cropped winter cereal should make an economic return rather than just providing stubble cover. This contrasts with Darling Downs growers who mainly expect to sow wheat irrespective of field conditions even if this occurs as late as August, well past the optimal wheat sowing window. The primary objective for these growers is that the wheat will provide stubble cover; a crop that succeeds in producing grain is viewed as a bonus. Wheat varieties would be adjusted depending on the lateness of a planting opportunity with several growers reporting both stubble and grain production success with cv LongReach Spitfire sown as late as

August following cotton. The lack of a suitable summer cereal for many of these areas compounds the impacts of being unable to sow a winter cereal. When the opportunity to plant wheat or barley is lost, a fallow field will remain without cover until the following winter which constitutes a significant erosion risk with summer storms.

The use of millet was discussed as a potential solution to this problem as it can be sown during the summer months to provide stubble cover. However, millet was considered to be a poor alternative cover crop option because:

- small seeds make it difficult to establish
- management to optimise stubble is difficult: If sprayed out too early it does not form lasting stubble and if sprayed out too late it can contribute a lot of seed to the field's seed bank creating a weed issue
- if taken through to grain it leaves poor stubble compared to winter cereals
- it was considered to host crown rot; a cover crop of millet is likely to build up this disease just prior to a following winter cereal therefore negating some of the disease breaking benefit provided by a cotton rotation

Sorghum is the other summer alternative but compared to winter cereals, it does not create the same degree of stubble cover, it requires much more soil water, and for several regions there is a lack of a viable market for the grain.

In summary, a key weakness of the dryland farming system when cotton has been used as a rotation is that an alternative cereal-like summer crop option that can provide both high stubble cover and grain where circumstances have prevented a winter cereal crop is lacking. The avoidance of pupae busting may make it easier to establish a winter cereal compared to waiting for enough rainfall to reconsolidate the surface after tillage has taken place. Whilst this might improve the opportunity to plant with a low level of rainfall, if the underlying profile is still depleted after cotton, the success of the established wheat remains questionable. Modelling with APSIM may provide insights into the seasonal probabilities associated with this problem

Summation – What are the needs for crop rotation and system RD&E?

Extensive research has been conducted on the suitability of various crop sequences for dryland cotton and general soil and system sustainability. Winter cereals have been identified as the most effective crop rotation for dryland cotton. Pulse crops were shown to be a poor choice from a systems perspective (inadequate stubble cover, poor soil moisture storage efficiency, and exacerbating weed and disease issues). Whilst recent high commodity prices have lead growers to consider utilising pulses as a direct lead-out or lead-in crop for dryland cotton, the fundamental farming system limitations of including pulses in a dryland cotton rotation remain. In fact, if high pulse prices became permanent, dryland growers would possibly be best served by maintaining the strong presence of winter cereals in the system and utilising pulses as a high value rotation crop instead of cotton. In the long term, high pulse prices are not likely to advantage cotton's status or growing frequency within the dryland farming system.

Given the extensive evidence for winter cereals being the most appropriate selection for both lead in and lead out crops in a dryland cotton system, and in the absence of any new rotation crop options, little would be gained from conducting further crop rotation studies to identify the best rotations for dryland cotton as raised by some dryland growers in the workshops.

A key crop sequencing weakness is the difficulty in establishing a crop that provides rapid stubble cover after dryland cotton. Developing, testing or extending tactics and information that improve the establishment and productivity of a winter cereal straight after cotton crop destruction would appear to be the most effective place to direct RD&E efforts in relation to crop rotations. This research objective will directly interrelate with the choices growers make regarding pupae busting tillage. The use of APSIM is likely to be helpful when examining the impact of seasonality and soil type. Modelling may provide unique insights as to how often a winter cereal crop could be expected to be established and result in useful stubble and yield (with and without tillage). Localised field trials to examine this problem without model validation is unlikely to provide answers that can be contextualised against seasonal variability, soil type and regional climatic differences.

The second issue requiring RD&E consideration is crop nutrition across the dryland farming system. With current practices, fertility decline is inevitable and unlikely to be solved by just focussing on the needs of a single crop in isolation to the rest of the system. Identifying the best physical method of fertiliser addition and most appropriate timing (taking into account the influence of crop type and sequences), and acknowledging opportunities for biological remobilisation and dispersal of nutrients within the soil profile will be essential for long term sustainability.

Component Issues Specific to Dryland Cotton in the Northern Region

Cotton establishment

A prominent issue raised by growers at each workshop was the difficulties that can be encountered trying to plant and establish a dryland cotton crop. Emergence problems occur when one or more factors coincide to prevent the effective placement, germination or emergence of cotton seed during or after the planting operation. The underlying factors may be either biophysical or linked to the environment in which the seed is placed. Developing solutions to emergence problems is consequently difficult as the circumstance contributing to failure will vary within and between fields and from region to region. Marshall (2002) summed up the challenge particularly well in stating that "Every grower needs to develop a system that suits their particular soil type and equipment".

For people to develop solutions to emergence problems it is important to be able to unpack each of the factors that might be contributing to the problem so that a tailored solution can be developed. Here we provide a brief overview of those factors from a dryland cotton perspective.

System factors

Nearly all growers utilised a long fallow after a winter cereal crop as the lead-in scenario for dryland cotton. From a systems perspective, this lead-in is optimal as it provides a fallow of 12 months, allowing soil moisture to accrue from rainfall whilst the standing cereal stubble protects the soil surface from erosion and moisture loss.

The interaction between the stubble and cotton establishment can be both positive and negative. Stubble can serve to protect the emerging seedlings and young crop from insect attack (*Helicoverpa* spp) as well as wind-related sand blasting damage (Cleary 2008). Stubble also serves to help retain moisture nearer to the soil surface, which can extend the period of time available for planting after a rainfall event. On the other hand, stubble can pose problems for establishment by altering levels of moisture retention throughout a field when the surface is uneven (exacerbating wet and dry patches) and creating difficulties for optimising planting equipment set-up. Stubble can also delay warming up of the soil profile constraining the window of opportunity for sowing (Cutforth and McConkey, 1997). To sum up, a cereal stubble fallow as the lead-in for a cotton crop is likely to provide the best circumstances for setting up a field to maximise the opportunity to plant and establish a cotton crop. It is dealing with stubble at the micro level that can cause issues when carrying out the planting operation.

Seed factors

Many growers suggested that changes that have taken place with the seed size of newer varieties had increased difficulties with establishment. The shift towards varieties with higher lint turn-out percentages that has reduced average seed size/density is thought to be a key factor limiting the robustness of seedlings to emerge, particularly when planted deeper in the soil profile to seek moisture. Varieties such as Sicot 74 are considered by growers to have reduced resilience and ability to emerge across a range of varying field circumstances.

In an effort to minimise the contribution that seed factors might have on crop establishment, strict grading and testing procedures are in place during the seed production and preparation processes utilised by CSD to ensure that all seed supplied for planting meets given criteria on specific gravity, germination and vigour (Quinn pers com 2016). However, it would be a fair assessment to suggest that varieties such the 74 types require more exacting attention to detail during the planting process when it comes to soil moisture, seed placement and pressure used to cover and firm over the seed in the planting trench.

Sicot 71 type varieties are considered to have seed characteristics that provide a greater degree of robustness when planting conditions are likely to be challenging. However, when asked at the dryland workshops whether or not this characteristic would influence varietal selection, the majority of growers indicated that they considered the yield potential differential between Sicot 74 and 71 types outweighed any advantages that might be gained in establishment ease. This would appear to be counter-intuitive given the long lead time, planting expense and potential opportunity costs for dryland cotton in the event of an establishment failure. Essentially, growers want both a farming system and planting techniques that enable reliable establishment of cotton across a range of conditions using the highest yield potential varieties (74 types), and believe that varietal selection should not have to be compromised by establishment considerations.

The utilisation of the world's highest standards for selecting, grading, testing and processing cotton seed destined for planting will not overcome germination issues after planting if conditions fall outside of the optimal range. Poor establishment often occurs when less than optimal planting techniques intersect with a period of cooler than expected temperatures. Cotton seed is very sensitive to cool temperatures during the early phases of germination when moisture is imbibed (Figure 1). If temperatures are not optimal after planting, cultivar type or seed characteristics are unlikely to make much difference to an emergence outcome. For dryland growers seed size and density (as an indirect measure of seed stored energy) is only likely to have an influence on a seedling's ability to emerge from conditions where the soil or seed placement are restrictive.

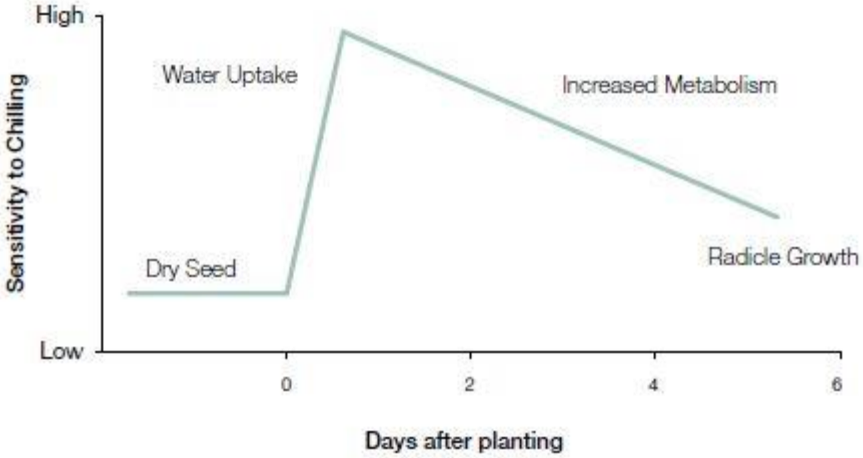


Figure 1 Sensitivity of seed to chilling during the germination process (taken from CSD Fast Start™ Guidelines).

Environmental factors affecting cotton establishment in dryland systems

Apart from temperature constraints, successful germination depends on placing the seed into soil with adequate moisture so that it makes sufficient surface contact to enable the seed to imbibe water. In dryland systems, soil moisture cannot be directly manipulated through irrigation to time a planting event or enable a replant. Once germination has commenced, emergence is then dependent on the radicle being able to penetrate the underlying soil to begin establishing a root system whilst the hypercotyl needs to be able to elongate and push through the overlying soil allowing cotyledon emergence. Sowing difficulties arise for dryland cotton when sufficiently moist soil occurs at depths greater than 5 cm. Placement of seed below 5 cm creates challenges for emergence as a greater depth of overlying soil limits the hypercotyl's ability to push the cotyledons through to the surface. Soil factors such as structure and surface compaction will also have a major bearing crop establishment ease.

At the workshops emergence issues were ranked most highly by participants from Goondiwindi and Moree compared with the Darling Downs and Upper Namoi. Liverpool Plains growers had specific concerns around emergence related to being able to plant at an optimal time (which requires suitable temperatures to coincide with ideal soil moisture conditions as opposed to soil type related difficulties).

Darling Downs growers indicated that moisture seeking (via removal of dry surface layer) to place cotton seed more deeply during sowing was a practice used in some seasons with reasonable success. Experiences shared by growers at the Goondiwindi and Moree workshops indicated a more varied responses had been achieved with moisture seeking tactics that aimed to engage with soil moisture at depths greater than 5cm.

Differences in soil type characteristics and to a lesser extent the local climate would appear to be a key causes for reported differences. Climatic factors are related to lower rainfall that limits the number of planting opportunities and higher temperatures that constrain the period where soil moisture remains optimal for planting after rainfall. The imperative to take advantage of planting moisture when it occurs is more time-critical for areas around Goondiwindi and west of Moree.

Soil factors

The inability of cotton to emerge from depth, compared with many other crops, limits crop establishment under marginal moisture conditions (CSD 2014). Establishment difficulties encountered by dryland growers, particularly in northern NSW under marginal moisture conditions, was subject to a desktop analysis by Hulme (2015). A key finding of this work was that the shallow depth of topsoil that is structurally stable in many regions is one of the biggest factors contributing to poor establishment of dryland cotton. Planting seed at depth below this top soil layer to seek moisture in poorly structured sub-soil typically leads to a phenomena called 'Kinze' crack whereby the sub-soil shrinks away from the sown seed in the planting trench resulting in inability to imbibe or seedling death.

Hulme (2015) postulated that the development of a Kinze crack following moisture seeking cotton at depths greater than 5 cm was an inevitable outcome of placing cotton seed into clayey moist soil types with peds of 10 cm or more. The reason for this is that due to poor structure the whole block of compacted soil acts as one unit; the seed trench created by the planter becomes the weakest part of the block and therefore where a crack is most likely to occur. This soil behaviour is very different to a seed trench made in structured soil where the multiple small peds provide for movement across the zone allowing multiple small cracks that do not result in the sown seed becoming stranded. Figure 2 taken from the technical report prepared by Hulme 2015 demonstrates this principal.

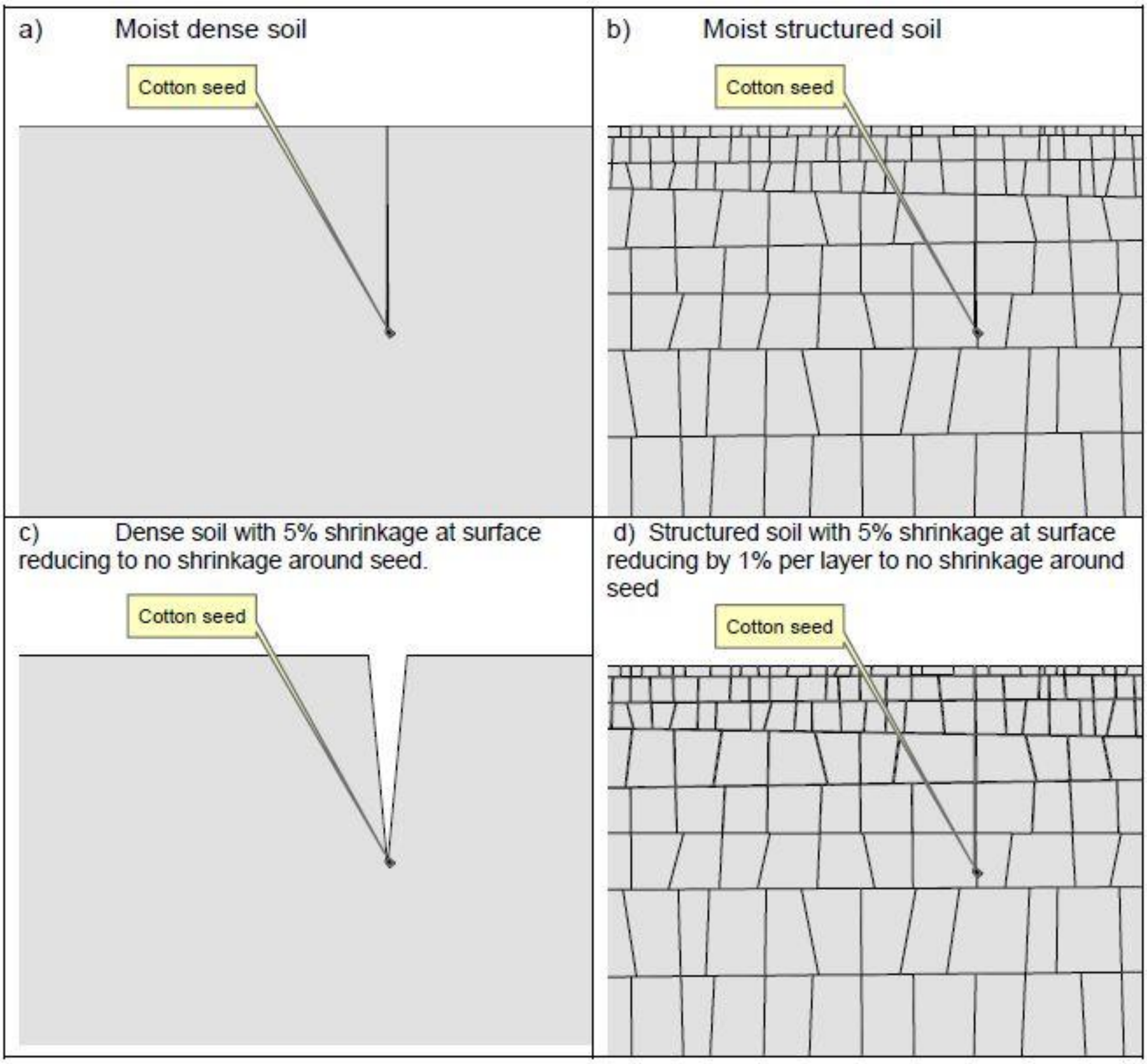


Figure 2 Diagram of theoretical shrinkage of compacted soil represented by one block of clay 150 mm wide by 80 mm deep and structured soil represented by 180 blocks of soil (taken from Hulme, 2015).

The key conclusion from this study was that anything that can improve the soil structure by decreasing ped size to something more akin to Figure 2b, in the top 15 cm of soil would assist in improving cotton emergence, particularly when moisture seeking at greater depth.

Tactics to overcome poor soil structure and aid emergence

Strip tillage

Effective soil tillage has the potential to create ideal seedbed conditions (i.e. soil moisture, temperature, and penetration resistance) for plant emergence, development, and unimpeded root growth. Strip tillage has the potential to create such conditions by combining the benefits of conventional tillage and no-tillage by disturbing the row and leaving the inter-row with intact residue cover (Vyn and Raimbault, 1993).

Hulme (2015) suggested that strategic strip tillage may overcome soil structural issues that are impacting the emergence of dryland cotton particularly when moisture seeking into soils where the friable surface layer is less than 10 cm in depth. The proposed tactic would be to enact targeted tillage to form a seed bed either side of a future planting line whilst leaving the rest of the field undisturbed. Ideally, for dryland cotton this would be conducted straight after the last winter cereal crop is harvested as the soil is dry at that time enabling the effective shattering of the poorly structured or compacted soil into smaller peds. The 12 month fallow period would then allow the disturbed soil to settle forming good tilth with subsequent wetting and drying from rainfall. On sloping ground it was proposed that tillage be delayed until after the risk of high intensity summer storms has declined (Hulme 2015).

A review of the literature regarding strip tillage shows that it is a well adopted practice in certain parts of the world. Potential benefits include improved soil temperatures compared with minimum till stubble cover and improved plant emergence similar to conventional tillage but without the associated moisture losses (Licht & Al-Kaisi 2005). Soil temperature was found to have an inverse relationship with the amount of residue cover present (Radke, 1982). The decrease in soil temperature is due to the surface residue reflecting solar radiation and insulating the soil surface (van Wijk, 1959). Increasing the width of the strip tilled area was found to be positively correlated with increasing temperature but negatively correlated with soil moisture (Celik *et al.* 2013). When contextualising these reported impacts it should be kept in mind that the stubble cover left behind after cereal crops in the northern hemisphere where these studies took place is much denser and more obstructive to subsequent cropping operations compared to Australia. Climatic conditions are also typically cooler and wetter during spring and therefore achieving timely planting where stubble can be an obstacle was a driver for the use of strip tillage within these regions.

Detailed experiments comparing strip tillage with minimum and conventional tillage were conducted at two sites (fine loam and silty clay loam soil) in Iowa (USA) over four years using corn as an indicator species were conducted by Licht & Al-Kaisi (2005). These studies found that increases in temperature were marginal and proportional to soil moisture (higher the moisture content the lower the temperature increase). Temperatures increased by 1.4-1.9°C only when air temperatures peaked around 19:00h. The emergence vigour of maize grown throughout the experiment was not significantly different to either the minimum tillage or conventional tillage treatments. Soil penetration resistance was found to be similar to minimum tillage and not as good as conventional tillage with no real changes found in the top 20 cm. Overall the authors concluded that strip-tillage may have an advantage over no-tillage for poorly drained soils but justification for implementing the system would dependent upon site-specific field conditions and grower objectives (Licht & Al-Kaisi 2005).

Very few studies report the impact of strip tillage for cotton emergence and establishment. Studies involving cotton have predominantly focused on production energy use efficiency (Gemtos 2008) and weed management (Clewis & Wilcut 2007). The only study focused on yield was conducted on a clay soil and gave inconclusive results (Morrisson 2002). None of these studies examined aspects of emergence related to the implementation of strip tillage.

Research examining the application of strip tillage for dryland cotton production was conducted by Marshall & Walker (1996). The focus of this work was investigating the potential to incorporate herbicides and nitrogen prior to planting as well as improving the seed bed for planting. Trials were conducted over two seasons during August prior to planting using three different assemblies: A PTO driven 30 cm wide rotary hoe, a 30 cm wide flat profile sweep, and two 15 cm beet knives. Each treatment produced a similar result, a cultivated strip approximately 30 cm wide and 8 cm deep. The condition of the soil post-tillage was found to be very dependent on soil moisture and soil compaction at the time of operation. Compacted areas resulted in a very cloddy seed bed and only the rotary hoe treatment produced appropriate tilth although it was noted that if it was too dry it was difficult to achieve a suitable depth with the hoe and if conditions were too moist it would just smear the soil.

Marshall & Walker (1996), concluded that whilst strip tilling had been practiced by some growers with success on some soil types at the time, others had attempted it and found it to be an abject failure, particularly on heavy black and grey clay soils. Outcomes were very much dependent on soil moisture conditions at the time of tillage and subsequent rainfall. Despite the level of interest when the research was conducted, the practice does not appear to be prominent on the Darling Downs today.

Hulmes' suggestion for using strip tillage to overcome the constraints of moisture seeking at planting in poorly structured soils is intuitively attractive. However, evidence in the literature related the application of strip tillage for overcoming structural soil constraints for cotton planting, particularly where sodicity is a factor have not been uncovered. The literature does however, make clear that the responses to strip tillage can be quite variable depending on crop type, soil type, weather conditions and what comparisons are been made regarding the impacts of strip tillage. Modelling with APSIM may provide insights as to when the application of strip tillage might be optimised from a timing perspective across regions.

Soil additives for overcoming emergence issues

Growers at the workshops in the Goondiwindi region raised the idea of whether or not GPS guidance systems could be used to apply highly targeted soil ameliorants to the planting line that may assist in overcoming sodicity-related soil structural constraints or enable moisture to be kept closer to the surface for longer for the benefit of cotton emergence. Suggestions included incorporating gypsum type products or polyacrylamide style wetting agents to the plant line some time prior to planting to improve soil conditions.

The soil constraints alluded to by growers attending the workshops are linked to the processes outlined by Hume (2015) that could also be described as hard setting. A phenomena where a massive apedal structure occurs in the topsoil and becomes very hard on drying. Sodic soils often demonstrate the characteristics of hard setting. In order to alleviate hard-set conditions, a combination of initial cultivation to shatter the massive layer, increased organic matter, and chemical amelioration of structure needs to occur (Mullins *et al.*, 1990). Chemical amelioration of the sodicity in the soil is primarily reliant on exchanging sodium and maintaining adequate electrolyte concentration in solution. The most common method for ameliorating a sodic soil is through the addition of gypsum ($CaSO_4.2H_2O$) which provides an electrolyte effect and can displace sodium from the exchange complex over the longer term (Qadir *et al.*, 2001).

Gypsum

The impact of adding gypsum to soil is dependent on a number of factors, including the gypsum source (purity), particle size which will determine longevity, the velocity of percolating solution with greater affect achieved with longer water contact times during rainfall infiltration, depth of gypsum incorporation, and the inherent soil characteristics (McLean-Bennett 2010).

The benefits of simply adding gypsum in a concentrated band to the planting line is therefore difficult to predict as it will depend on the above factors and the extent of sodicity-induced structural issues. It is likely that for most soil types an improvement in surface structure would be observed allowing cotyledons to emerge more easily as well an improving the rate of rainfall infiltration. Incorporating gypsum is likely to improve its impact as tillage breaks up massive ped structures, allowing gypsum entry to provide ongoing chemical amelioration. The viability of such an approach will depend on a range of factors (amount of gypsum required, soil characteristics, expected length of affect, and frequency of cotton in the crop sequence). The use of gypsum during a strip tillage operation may add longer term value to this type of operation. However, it may represent better value to add gypsum across the entire field before a general tillage operation (e.g. pupae busting) as this would provide benefits to all crops within the farming system. The cost: benefit for applying gypsum will depend on the soil type, level of sodicity and expected benefits for crop productivity in the system. These impacts can take an extended period of time to assess.

Polyacrylamides

The application of water storing/attracting polyacrylamide type products to modify the immediate planting environment is another option that might be considered to assist overcoming environmental constraints for emergence. Water-storing polymers have been developed to facilitate water availability during drought periods. Polymer granules can be mixed with soil to increase germination and improve soil conditions and reduce the amount of irrigation or rainfall required during drought or in saline-prone areas (Känkänen *et al.*, 2011). Such highly hydrophilic polymers can store water up to 1000 times their weight and potential exists to fortify these products with nutrients or growth promoting agents.

The use of these products has generally been limited to high value production purposes in horticulture, landscaping, golf-course construction and hobby gardening. The literature on the use of polyacrylamide type products to assist with modifying the soil environment to assess seedling establishment for broad acre crops is limited, with most experiments being exploratory by nature and no examples found of commercial scale use beyond the use of polyacrylamide products for irrigation-related purposes.

Studies conducted by Cook *et al.* (1986) with lucerne showed that emergence could be improved when soils were treated with polyacrylamide solutions, but not granular forms of the product. Liquid polyacrylamide was found to keep soil aggregates stable but did not improve structure.

Seedling emergence is often impeded by surface crusting. A laboratory study to compare several polyacrylamide products and guar for reducing crust hardness and enhancing seedling emergence found that cotton seedling emergence could be improved compared to untreated soil (Helalia & Letey 1989). Further testing with smaller seeded species such as tomatoes proved inconclusive. Similar exploratory studies were conducted by Rapp *et. al.*, (2000) who compared polyacrylamides with phosphogypsum and examined the products' impact on crusting and surface evaporation on a sodic silty loam soil type in which cotton was used as a test species. This study found that the impact of crusting on emergence was a lesser factor than the impact of the soil evaporation rate for cotton emergence with benefits derived from the addition of both phosphogypsum with polyacrylamide.

Volkmar and Chang (1995) reported one of the few examples where polyacrylamides were tested under commercial circumstances for broad acre crops. A concern that they wanted to test was whether or not the superabsorbent properties of these products would be constrained from the pressure of overlying soil when applied commercially to fields. A potential fault of polyacrylamide studies conducted in laboratory pot trials is that they are less likely to experience soil factors that would constrain crystal expansion. Field testing confirmed this constraint; water retention achieved with two different polyacrylamide products decreased by about 30% when crystal expansion was restricted by surrounding soil. The other critical finding of their studies was that the recommended rates for the two commercially available products tested were found to be woefully inadequate with significant growth gains only achieved with barley at rates that were 64 times the manufacturer recommended rate (equivalent of 0.19% of polymer per unit mass of soil). The study conclusion was that the results did not support the use of hydrophilic polyacrylamides as field amendments for overcoming dry conditions (Volkmar & Chang 1995).

A similar study was conducted under field conditions in Finland to examine the use of polyacrylamides to overcome typical dry conditions impacting the ability to establishment of canola (Känkänen *et al.* 2011). Initial experiments examined the effectiveness of applying crystal type polyacrylamides with seed during the planting operation which failed to give a response. However, a second series of 5 experiments examined the use of liquid polyacrylamide formulations injected directly beneath the seed (see Figure 3).

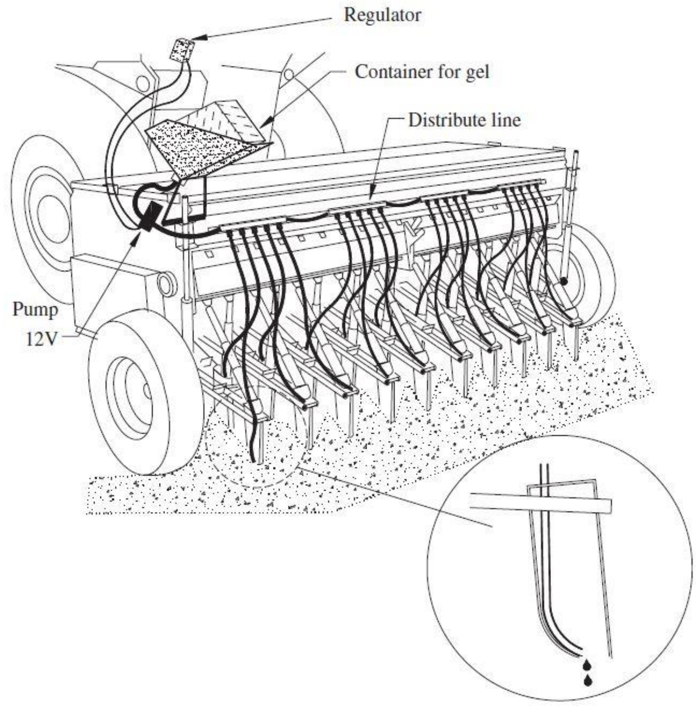


Figure 3. A schematic of an accessory used to place hydrated polymer straight under the seeds during planting (taken from Känkänen *et al.* (2011)

The application of polyacrylamide gel at planting significantly improved canola emergence but did not have an impact on crop yield. The use of polyacrylamide gel did not reduce the need for careful preparation of the soil bed and accurate timing of sowing, but when these prerequisites were fulfilled, the gel sustained early establishment and seedling growth. This impact was clear when circumstances after sowing did not favour germination or early establishment. However, the authors also suggest that accurate placing of polyacrylamide gel under the seeds during planting is challenging and made no comment on associated costs (Känkänen *et al.* (2011).

Recently similar trials have been conducted by Sacoa Pty Ltd in Australia examining the use of polyacrylamides for improving the establishment of canola in sandy hydrophobic soils in Western Australia's grain belt. Their developmental product (SE14) has shown promise for improving canola germination and establishment under dry conditions when the product is combined with water injection.

Water injection and seed soaking

Placement of water into the seeding trench (water injection) during the cotton planting operation has been considered by many growers and occasionally put into practice over the last 30 years. The premise of water injecting is to ensure that the imbibing process initiates immediately after planting and to also limit the drying back of the seed trench due to soil disturbance and exposure to the air during planting.

Marshall (1995) reported the practice of water injection being utilised by Darling Downs growers. The technique is also reported in the Dryland Production Guideline 3rd edition (CRDC 2002) as the addition of water to reduce dry-back and speed up moisture imbibing, whilst also utilising it as an opportunity to apply starter fertiliser and insecticides for soil insects. Water rates used varied from 500-2000 L/ha with 1000 L/ha being a common rate. Plant vigour notably improved with water injection but establishment percentages did not necessarily change. Water injection did not provide a substitute for insufficient planting moisture in the soil and the process of applying the volumes of water required typically reduced the operational efficiency of planting by 20-40% in terms of hectares covered per day. If water was the only additive used the efficacy of water injection was questionable both economically and agronomically. Marshall

(1995) notes that what growers gained in crop establishment was often lost in terms of not always being able to get the total area sown due to slower planting rates and the field becoming too dry in the interim to continue planting.

Seed soaking has been another tactic promoted from time to time (Bunn & Barlow 1989; Marshall 1995; Eveleigh 2017) to overcome marginal soil moisture conditions for cotton planting. It entails soaking cotton seed in water for two to three hours, letting it drain for three to four hours, and planting it within 24 hours. Eveleigh (2017) suggests adding water at a ratio of 8 litres per 20 kg of seed which enables most of the water to be imbibed, thus lowering the risk of losing seed dressings in the soaking process. Subsequent experiments testing this approach found that emergence was more rapid but ultimate establishment percentages differed little between soaked and un-soaked seeds, which is similar to the treatment effects reported for water injection (Marshall 1995). Like water injection, the practicalities and limitations for using seed soaking as a solution for marginal soil moisture planting conditions are self-evident.

Could RD&E on planting zone amelioration tactics deliver for dryland cotton growers?

A number of tactics that could either improve soil conditions in the planting zone or be added with seed during planting have been reviewed. The addition of gypsum may be a suitable tactic to improve soil surface structure and ameliorate issues that make it difficult for cotton to emerge. An added advantage of gypsum application would be improved soil moisture infiltration, creating other system benefits. The overall impact of gypsum will depend on soil type characteristics and the form, rate and zone to which gypsum is applied. It is difficult to comment on the cost versus benefit of applying gypsum as the product price varies depending on location, whilst paddock level factors will determine the appropriate rate and likely benefit. Given that the benefits of gypsum are well understood and its usage is commonplace in agriculture, if gypsum could cost-effectively solve emergence issues it is likely that people would already being utilising such a strategy. Few growers mentioned gypsum usage as a viable option so it is likely that costs probably outweigh potential benefits.

The addition of polyacrylamide crystals to the plant line in a bid to manipulate soil moisture conditions for planting would appear from the literature to be uneconomic and have minimal chance of success. It is unlikely therefore that additional R&D in this area would deliver different results.

The injection of water during the planting operation is unlikely to deliver significant increases in the level of establishment under dry conditions. Water injection will not substitute for inadequate planting moisture and therefore the window of applicability is likely to be narrow in that it may only extend the viable planting period by several days. In some seasons this could be of considerable value to a grower who has invested heavily in setting the system up for a dryland cotton crop and would otherwise be faced with a missed planting opportunity. The addition of polyacrylamide gel products such as SE14 as part of a water injecting method may provide an opportunity to increase planting efficiency by maintaining the emergence benefits derived from water injecting but with reduced water volumes. Product costs would need to be weighed against any efficiency gains. At this stage the testing of SE14 as a product that may improve establishment for specific planting scenarios may be a worthwhile but short term R&D objective.

Seed soaking has major practical seed handling limitations that prevent it from being a widespread tactic for overcoming marginal moisture planting conditions. Perhaps a novel device that mechanically soaks and handles seed in a way that directly integrates with the planter or planting operation would overcome the current limitations associated with manually handling wet seed. However, it is unlikely that any company would develop such a device for a minor market particularly when marginal planting conditions do not occur every year.

The concept of strip tillage is an intuitively attractive solution to the constraint of poorly structured sodic soils. From and RD&E perspective, examining the impacts of strip tillage in such a way to be able to make firm recommendations would be difficult as the impact will be highly variable between sites and soil types and affected by seasonal variability. The challenges of determining whether or not strip tillage is something that growers should invest in was well summed up by Marshall and Walker (1996) who reported that it worked successfully in some fields and was an abject failure in others. Where successful, the benefits of strip tillage need to be weighed up against the low frequency of cotton (once every 3-5 years) in the drier regions where establishment is more of an issue as the practice will not provide advantages for other crops grown in the system during that time (as row spacings do not align). Strip tillage therefore must be economic solely from a cotton productivity perspective. It may prove more attractive if dedicated strip tillage equipment could also conduct pupae busting to the defined band either side of the plant row and provide effective crop destruction. This might help offset capital equipment costs.

Working with growers who have equipment that could be deployed or modified to enact strip tillage as a development extension exercise may be the best model for exploring the potential of strip tillage in difficult soil types and to collect basic data on suitability for improving establishment.

Planting configuration (row spacing)

Row spacing was raised as an issue in some regions (Moree, Quirindi and Boggabri). The concerns for row spacing were not specific but tended to centre on the suitability of existing configurations in relation to the rest of the farming system and controlled traffic operations, lack of local validation, the relationship between plant stand within the row and row spacing, and to a lesser extent the potential for using row spacing to manipulate crop maturity prior to the 31 March defoliation date for Bollgard 3.

The body of research underpinning row spacing decisions is vast. Selecting a row configuration is complex as it entails many considerations that overlap with personal attitudes to risk. Row configuration choice can affect lint yield and quality potential, machinery requirements, agronomic management, input costs and therefore economic returns (Bange *et al.*, 2005).

For the purpose of this review we do not want to describe in detail the many row spacing trials and comparisons that have been made by researchers and CSD, however we will highlight some basic points regarding planting configuration from reviewing a number of research reports by Bange, Goyne, Marshall, Stiller and others.

The configuration that best suits individual dryland cotton situations varies depending on factors such as soil type, rainfall patterns, the other crops in the farming system, equipment availability etc. The basic premise for utilising different configurations is to provide a greater reserve of soil moisture beside the planted rows, which delivers a buffer in drier seasons allowing extended crop growth. Different configurations are essentially a range of deviations from conventionally spaced solid plantings on 1 m row spacings. This might entail leaving out every third row (single skip) or two in two out (double skip) or evenly spaced rows at increased spacing (1.5 m wide rows). The primary consideration of different row configurations is how yield potential compares to the likely yield of a solid plant configuration in a season with good rainfall and assessing the risk of a lower-than average rainfall year. Lint quality is the second most important consideration as wider row spacings provide the chance of improved lint quality when seasonal conditions are drier than anticipated.

Many experiments and trials have been conducted examining how yield potential in relation to solid plant cotton at a range of dryland sites over many years. This work is best captured and summed up by Bange *et al* (2005) who collectively compared the results from the work of Pyke

(1991), Marshall *et al.* (1994), Hearn (unpublished data) and Goyne (2000) who each studied single and double skip configurations in comparison with solid planting (Figure 4).

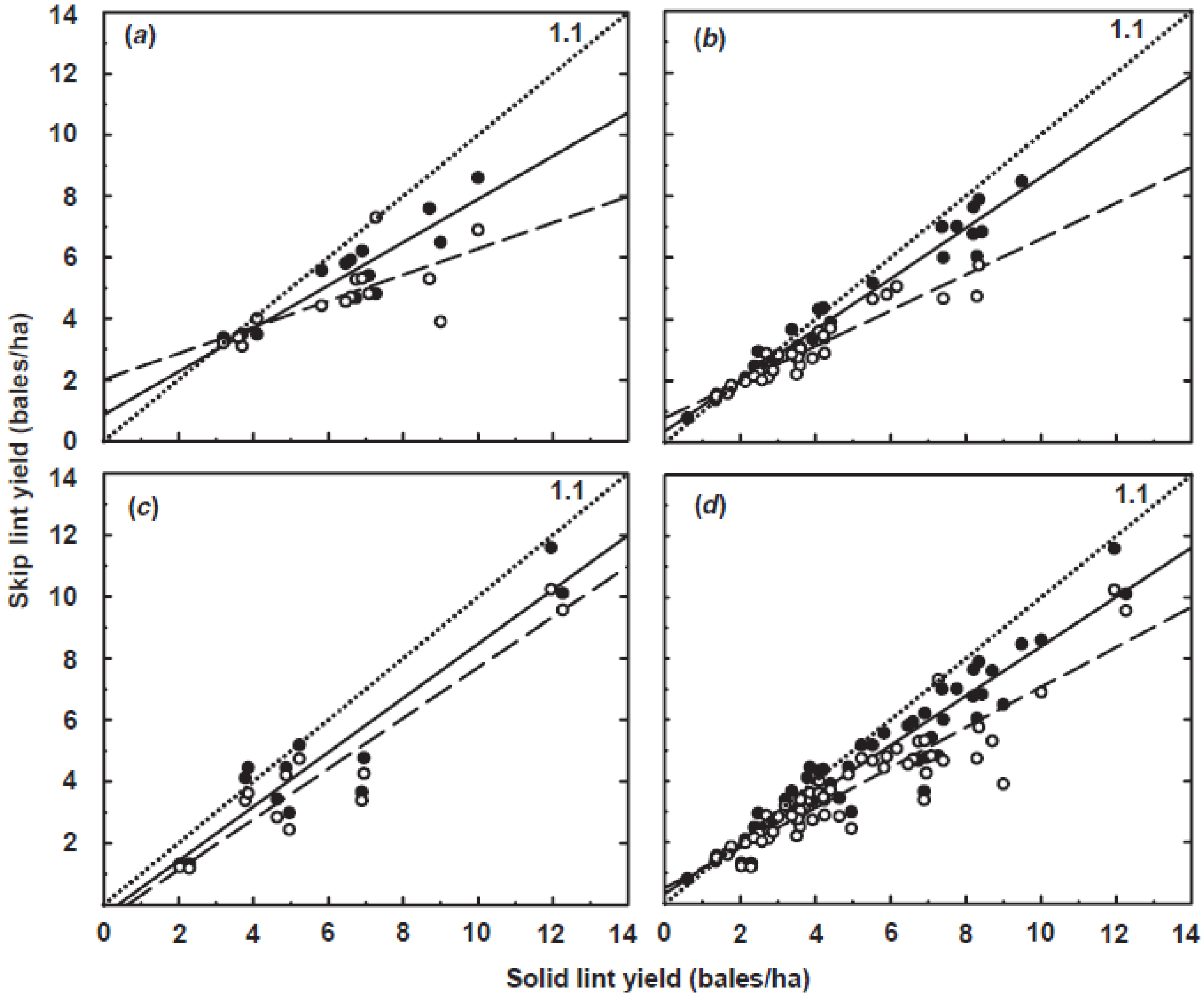


Figure 4 Responses derived from measured field data that show the relationship of lint yield (bales/ha) of skip row configurations v. lint yield (bales/ha) of solid row configurations. Solid lines are single skip and dashed lines are double skip configurations. 1:1 lines are given (dotted). Data are from (a) Goyne (2000), (b) Pyke (1991) and Marshall *et al.* (1994b), (c) Hearn (unpublished data), and combined.

In studies conducted by Goyne (2000) in the high yielding area of the Darling Downs, skip row configurations did not suffer a penalty until solid yields were >3 bales/ha. Studies by Pyke (1991) and Marshall *et al.*, (1994b) on more diverse soil types at Biloela and Dalby showed that skip configurations suffered yield penalties at <3 bales/ha. Hearn's studies at Narrabri showed that lint yield was less across the whole yield range, but some supplementary irrigation had been applied which would have disadvantaged the skip row treatments. An analysis of the data combined suggested single skip cotton yielded less when solid planted yields exceeded 1.6 bales/ha and 1.5 bales/ha for double skip. These results indicate that when yields of solid plantings are high (in seasons when moisture is less limiting) there is an associated yield penalty with skip configurations.

However, profitability is influenced by not only yield, but lint quality and relative input costs as well. Solid plantings of cotton require more resources (seed, pesticides and aerial operations) whilst moisture stress during the first 20 days of boll development can lead to short fibre length for which discounts are severe. A summary of configuration and lint quality studies based on work by Pyke in Biloela during the early 1990s, reported by Marshall *et al.*, (1994a), Goyne (2000) and CSD based on variety trials over four seasons from 1997–2000 provided in the Australian Dryland Cotton Production Guideline 3rd Ed showed that fibre length was below base grade in

56% of crops grown as solid plantings compared to 11% for skip row configurations. The degree of fibre shortness was also more severe for solid plantings (30%) whereas skip row configurations typically fell just below base grade requirements.

Bange *et al.*, (2005) went one step further, conducting a combined analysis of the results achieved in these studies and balancing yield against input costs and lint quality factors. When input costs are accounted for and lint quality discounts applied the crossover point for profitability with different configurations becomes much clearer (Figure 5). When production costs are included (Figure 5*a,b*), the gross margin for skip row cotton only became less than that of solid planted cotton once the potential yield of the solid planted cotton exceeded 6.2 bales/ha for single skip and 4.8 bales/ha or more for double skip configurations. However, when potential discounts for staple length are also taken into account, substantial changes take place for solid planted cotton compared to either skip row configuration. Under this scenario, the gross margins of the solid plant configurations stay below the skip row configurations (Figure 5 *c,d*) (Bange et al. 2005). What this analysis demonstrates is that there can be financial gains from electing to grow skip row cotton compared to solid planted cotton but these are derived primarily from production cost savings and the reduced incidence of lint quality discounts.

Further work and analysis of the influence of configuration were reported by Bange *et al.*, (2012) taking into account newer practices such as super singles (one row present and two skipped) and alternate row (one present, one skipped). The results from this work followed similar patterns to those already reviewed here with crossover points for yield potential varying depending on the dryness of the season. Super singles performed better only when the yield potential for double skip was low <2.3 bales/ha (e.g. a dry year) whilst alternate row configurations were found to be either better or the same as double skip. The more recent trials though coincided with considerable in season rainfall with the yields of 3.7 bales/ha attained in double skip Bange *et al* (2012).

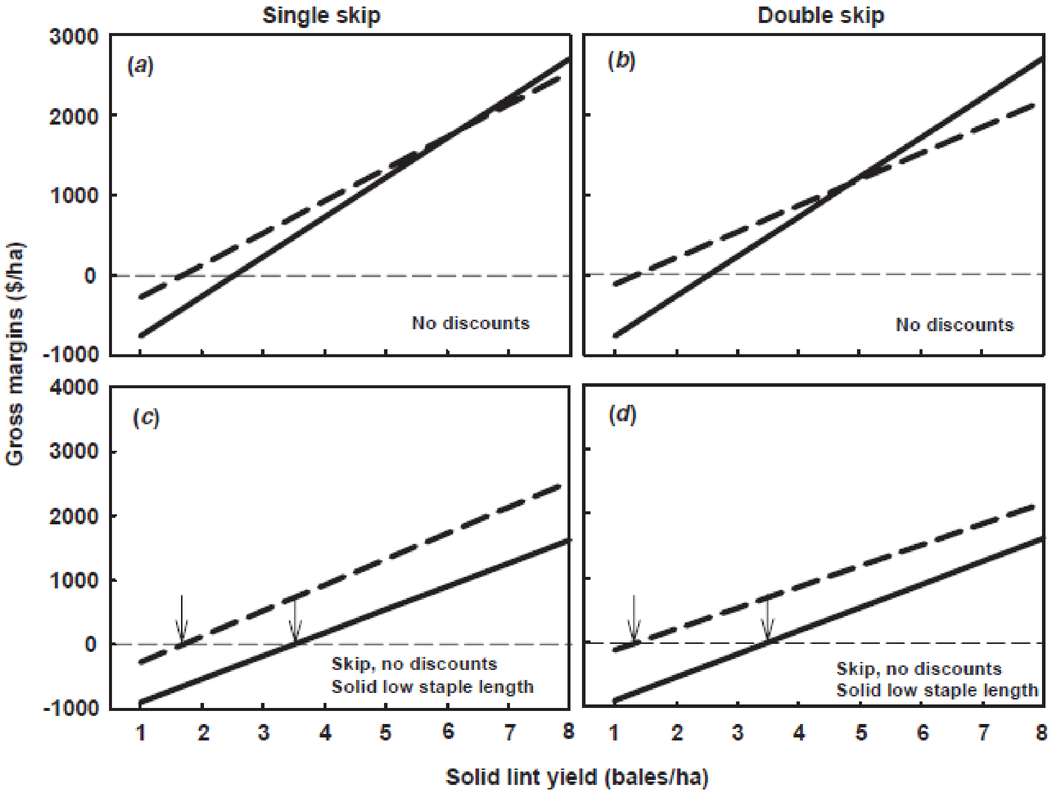
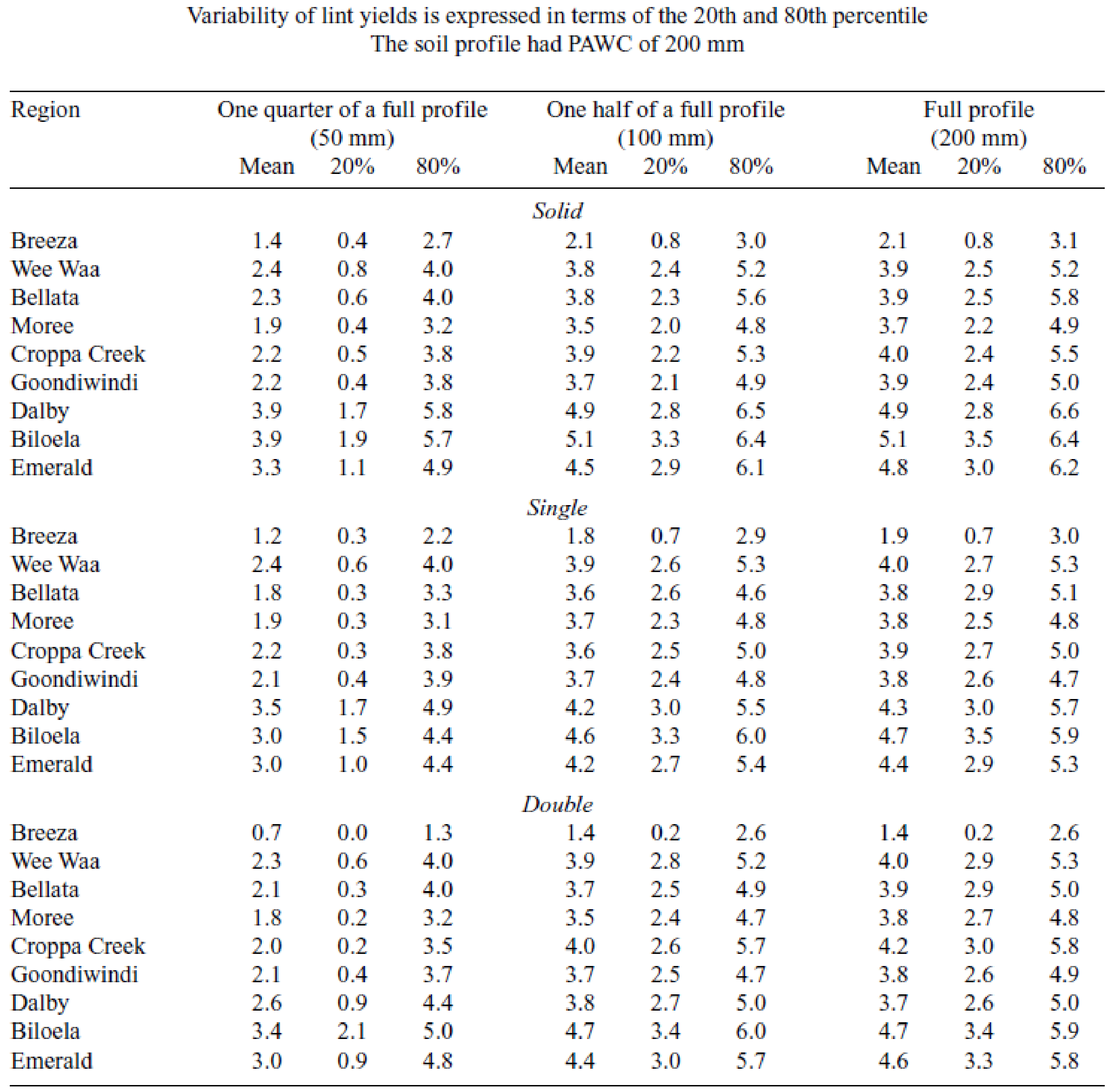


Figure 5 Economic comparison of skip row configurations compare with solid, accounting for costs and lint yield. (*a,b*) are without discounts for lint quality (*c,d*) taking into account discounts for reduced fibre length. The arrows for (*c*) and (*d*) highlights the break-even lint yield point (solid configuration, solid lines; and skip configurations, dashed lines).

Bange *et al.*, (2005) used modelling to examine one other very interesting factor that would be expected to alter people's decision-making processes for configuration selection: the impact of soil water content in the profile at planting. Many growers at the workshops indicated that they needed their profiles to be 75-100% before they would consider sowing dryland cotton. One tactic that could be expected to lower the risks of crop failure when presented with limited soil water at planting would be the selection of wider row configuration. Simulation outputs from Ozcot for a wide number of regions indicated that increasing plant available water content (PAWC) from 0.25 to 0.5 increased mean lint yield significantly. Increasing PAWC further from 0.5 to full capacity gave very little further increase in yield for any of the row spacings (Bange *et al*, 2005). Surprisingly, even the skip configurations made little difference to the final outcome irrespective of starting moisture. What these simulation results highlight is that the end of season yield outcome is more dependent on in-crop rainfall occurring during flowering than soil moisture at planting. The simulations output table from Bange *et al.* (2005) is reproduced here for convenience at Excerpt 1. The result very strongly demonstrates that the selection of row configuration needs to be based on broad range of factors such as likely rainfall patterns or soil type characteristics and **is not** something that should be decided just on soil PAWC at planting.

Excerpt 1. Estimates of potential lint yield (bales/ha) calculated using OZCOT simulation model, for different row configurations (Solid, single and double) for three starting soil water contents at sites in Qld and NSW – from Bange *et al.*, (2005).



Variability of lint yields is expressed in terms of the 20th and 80th percentile
The soil profile had PAWC of 200 mm

Region	One quarter of a full profile (50 mm)			One half of a full profile (100 mm)			Full profile (200 mm)		
	Mean	20%	80%	Mean	20%	80%	Mean	20%	80%
				Solid					
Breeza	1.4	0.4	2.7	2.1	0.8	3.0	2.1	0.8	3.1
Wee Waa	2.4	0.8	4.0	3.8	2.4	5.2	3.9	2.5	5.2
Bellata	2.3	0.6	4.0	3.8	2.3	5.6	3.9	2.5	5.8
Moree	1.9	0.4	3.2	3.5	2.0	4.8	3.7	2.2	4.9
Croppa Creek	2.2	0.5	3.8	3.9	2.2	5.3	4.0	2.4	5.5
Goondiwindi	2.2	0.4	3.8	3.7	2.1	4.9	3.9	2.4	5.0
Dalby	3.9	1.7	5.8	4.9	2.8	6.5	4.9	2.8	6.6
Biloela	3.9	1.9	5.7	5.1	3.3	6.4	5.1	3.5	6.4
Emerald	3.3	1.1	4.9	4.5	2.9	6.1	4.8	3.0	6.2
				Single					
Breeza	1.2	0.3	2.2	1.8	0.7	2.9	1.9	0.7	3.0
Wee Waa	2.4	0.6	4.0	3.9	2.6	5.3	4.0	2.7	5.3
Bellata	1.8	0.3	3.3	3.6	2.6	4.6	3.8	2.9	5.1
Moree	1.9	0.3	3.1	3.7	2.3	4.8	3.8	2.5	4.8
Croppa Creek	2.2	0.3	3.8	3.6	2.5	5.0	3.9	2.7	5.0
Goondiwindi	2.1	0.4	3.9	3.7	2.4	4.8	3.8	2.6	4.7
Dalby	3.5	1.7	4.9	4.2	3.0	5.5	4.3	3.0	5.7
Biloela	3.0	1.5	4.4	4.6	3.3	6.0	4.7	3.5	5.9
Emerald	3.0	1.0	4.4	4.2	2.7	5.4	4.4	2.9	5.3
				Double					
Breeza	0.7	0.0	1.3	1.4	0.2	2.6	1.4	0.2	2.6
Wee Waa	2.3	0.6	4.0	3.9	2.8	5.2	4.0	2.9	5.3
Bellata	2.1	0.3	4.0	3.7	2.5	4.9	3.9	2.9	5.0
Moree	1.8	0.2	3.2	3.5	2.4	4.7	3.8	2.7	4.8
Croppa Creek	2.0	0.2	3.5	4.0	2.6	5.7	4.2	3.0	5.8
Goondiwindi	2.1	0.4	3.7	3.7	2.5	4.7	3.8	2.6	4.9
Dalby	2.6	0.9	4.4	3.8	2.7	5.0	3.7	2.6	5.0
Biloela	3.4	2.1	5.0	4.7	3.4	6.0	4.7	3.4	5.9
Emerald	3.0	0.9	4.8	4.4	3.0	5.7	4.6	3.3	5.8

Summation - Row configuration, dryland cotton & RD&E

Each of the above studies show that the crossover point in terms of the yield potential of one configuration versus another will vary between seasons. Perhaps more importantly, production costs and discounts need to be taken into account before valid comparisons can be made (as demonstrated by Figure 5). The research and industry literature indicate that single skip row configurations (or similar wide row tactics) in most production areas probably represent a good balancing point between yield potential and profitability and that solid planted configurations should mainly be considered for areas that traditionally have the highest yield potential such as the inner Darling Downs. Beyond this, growers need to balance configuration decisions around equipment and what works well with the other cropping rotations that occur in the broader system.

Row spacing has been extensively examined by CSD and a number of other researchers over the last 20-30 years. The principles reported on here were identified in the mid-90s and have changed little since. Unless new cotton cultivars were to vary markedly (in terms of fibre quality parameters or growth habit), which might justify a re-examination of the trade-offs between yield, quality and gross margin, there would appear to be very few reasons to conduct any additional research on dryland cotton row spacing interactions.

Growers have a high level of interest and questions around the trade-offs for different cotton configurations, and the very human tendency to wonder about 'what-ifs', particularly if others use different approaches and obtain different results. Extension with a focus on validating previous research on these issues would be clearly beneficial as the impact of configurations can vary substantially between seasons even at the same location which often leads to grower confusion.

Cotton varieties

The limited choice of cotton varieties for dryland cotton production was raised by a number of workshop participants and indeed a review of the literature quickly demonstrates that prior to the end of the Bollgard 2 era there were many more varieties available to growers. The Australian dryland cotton production guide (CRDC 1997) provides varietal notes for nine dryland cotton varieties commonly grown at the time of publication. The most recent variety guidelines provided by Monsanto and CSD have five varieties with Bollgard 3 traits of which only three are recommended for dryland production (http://bollgard3.com.au/grower-resources/varieties/).

Compared to even 10 years ago, varietal choice has diminished. This reduction is arguably an inevitable outcome of pursuing ever-increasing yield potential combined with the range of other traits such as disease resistance or fibre quality characteristics. The result has tended to become self-perpetuating; growers vote with their feet each season and plant only what they consider to be the best variety (yield, disease rating, lint quality etc.). The Bollgard 2 era began with a range of varieties during the first three years (Sicot 43, 70, 71 & 80, Sicala 60, Siokra 24 & V18), but when the higher yield potential Sicot 74 and 75 were released, the growing of all but Sicot 71 dropped to minimal amounts. Another demonstration of how quickly varietal selections can change is how okra leaf varieties rapidly fell out of favour due to the superior yield potential of Sicot 71 and 74 in dryland trials combined with a higher incidence of pin trash contaminating lint from okra leaf varieties under certain circumstances.

Ironically therefore, the decline in varietal choice has been primarily due to the overwhelming success of more recent CSIRO-developed varieties and their exceptional performance in such a diverse range of circumstances.

Lint discounts for short staple were one of the key factors undermining the profitability of solid planted cotton as identified by Bange *et al.*, (2005). If the likelihood of lint discounts is significantly reduced with long staple varieties a greater proportion of dryland cotton crops may be able to be grown on narrower row spacings. This concept has been tried by some dryland growers utilising specialist extra long staple varieties with reasonable results on the Darling Downs (Marshall per com 2017) suggesting potential to be used as a strategy for increasing the success of solid planting which might manipulating yield potential, crop maturity, and provide greater crop competition with weeds.

Premium grade specialist long staple varieties like as the Bollgard 2 350B may provide an opportunity for dryland growers to manipulate how cotton could be grown in their system. Growers in short season regions (Liverpool Plains) or those wanting to manipulate crop maturity to avoid pupae busting could use narrower row spacings with a safety margin against short fibre length discounts by growing such varieties. In higher yielding areas suitable for solid planting, these varieties could provide yield rewards in good seasons and a buffer against short fibre discounts in seasons with limited rainfall. Other benefits that might be derived from narrower row spacing with long staple varieties may be a decrease in weed problems due to the extra competition provided by the cotton crop.

Growers were asked at the workshops to list the type of characteristics that they would select if they could design their own cultivar. Naturally growers wanted to retain all of the gains made with existing varieties so these characteristics would be in addition to what is currently available. Table 7 captures some of these thoughts and ideas.

Table 7. Theoretical characteristics that growers would like to add to an existing high yielding, high quality cultivar as a purpose bred dryland variety.

Trait	Reasons	System advantages
High seed vigour	Ability to emerge under difficult conditions (soil structure and cold)	Ability to plant dryland cotton in more places and under harsher circumstances
Better coleoptile strength	Ability to emerge from deeper depths at planting	Greater reliability for dryland cotton establishment when moisture seeking
Fixed determinacy	Variety that grows more like cereals or beans. Variety would fruit quickly, have a fixed number of branches, and stop	Quick crop finished in four months that has good yield potential for the time spent in the ground. An efficient user of resources (time and soil water). Could better compete with sorghum water usage.
Termination gene for cotton	The ability to switch the plant off with some sort of trigger spray or similar	Effective crop destruction

Varietal development is outside of the scope of this review but very clearly the development of new cultivars that have improved lint quality or drought tolerance could have future implications for how dryland cotton is grown, both as a crop and used as a rotation within the farming system.

Crop modelling and decision making

Many of the questions raised by growers in the workshops are inherently difficult to answer by conducting short to medium term experiments because the outcomes often depend on the interaction between seasonal and soil type factors over long periods of time. Modelling offers a way to test ideas and assumptions about the impacts of different tactics over the continuum of time. A very powerful demonstration of this was provided in the row spacing section of this review where Bange *et al.*, (2005) uses the Ozcot model to test whether soil moisture at planting affects the lint yield potential of cotton planted on differently spaced skip rows.

Agricultural modelling has evolved significantly over the last 20 years with advances in computing power. Agricultural systems models worldwide are increasingly being used to explore options and solutions within the domains of food security, climate change adaptation and mitigation, and carbon trading. Of particular note is APSIM (Agricultural Production Systems sIMulator), which has been developed in Australia and is increasingly being applied and adapted to seek answers to complex agricultural and systems problems (Holzworth *et al.*, 2014). APSIM has evolved into a framework containing a range of key cropping models such as OZCOT that can be used to explore changes in agricultural landscapes with capability ranging from simulation of gene expression through to simulating treatment structures over multi-field farms and beyond (Holzworth *et al.*, 2014).

Although programs such as APSIM have become more advanced and sophisticated, the use of modelling to address problems in the cotton industry seems to have decreased over the last 10 years. A review of project reports within CRDC's Inside Cotton uncovered a range of projects with specific objectives to use and test models such as OZCOT and APSIM to answer an assortment of cotton growth and development questions and conduct systems analysis. It would appear that the departure from the cotton industry of several key researchers who prominently led this work coincided with the closure of the second Cotton CRC. Beyond production-based modelling conducted by Bange and Braunack for recent editions of the Australian Cotton Production Manual, the occasional paper such as Bange *et al.* 2005, and the use of OZCOT for exploring production constraints in new regions of Northern Australia (Yeates pers com 2017) the use of models within the cotton industry appears to have waned significantly.

Modelling has the potential to provide insights into many dryland cotton RD&E issues. Nearly all of the topics examined in this review would benefit from a modelling component to provide a clearer idea of the likelihood of treatment outcomes over a continuum of seasons. For example modelling the impacts of different management approaches for pupae busting when combined with local validations would generally be the only way to resolve such a complex question where results are difficult to extrapolate from a single field trial due to seasonal and soil type variability.

Modelling is not a panacea for solving agricultural problems. However, when combined with structured research questions, experimentation and, most importantly, real life validation, it can be a very powerful tool for assessing treatment impacts. Conducting RD&E without complimentary modelling and validation on most of the topics reviewed here would simply create one-off district level trial results with limited ability to have impact over space and time.

An investment in modelling relevant to dryland cotton systems may be something that CRDC could consider with relevant stakeholders for the future.

Climate forecasting

Growers raised climate forecasting as a vital but frustrating tool for use in their businesses. There was general agreement that forecasting tools and weather guidance had improved significantly over the last decade. However, there was equal frustration with the perceived lack of reliability of medium term forecasts, particularly 3-5 month rainfall outlooks related to ENSO modelling. Growers found short term weather forecasts to be useful and relatively accurate. Pre-seasonal outlooks were considered to be still highly variable except where very strong La Niña or El Niño conditions were influencing model projections.

Grower understanding of weather forecasts would appear to be reasonable with most growers utilising a range of tools, predominately web-based. A comment made by some growers was that it would be good to see a range of models put thought a hind-casting assessment to identify which models had been the most accurate over time at predicting climate outlooks.

All growers agreed that anything that could be done to increase the reliability of existing forecasting services or develop new methods or techniques for better predicting temperatures and rainfall would be very beneficial to business decision-making and planning of short term operations.

General conclusions

Growing cotton as part of the dryland farming system

Given favourable seasonal conditions, dryland cotton can generate significant profits for growers compared to other determinant summer grain/pulse cropping options. Cotton's lucrative appeal is tempered by its high soil moisture requirements, trait licensing, RMP compliance costs and inability to provide ground cover post-crop. The frequency at which cotton might be sown within the overall crop sequence depends on a range of factors including but not limited to: soil moisture, capital investment, relative commodity prices, previous experience and attitudes towards risk. Like all crops, cotton offers both advantages and disadvantages for the farming system, many of which have been explored in this review.

Appealing agronomic features of cotton compared to other summer crop options include an indeterminate habit that enables increased crop yield potential in good seasons and a deep taproot system that can exploit moisture and nutrient reserves at depth in the soil profile. Roundup Ready Flex ™ offers the ability to control both broadleaf and grass weeds with over-the-top glyphosate applications, although this practice is both threatened by and a contributor to the problem of glyphosate resistant weeds in the farming system. The main downsides of growing cotton in rotation with grain crops is the minimum profile moisture required to enable planting (>50% PAWC) requiring a long fallow lead-in period together with the time required post-cotton to sufficiently recharge the profile to enable a following cover or grain crop to be successful. The latter is problematic for maintaining soil cover to prevent erosion and improve infiltration.

Will Bollgard 3 be a catalyst for industry expansion?

There is an expectation amongst part of the cotton industry that Bollgard 3 will be a catalyst for dryland industry expansion due to the more flexible planting window, smaller refuge and less arduous pupae busting tillage requirements of the RMP. However, as discussed in the report, likely benefits derived from these changes including increased planting opportunity (particularly for northern growers), improved productivity (reduced refuge area) and timelier, selective tillage won't necessarily result in an automatic wholescale expansion of dryland cotton acreage.

Growers reported an alternate range of factors that may influence the expansion of dryland cotton production. With the exception of the Liverpool Plains and to a lesser extent the region situated to the north-east of Moree, most growers perceived there to be limited potential for dryland cotton expansion in terms of untapped neighbouring districts or where grain growers in existing dryland cotton regions might opt to add cotton as a regular new crop rotation. Impediments to increased dryland cotton expansion were thought to include:

- Many growers being intimidated by the complexity of cotton compared to existing summer grains e.g. planting, utilising consultants, marketing, insect management, etc
- Perception of production risk associated with phenoxy herbicide drift. Many growers also perceive cotton as being incompatible with their own sorghum production for this reason
- Lack of suitable equipment (planters and pupae busting tillage equipment)
- Financial risks associated with significant outlays required for cotton, particularly if the crop fails
- Incompatibility of contract picking equipment (JD7760) with controlled traffic zero tillage systems
- Relative expense of dryland cotton production compared to irrigated cotton (percentage of input costs relative to yield potential)
- General lack of further acreage with suitable soils (production for many growers is already at a maximum)

- Lack of expertise/confidence with cotton production practices
- Perceived expense of genetic trait technology fees and insect management
- Perceived changes in summer rainfall patterns (becoming lower or infrequent) combined with hotter temperatures making summer dryland cropping generally questionable
- Cotton price relative to other crop commodities

Actions that address the impediments reported by growers above, as well as those throughout this review would perhaps do more to increase the area and/or success of dryland cotton grown. For example, if the CSIRO breeding program were able to develop an extra-long staple, high yielding, okra leaf (more drought tolerant) cotton variety, this may enable cotton to enter some of the drier transitional cropping areas such as the region between Chinchilla and Roma in Queensland that predominantly grows sorghum as a summer cropping option due to shallower soils and lower rainfall. Similarly, if the price differential of cotton relative to sorghum were to remain high, growers could be expected to increasingly shift away from sorghum in favour of cotton, with many growers indicating that the price differential is important part of their crop selection decisions.

Responses from the Liverpool Plains diverged from other regions because cotton is a relatively new and expanding dryland and irrigated cropping option. The shift of cotton into less traditional cooler season regions has been the cotton industry's biggest success story of the last decade. The performance of cotton in these regions has been excellent and the success of pioneering growers has in turn spurred other growers to test cotton production. The participation and enthusiasm expressed by growers for dryland cotton production at the Quirindi workshop was reflective of a young, vibrant and growing industry. Many of the issues raised and discussed were similar to those that have been encountered in other new regions such as Griffith and the Burdekin. Many of the questions raised by growers were of a more basic nature about getting the best from dryland cotton from both a production and systems perspective. There is a significant opportunity to assist the expansion of dryland cotton on the Liverpool Plains with a concerted D&E effort that supports new growers.

Research priorities and areas for investigation

Some of the challenges identified in this report apply not just to cotton but to the entire farming system. Issues associated with tillage, compaction, nutrition, weeds and crop sequencing have implications for the broader farming system and are not likely to be solved by cotton-centric RD&E and require a grains focus over extended periods (2-4 years). Consequently a valid approach would be to seek GRDC co-investment in addressing such issues.

Other issues such as crop establishment, crop destruction, varietal development, and row spacing are more specific to cotton production but still have potential to generate impacts elsewhere in the system. Interestingly very few growers raised specific in-crop cotton agronomic management issues for dryland cotton spanning the period between emergence and defoliation.

After consulting with dryland cotton growers from across northern NSW and southern Queensland and being made aware of research priorities identified in other forums, four recurring themes emerged at each meeting, indicating potential areas for RD&E investment. These were-

1. Seedling establishment reliability
2. Tactics to improve the transition from cotton back to grains and if changes to pupae busting assisted in this regard
3. Development of minimal tillage crop destruction tactics
4. Improved integrated management of summer weeds (Appendix 1).

A number of other issues were also raised but many of these were not repeated across the five workshop locations.

During this review, published literature, trial reports and industry literature have been examined to discern the extent of previous work that may have occurred in relation to the four primary topics above together with other topics that featured prominently within individual workshops (e.g. rotations and row configuration). In many instances, past research was found to have been done on topics related to these priorities and that many of the outcomes reported are highly applicable for the current dryland production system.

Potential gaps for research and development that have not been adequately addressed by previous research include:

- Determining the systems effects that might arise with changes to pupae busting tillage for the dryland farming system. Unknowns include methods that might be employed over time and resulting impact on soil, weed, cotton crop destruction and lead-out grain crop sequences.
- Investigation of crop destruction techniques (physical or chemical) that deliver timely, effective and, if required, AVPMA registration for crop destruction.
- Utilising modelling combined with structured research questions, experimentation and, most importantly, real life validation, as a tool for assessing and extrapolating treatment impacts. Conducting RD&E without complimentary modelling and validation would simply create one-off district level trial results (for which the examples are many) with limited ability to create lasting impacts across regions and seasons. Potential applications for modelling might include -
    - Use of OZCOT to determine the likely seasonal frequency that cotton crops would mature prior to a set defoliation date to avoid pupae busting tillage.
    - Use of APSIM to determine the contribution that seasonal, soil type and geographic variations might have on the measured impacts of tillage on lead-out crop success or the impact of strip tillage on resultant seed bed condition.
    - Use of APSIM in combination with cereal cultivar information to investigate the limits for late sowing of winter cereals for the purposes of generating stubble cover, grain, or both across regions.

- Ensure that weed management research is targeting species across the entire farming system and not just within particular commodities
- The potential opportunity for dryland cotton expansion with the development of longer staple length varieties allowing for greater flexibility with row spacing and crop timing with reduced risk of low rainfall season related lint quality discounts.
- Establishment of research forums once a year to promote and peer review current work areas (unlike conferences that tend to attract the presentation of completed work). Enhanced collaboration within agencies and across RDC's will result in broader research outcomes for the whole farming system, with outcomes more likely to be adopted.

Efforts in these areas would address most of the current questions from growers keen to achieve better integration of cotton and grain. Where appropriate, any R&D undertaken would need to have a regional focus to ensure grower engagement but should also aim to partner with the pulse and grains industry where applicable to ensure results are relevant and reliable.

Extension priorities and strategies

The experience of conducting both the grower workshops and this review has highlighted a seeming disjunction between the wide array of production-related questions raised by growers and the breadth of independently developed and well-researched information that could provide ready-made solutions. Consequently, it is reasonable to examine how effective the cotton industry's extension program have been in meeting the information needs of its dryland growers.

Rather than ascribing fault, it is important to try and identify the reasons for why many growers would seem to be unware of the sizable R&D efforts that have been made to develop solutions for a wide range of topics related to dryland cotton production over a 20-30 year period. This is intriguing given that concerted efforts have been made by many excellent extension people across a range of platforms and formats to inform dryland growers of production practice advice that address many of questions/topics that were raised (see Appendix 1).

Over this period, CSD in particular has produced a wide array of information products including an excellent dryland cotton guideline that covers many issues in an easy to read and information-rich format. The 2nd Australian Cotton CRC and CRDC also produced a series of dryland cotton production guidelines, the last of which was published in 2002. In the last 15 years, subsequent industry publications such as the annual Australian Cotton Production Guidelines have focussed predominantly on irrigated production, however, other CSD-generated extension materials that aim to provide a distillation of the latest thinking and research for dryland production have also been regularly updated and made available.

Given the potential to tackle many grower concerns with answers from existing information, the dryland industry would clearly benefit from a concerted extension program. A starting point would be identifying why the penetration of R&D outcomes would appear to be lower for dryland cotton compared to the irrigated sector. In the workshops, many growers expressed the view that a lot of research was not relevant to their needs due to it being conducted for the 'wrong purpose' or in the 'wrong place'. In particular, New South Wales growers expressed the view that there is little in common between production constraints in Queensland compared with NSW. Since a significant proportion of historical research has been conducted in Queensland, this maybe a barrier to adoption by growers. Similarly, growers saw little applicability for R&D information generated within the irrigated sector, even where there are issues in common with dryland cotton.

Regardless of whether these barriers are real or perceived, the grower views expressed both during the workshops and at the new Dryland Cotton Association meetings regarding RD&E need to be taken into account when contemplating how an effective extension strategy might be developed.

One approach might be to consider this challenge from the ground up. A range of factors to consider could include:

- What is the status quo?
- Who is out there providing information and for what purpose – commercial, grains, cotton, public, private etc.?
- What are the paradigms currently used by growers and their consultants for decision making?
- What are the preferred mechanisms for information delivery (written, audio, small groups etc)?
- What are the potential gains associated with solving particular problems?
- How do potential dryland growers see themselves (cotton, occasional cotton or opportunistic cotton growers) and how would this influence an extension strategy?
- Skill level of growers and whether information needs to be stratified for different target audiences as outlined in the previous point

An opportunity exists to target extension efforts against a number of issues identified by this review. Dedicated campaigns could be undertaken to ensure growers and consultants are made aware of existing knowledge (such as issues related to cotton seed bed preparation and subsequent establishment). However, regional paradigms, production constraints and goals would need to be considered when information is being extended.

Importantly an extension program should aim to provide growers with information and assistance in a way that engenders the development of critical thinking and problem solving skills. Providing facts will only take people so far; encouraging growers to use critical thinking techniques and to test the application of those facts either through action learning processes on their own farms or via shared demonstration sites is an approach that may provide longer lasting outcomes. The incremental and practical demonstration of facts and concepts in collaboration with grower groups over time can be a powerful way of encouraging practice change. Such an approach though is a more costly extension model requiring greater planning, direct engagement and an understanding of formal adult learning extension processes. A focus on avoiding the perception of individual benefit has encouraged modern extension approaches to be more generalised, and more reactive to the issue of the day, favouring shorter campaigns that relay large volumes of information to broad audiences.

A foundation step will be to consider a broad range of factors (e.g. demographics, seasonality, networks, social factors, consultants etc) in determining what an effective extension strategy might look like. If, for example, there is a strong perception that regional variability does not allow results to be transferred between districts, an extension strategy devoid of local demonstration/validation components or lacking local grower champions is unlikely to succeed.

One of our key conclusions from the grower workshops and subsequent literature review is that many of the issues that growers have raised as dryland cotton production impediments have existing solutions for which further research would add little new information. Therefore, extension has the potential to bring about real changes and may represent a significant value proposition as opposed to repeating old research in alternate areas. This is a topic that need to be considered by a number of stakeholders (extension specialists, dryland grower representatives, CRDC, CSD, researchers, and agronomists) to consider the development of an appropriate strategy for dryland cotton extension and which parts are done by different stakeholders.

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Review Appendix 1

Dryland Cotton Farming systems – Focus Group Notes

During the spring and summer of 2016/17, meetings took place at Quirindi, Goondiwindi, Dalby, Boggabri and Moree. These meetings were professionally facilitated by Sally Dickinson (Cotton Info) and the attendees were local dryland cotton growers as well as some advisors. Meetings went for around 3 hours and discussions focussed on aspects of their dryland crop production system. Specifically, the opportunities afforded by the revised RMP for Bollgard 3, components of their cropping program and subsequent strengths and weaknesses as well as threats and opportunities for cotton production in the region.

The following report summarises the key findings from each meeting.

The term 'farming system' can be defined many different ways. For this purpose, farming system refers to crop sequence and an understanding of what drives crop choices.

Table 1 Typical cropping sequences for each region

Location	Crop sequences
Quirindi	Across the district farming practices are predominantly opportunistic, due to high PAWC soils and a 60/40 split in winter-summer dominant rainfall patterns. A common sequence for those growing cotton includes: Ct – LF* – wheat – sorghum (*2) – wheat/barley (chickpea are opportunity) – LF – Ct *No opportunity to sow wheat because it is usually too late in the season for enough moisture. Soil is exposed in the LF after cotton, could plant sorghum in spring, BUT this is not optimal due to summer grass weed issues which is a driver for cotton adoption.
West of Gunnedah	No two sorghums in a row (insufficient PAW). If there is PAW more likely sorghum- mungs- sorgh (not Ct) Ct – LF – durum wheat (or canola then a durum wheat) – LF – Ct or Ct – LF – durum wheat (or canola then a durum wheat*) – LF – Sorgh – LF – wheat – LF - Ct *Drop 1 t/ha if you go from a canola – LF to summer crop due to low AMF. Double crop occurrence is 1 in 20 years. PAW is major component driving crop selection. Chickpeas are only? problematic due to virus, disease, asco, phytophora (bitten badly in 2010) Lack of stubble cover post cotton, un-resolved. Chickpeas are an option, but wheat and barley sprayed out is also option but Crown rot, fusarium, head blight etc carryover is an issue. Consider cropping frequency to make money, not so much the high value thirsty crops (such as cotton). GM for the average DC of 4-5 bales/ha across the region can be low particularly if lint quality discounts up to $80/bale are applied (short fibre and low micronaire). If you don't have sufficient moisture in the profile from Jan-March you will have severe yield and quality reduction in dryland cotton. Mungbeans seem to do better in the region but increase Root Lesion Nematode? and are susceptible to fusarium (which one?).
Boggabri/Mullaley	Hard setting red country Ct – Durum – Canola – Durum – Ct OR, Ct – Sorghum (1 or 2) – canola – Durum – Ct Grey Vertosol* Ct – durum – Ct (put 50N under durum..screenings??) Ct – barley (tends to be tougher requiring less PAW c/o wheat) - FB – Durum – Ct (Fabas are preferred as more robust and fix more N) Ct – Durum or short season wheat or chickpeas – LF – Ct (liquid and SOA applied 12 months out from planting Ct.) River country which is silty but can set hard, is farmed as per grey vertosols, however the country dries faster, has lower PAWC and produces lower crop yields. Starter used in all crops, and N applied only to cereals.

	Sorghum is not popular with limited local market opportunities and low yield potential. *summer cropping in the region seems to be undergoing a reduction in area, likely due to excessive transpiration and unreliability of summer rainfall. DC advertising is everywhere.
Goondiwindi	Wheat – chickpea – Wheat – Ct sorgh – sorgh – chicks/wheat The reason for doing either cotton or sorghum is profile moisture. (150mm cotton, 100mm sorghum). Cropping sequences are residual herbicide affected. If atrazine is present sorghum is sown, if turbine (Terbuthylazine) is present either sorghum or cotton is sown. Wheat – Chickpea – wheat – cotton – wheat/cover crop 2-3 winter crops in a row and 2 summer crops in a row gives you rotational benefits. Other summer options include mungbean and occasionally sesame.
Dalby	Systems are largely differentiated by soil type and PAW. Typical rotations for the three dominant soil types located on the Darling Downs are as follows: Brigalow soils (250 mm PAW) Cotton – Wheat grain/chickpeas – LF – Ct (if <FULL PAWC widen skip) OR Sorghum is planted after LF (selection will depend on grain price) Jimbour/Bongeen/Jondaryan soils (280-320 mm PAW) Ct – CC (millet, milky dough) – LF - Ct Ct – Wht – LF - Ct Ct – CC (wheat) – LF Sorgh (2) - Ct (if grass weeds, go back into Ct earlier). Flipping between Ct and Sorgh, depends on $, summer grass populations and the soil type for the particular field. Box soil Ct – LF – Sorgh (2) - Ct (Ct volunteer/ratoon management, build PAWC for Ct, and alleviates surface crusting in sodic areas) OR instead of 2 sorgh, plant mungs or back to cotton. ISSUE: Sorghum is a more difficult crop to control Ct volunteers if there are multiple emergence events. Ct – wheat (2) and/or chickpeas – LF - Ct (longer time to build PAWC) Ct – wheat/barley OR Millet (Sept/Oct) – Ct (rainfall driven) Winter only crops (sandy ridges, high Chlorides)
Moree	East of the Newell Hiway Ct – Chk (opport) – Wht – Ct (or maize) OR Ct – LF – Wht – LF - Ct Ct – Chk/ barley (opport) – Wht – Chk – Wht –Ct Ct – Chk – Wht – Barley – Ct Commodity prices are driver for crop sequencing choices. High Chk prices have resulted in less LF. If Ct is missed Chk are sown. Chks provide a reasonably weed free lead into Ct. West of Newell Hiway Ct – LF - Chk – Wht* – Ct Ct – Wht – Chk – Wht – Ct (rotation extended to 7 years if Fabas & wht added) Ct – Chk – Wht – Barley – Ct Barley is better stubble than wheat *Despite being harvested, in most cases wheat is primarily grown for the advantage of stubble production as opposed to the value of grain. West of the Newell it is too hot for sorghum with it often cooking in the boot and failing to make a decent head. Millet cover crops have been used and are successful in maximising moisture interception and retention (sometimes too well). However the downsides include hosting crown rot, are difficult to achieve establishment, and the timing for termination with herbicide is difficult (too early and no stubble too late and it makes seed). This has resulted in minimal millet cover cropping adoption. A summer legume that is easy to establish, with reasonable stubble strength would be an ideal system addition – New Pigeon Peas variety?.

Implications of the Bollgard 3 RMP for Cotton Farming Systems

The recent changes made to the RMP for Bollgard 3, including modified pupae busting requirements, reduction in refuge area percentages and open planting windows were discussed in relation to affecting aspects of the production system.

Table 2 details the perceived implications of pupae busting (PB) and extended planting windows on farming operations and cropping programs. It was agreed that the decrease in area planted to refuge as a result of cotton will not alter the farming system but generally increase cotton profitability.

Table 2 Implications of the revised RMP for Bollgard 3

	Pupae busting	
	Positive	Negative
Quirindi	For the southern cooler end of valley, possible defoliation <31st March – means no till, which leads to improved soil structure, potential double crop opportunity and rapid stubble cover, greater moisture infiltration and retention into profile and savings on fuel/time etc. These advantages will need to be contrasted with any losses associated with tactics that may prematurely induce cut out to ensure defoliation timing by March 31st. In warmer areas there is potential to use narrower row spacing to manage cut out by 31st March to avoid doing any PB. Potential trade-offs for lint quality is unknown. Reduction in PB means reduced moisture loss through evaporation, and maintains some initial ground cover which is crucial for erosion risk on sloping country. PB can be an opportunity to conduct strategic tillage to address longer term accumulated compaction and remove volunteers. It is also an opportunity to deep rip and fertilise.	PB incorporates resistant weed seeds No short season Ct variety available to capitalise on PB changes PB is hard on gear/equipment PB causes cover reduction and reduces potential water infiltration and retention. It makes the next crop more difficult to establish. The best method for achieving effective crop destruction without pupae busting is unknown and largely untested. Various ideas from puller mulching (excel eliminator) through to stump spraying and mulching will be explored by different growers. All agreed that achieving effective crop destruction would be important.
Boggabri/Mullaley	PB is good for controlling weeds (particularly large weeds). PB is a valuable asset, cultivations offers the opportunity to control Feather Top Rhodes and barnyard grasses, levelling out country, and incorporation of stratified nutrients. It also enables the opportunity to add P and K at depth. (surface cover has been fully degraded by the time pupae busting occurs anyway) Effectiveness of methods: A 50% overlap tyne to 10cm works the plant line best. Root cutting also works well but set up is important. Using spray bars to dribble chemical post mulching not overly successful. Root cutting is expensive for a Dryland grower Puller mulcher works well in dry, but stalks are slippery when wet. Efficacy is very dependent on conditions. A ground driven self-propelled machine for crop destruction/PB would be ideal.	PB was bad with beds Some years PB coincides with a planting opportunity for a winter crop. Similarly, if you have a wet cotton harvest, and wish to plant a cereal, PB is detrimental. Nb. Cotton dries out the whole profile, all the way down, not PB will only provide a planting opportunity and does not guarantee a viable crop (WRT refuge plantings…pigeon pea varieties for dryland are exceptionally hard to get out of the ground. Others are putting conventional cotton in amongst Bollgard 3 plantings).

	Ratoon management is a real issue so PB will continue. PB can be a localised benefit to remove cotton. Managing cotton for cut out so PB doesn't have to take place will be tricky.	
Goondiwindi	PB is an opportunity to put more immobile nutrients into the profile. Most DC is preceded by long fallow, which decreases VAM, hence P response by cotton (25kg starter with seed). Time of sowing will dictate defoliation timing and whether or not PB is conducted. Most growers will be unlikely to take advantage of no pupae busting as defoliation in most seasons will be commenced after 31st March. Crop destruction - Steel works much better than herbicide options. Opportunity to deep rip and renovate tramlines	In a no till situation – good litter after cotton is mulched and left on surface. Once you PB you lose it. Tillage (PB) reduces soil porosity, affecting subsequent establishment of crops. If you are pupae busting and rip cotton out, it is very difficult to establish a following cereal crop, leaving the soil potentially exposed over the following summer. To remove the stub cotton you could follow up with a monocot cover crop (competition reduces cotton growth) and implement targeted spraying to control regrowth. Very expensive (strip till and rip) added to mulching and slashing within one month of harvest. Without pupae busting getting the tap root destroyed will be challenging.
Dalby	Bollgard 3 gives you the opportunity to cultivate or not cultivate, however rather than time defoliation for PB rules, timing is dependent on the season and the crop potential. PB busting kills cotton better than any chemical options around. There is really no alternative to steel for effective crop destruction. Depending on soil type some growers will PB then chisel plough and kelly disc. The cultivation controls perennial weeds (fleabane), releases organic N, repairs tramlines and levels surface soil maximising water capture and minimising erosion. Other growers, don't cultivate after PB preferring a lumpy surface to capture rainfall. PB provides an opportunity for incorporation of inorganic nutrient, bio solids and manures. PB ensures crop destruction which is important for control of cotton bunchy top disease and secondary pests.	By not PB there is a potential threat to the RMP, with cotton bushes in Spring providing a green bridge for both pests and disease. Without PB the weed spectrum is likely to alter.
Moree	Not PB east of the Newell means greater opportunity for double cropping., BUT 8 out of 10 years won't get a double crop anyway. Opportunity to remediate compacted soil and but it is critical that soil conditions are right for a successful operation. Those not PB will periodically treat the stump with herbicides (weedit optical sprayer), killing ratoon cotton over time. Chks following cotton allow the use of Balance which helps kill ratoon and volunteer cotton. Need more pupae busting research that contexts how Helicoverpa are cycling in the farming system now as opposed to 20 years ago. Survival is less with BG3 so therefore it is an expensive exercise to target minimal escapes. The data upon which current recommendations are based could be dated. There is a lack of clarity around the quality of pupae busting operations e.g. different people	The cost of the operation and loss of any remaining cover.

	get ticked off for different levels of soil disturbance (harrow to deep ripping). Similarly, many growers believe refuges are not managed properly. The defoliation date of 31 March is too early.	
	Extended cotton planting windows	
	Positive	Negative
Quirindi	With a climatically defined narrow planting window (2-4 weeks during October) it was agreed that the planting window changes were of little benefit to local growers.	
Boggabri/Mullaley	Mid November is considered typical but growers will plant into early December to miss January heat. However there are winter crop trade-offs with late cotton planting. The driver for planting time is dependent on whether or not cotton is the pillar crop for the farming system. They would rather have low yielding Ct followed by low yielding cereal, c/o with high yielding Ct. Availability of moisture is a key driver for when planting is done. Note: conventional cotton is used for refugees as pigeon pea has unreliable establishment.	Pushing planting date later is always risky as it is a challenge as to whether or not a wet autumn which would affect picking can be predicted. However, picking in the colder weather results in better lint quality. It seems that earlier finishes over the last 5 years have coincided with rain events that have given rise to greater lint discounts. It would seem that fungal boll rot and tight lock pathogens prosper better under the warm and humid conditions when it rains in Feb/March.
Goondiwindi	Having additional time in November will be a big thing around Goondi region as it is a juggling act between planting cotton/grain harvesting/ sowing grain/harvest cotton. Bollgard 3 has extended the planting opportunity by about two weeks. Some growers will use multiple planting opportunities (end Sep + end November) to stagger risk (labour, season etc) and debt structure. Beyond this climate constraints limit planting eg soil temperature or end of season constraints. Rule of thumb: later you plant the closer you can put the rows.	Residual herbicides can be a limitation if planting earlier. December plant is considered risky as yield and harvest become very dependent on having favourable autumn conditions)
Dalby	More cotton could be planted however 95% of cotton is sown within the original planting window (mid to late October). Whilst a December plant is not considered ideal, an extended window offers the opportunity to do so particularly in years that have a drier than average spring. However some growers will substitute sorghum for cotton if they are faced with a December plant, due to limited cotton yield potential.	
Moree	A wider planting window provides more opportunity to realise a planting opportunity in paddocks that have been prepared for cotton with a long fallow. A later plant is useful for those paddocks coming out of chickpeas and might be double cropped. Planting earlier in the window may increase double crop opportunity post cotton (particularly east of Newell).	

	There is a sweet spot around 15th November, however further east you can plant early October as it isn't as hot.	

Cotton grown in rotation with grain crops offers both advantages and challenges to production systems. What works well from a systems perspective in each region was discussed and is documented in *Table 3*, whilst the challenges associate with current systems is documented in *Table 4*.

Table 3 Strengths of the farming system employed in a region.

Location	Positive aspects of the farming system
Quirindi	The current production system offers opportunity for diverse crop options (including cotton in the mix) which spread risk and cash flow opportunities, rotates herbicide chemistry, reduces disease incidence, and allows growers flexibility to manage commodity prices, and better utilise rainfall. Cotton sown into wheat stubble reduces seedling wind blasting. Cotton market has different global influences compared to grain markets and therefore offers diversity. Roundup Ready Flex cotton allows in-crop broadleaf and grass weed control (easy, cheap and effective). Particularly important from a summer grass perspective (Barnyard, Johnsons and sorghum off types – shatter cane). Sorghum does not offer effective control options for controlling summer grasses, and the use of residual type herbicides are risky in an opportunistic cropping area. Region is virtually 100% zero till. Cotton is an efficient soil profile forager for nutrients requiring less N than sorghum. Tactic is therefore to well fertilise the crop preceding cotton. Tap rooted crops like cotton have increased drought resilience. Cotton row spacing can be adjusted to reflect moisture for the time of sowing ie. can be sown on wider rows if the profile is drier, or close together if a late plant (Cotton is typically sown on full moisture typically Oct plant – single skip; Nov/Dec solid plant).
Boggabri - Mullaley	Gross margins of their current system are working, due to the crop diversity. Cropping diversity offers better weed (monocot and dicot) control through rotation of chemistry, varied crop root activity, exchange and continuity of beneficial insects between winter and summer crops. Cotton is often not the most profitable crop (depends on lint quality discounts) when farms are dryland cropping only, but it fits within the system and there aren't too many good summer crop alternatives. For those with irrigated cotton, there are scales of efficiency by also growing dryland cotton. Cotton into long fallow into durum wheat in long fallow Cotton provides the most consistent yields. MAP and N applied to what crop (I thought cereals???) Provides residual nutrition Liquid fertiliser at planting allows rates to be better matched to PAW at sowing. There are a few logistical issues associated with this approach that need to be overcome (handling and mechanisation). Round bale pickers are tremendous c/o modules. Very labour efficient. Cotton tap root tends to give it more drought tolerance c/o other summer alternatives. Cotton is a good forager for residual N in the profile, particularly where there may be accumulated bands at depth. Inter-row cultivation on chocolate vertosols prevents evaporation from deeper in the soil profile. There is a trade off with this though as it can reduce in crop infiltration from storm rainfall. Great forward selling and marketing opportunities with cotton. Having Ct in the rotation reduces Fusarium *sp.* Inoculum levels (corn and sorghum are hosts) Ct will perform better on salty country compared to other summer crop options. So in cases where sodicity at depth is an issue, cotton is an ideal option. Having cotton in the system provides diversity of beneficial insects, and pests such as less midge and Helicoverpa in sorghum Having contractors look after cotton reduces year round workload. By hiring a picker you are also hiring labour.
Goondiwindi	Crop rotations are reflective of PAWC/soil type and there are different PAWC trigger points for various crops (ie. ¾ PAWC plant sorghum, 100% PAWC plant cotton). Stubble - aim for >30% cover, don't grow consecutive low residue crops as they decrease fallow efficiency. - helps break down residual herbicide, and may allow additional planting opportunities

Location	Positive aspects of the farming system
	- From a cotton perspective, getting a planting rain of >30mm is a 50% chance from October – November. Stubble is crucial to good fallow efficiency and summer crop success. From a systems efficiency perspective, a LF with good stubble means fallow efficiency increases producing high yield and returns, however water use efficiency across the system decreases. Set rotation is stable, 3 - 5 year rotation (reliable, repeatable, economies of scale, handle agronomy issues better). There is flexibility with summer crops (sorghum, cotton, mungbeans and sesame). Two winters or two summer crops consecutively, gives better weed* and disease benefit compared to one only. *Crop rotation allows IWM (row spacing, competitive crops, strategic tillage) Cotton is a good forager for nutrient (N bulges), so preceding crops (wheat) are well fertilised with P and N. Cotton tolerates local salinity better than other crops. The rotation spreads the climatic risk, workload/labour/equipment and cashflow.
Dalby	After cotton crops, millet can be sown as a cover crop. Up to milky dough spring sown millet uses approximately 30cm of moisture from the profile. The following cotton is completely reliant on moisture stored by the sprayed out millet crop. Growers with grain crops in their system, dry sow a winter cereal crop after cotton and take it through to grain. The cereal produces strong stubble and causes the profile to crack, allowing the profile to fill from the bottom up. For these growers a cereal following cotton where possible was preferred to a spring sown millet. Chickpea following cotton does not provide adequate stubble to capture and retain moisture, so often a millet or cereal (wheat or sorghum) will need to be sown before returning to cotton. Cotton after LF (following a winter cereal) is about ¾ to a bale better on average compared to a fallow following a summer crop. Many growers are more comfortable (less chance of crop failure) growing grain crops hence they feature frequently in systems. Weed control with RR flex and then fallow is helpful for weed management (Broadleaf and grasses). A urocloa species of grass is particularly problematic. Grain crops in systems allow for herbicide rotation minimising the risk of herbicide resistance emerging in weed populations. Sorghum crops are often better after cotton – possibly due to short term benefits of tillage and mixing of layered nutrients (PB). Very low disease (foliar and root) pressure with system on the downs. Cotton in the system controls *P. thornei* and sorghum off types (shatter cane). Fertiliser for cotton is drilled in June/July prior to that summer planting. Generally, growers don't apply fertiliser for cotton in the previous crop. Stubble Cover: Reduces heat on the ground reducing evaporation. Reduces erosion potential from summer storms. Infiltration has to occur where it falls (want rapid infiltration). Can't grow crops on in-crop rainfall, need stored moisture. Increased Fallow Use efficiency (different crops vary) Once water begins to move it is of no use to you. Need to avoid sealing to prevent water running. Can do this by using stubble or roughing up with cultivation. However, cultivation does not cause cracks like a crop does, plus it destroys porosity and root channels. Evenness of profile moisture depends on good stubble cover Root channels from stubble are important for infiltration Prevents wind burn and sand blasting of seedlings The more stubble the better – can't have too much mulch Cover cropping contributes to the labile carbon pool and doesn't remove nutrient from the system. Organic matter improves texture, stores nutrient, improves moisture holding capacity, provides food for microbes.
Moree	Majority of the costs associated with DC is at the end of the season (c/o with grain crops where the majority of costs are upfront), which coincides with receiving crop income. DC can have a high gross margin compared with other summer crop options. Compared with determinant summer crop species, Ct has greater yield potential, being able to switch between vegetative and reproductive phases in response to seasonal conditions. Cotton (combined with a LF) is the most reliable summer crop option which addresses weeds (in the fallow - Black oats, phalaris and ryegrass) and disease (Yellow Leaf spot, Rust and crown rot) constraints. Cultivation out of cotton removes older weeds such as fleabane and feather top rhodes grass. Controlling grasses in sorghum and

Location	Positive aspects of the farming system
	maize (grown in the east) that host crown rot can be challenging. Canola has been tried as a disease break but high CR infestations post canola, suggest more than one year break is required. Generally two winter crops in a row is the most successful approach for managing weeds (switching between summer and winter crops each season does not provide a large enough break). Ct followed by double crop chickpeas also works very well but is lean for stubble cover. Post chickpeas with low residue there is an opportunity for cultivation to clean up winter weeds In terms of controlling weeds Need two winters to control weeds Camera spraying /weedit is useful but you don't save money on chemical and they work better on level country. Cameras do miss bits, but the strength of this technology is improving. Being able to target survivors that might be resistant weeds is very useful. Would be good if memory sensors can be installed so that repeat survivors or problem areas are identified. These sprayers can also be useful for chasing volunteer cotton. Working is preferable to using 2-4-D. The farming system generally aims to ensure a cropping frequency that maintains ground cover (except post cotton, particularly with PB). The root system of cotton has advantages over cereal crop options. It handles sodicity, cracks open the profile and forages for nutrient (esp. N) and water from deeper layers in the profile. Endpoint royalty is advantageous in that you only pay if you pick however the costing of it is still very expensive. Having DC as part of a system where irrigated cotton is grown increases farm efficiency. The two activities are complimentary (timing of operations vary) and allow better capital equipment utilisation. Cotton picking with contractors is advantageous as growers are able to get on with other jobs. The crop sequence maximises moisture accumulation. Planting crops less frequently to accumulate soil water often results in higher income compared with growing crops on low moisture.

Table 4 Disadvantages and issues imposed by the production system

Location	Challenges imposed by the farming system
Quirindi	The lead time into and out of cotton is problematic. After cotton, country is exposed - without cover due to pupae busting leading to decreased fallow efficiency (around 25%) thus increasing the time to get back into grain rotation crops. Cotton doesn't allow a quick return to grain opportunity cropping which would have many benefits. In a reasonably new area, limited contractors and significant investment for new machinery is required to handle cotton. Plus cotton pickers do not align with long standing controlled traffic tram lines leading to compaction across the paddock. The disruption to fields can be severe particularly in some instances where tramlines have been in place for over 15 years. Disruption occurs from pickers and then pupae busting. Establishment issues, cold soil temps at planting. Ironically this can be exacerbated by stubble cover. Cotton is considered difficult to grow within the tight climatic window, as it is sown in colder conditions so that it finishes at a suitable time to avoid potentially wetter conditions during Autumn interfering with picking. Early insect pressure in cotton as planting coincides with maturity of winter crops and a migration of pests out of these fields eg. thrips out of cereals and rutherglen bugs out of canola. There is a lack of registered insecticides that provide efficacious control of mass-immigrating rutherglen bugs. Using spraying equipment across a range of crops, increases boom contamination risks for cotton eg. 2,4-D. The risk of drift is also significant as cotton is still relatively new in the district and seen by some to be a disrupter to what have been acceptable practices for phenoxy products in summer grains. The uptake of cotton has faced district resistance from some for this reason. Weed resistance – planting 60" doesn't provide good canopy cover to shade out hard to kill weeds. Cotton takes a long time in the ground compared with other typical summer grains (sorghum, mungbeans) and also has a long lead time pre and post crop. Changes to pupae busting rules may not be of any benefit if you need to use deep tillage to ameliorate the compaction from 7760 pickers.
Boggabri - Mullaley	Cotton season length. Using varieties suitable for irrigation with a long growing season. Pix strategies for dryland are not well understood. They can be a weakness or a strength depending on season. Would like a good short season variety. Fibre quality. Normally it is micronaire and length that is problematic, however last year it was strength and colour. The discounts applied are hefty for a dryland grower.

Location	Challenges imposed by the farming system
	The high water use of cotton means there is a long recharge period post crop (refilling and no cover). BUT a strength is it can be more drought tolerant c/o with other summer crops. In terms of water use wheat following sorghum yields ½ t/ha more than wheat following cotton, in a water limited area, not disease limited (ie if disease limited, wheat following cotton will be better than that following sorghum). Row spacing conundrum for the local area. With 3 m controlled traffic what does better; cotton at 5 plants/m @ 60" or 7-8 plants/m @ 70". Again this is season and soil type affected. Hard to control weeds are emerging in the system e.g. windmill grass and fleabane. The reliance on glyphosate in the cotton crop is not enough to control them, so weed control is slipping. Weed control in winter crop (tordon etc) is perhaps better than herbicide control options in cotton. Sow thistle resistance is a big issue in cotton and mungs (not so bad in sorghum and corn). Controlling in the fallow without reliance on glyphosate is hard without using residuals. Cotton does not provide good weed control for roundup ready or group A (check) resistant weeds (already on the plains). There are however other options, including shielded boom, inter-row spraying and cultivation. Bollgard 3 licensing for Dryland Cotton. It is too high. Seed quality. Consistency of getting good establishment. Also consistency between seasons. This year quality was better but the result was too many plants per metre row as compensatory planting rate was not necessary. This is difficult to plan for if it keeps changing. Machinery logistics. Early insect pressure but this can vary depending on winter seasonal conditions and summer planting opportunity. Ratoon cotton in summer fallows Getting a planting opportunity to get good establishment of cotton Traffic over the paddock. Not so bad with 9m but 12 m is problematic. Across the system, there are limited fallow options to avoid the 'drift' onto cotton. 2 4_D damage in cotton is not yet sorted. There is definitely awareness of impact of 2 4-D to cotton but growers in the district are not sure why it is drifting. There is likely to be more to this issue than just nozzle selection and droplet drift.
Goondiwindi	Prolonging the retention of moisture in the top 5cm is through cover which is critical as it allows sowing flexibility and timely establishment. Everything that occurs needs to set you up for a cotton planting opportunity. By the time you get to a planting opportunity, you have made significant investment, herbicide $$ spent across a considerable area over an extended period. Unreliability of planting moisture for cotton. If you have planting moisture it provides you with emergence, which increases the probability of a high yielding crop, and minimises seedling issues. Cotton doesn't emerge well from depth, surface crusting, low temperature, or waterlogging. <u>Once you get cotton established you will break even at the minimum.</u> Transitioning from cotton crops back to grain crops is challenging – issues are dry profile to depth and disturbance from pupae busting. Easier following grain crops. Post-harvest management of fields after cotton is a significant challenge. Controlling cotton volunteers in the following summer grain crop is difficult with summer crops often 'hiding' the cotton volunteers. There are too many missed cotton planting opportunities due to the constraint of not having surface moisture to establish a crop in a given window. This creates a secondary problem in that many fields run with high PAWC for extended periods which can lead to salinity issues – conundrum is profile moisture vs surface moisture. There is a strong perception that only a low proportion of rainfall (25%) is being turned into crop due to inadequate sowing opportunities. Window flexibility with cotton will help with this although overall season length constraints apply. Weed management for summer grasses (Feather top Rhodes and barnyard) is becoming more problematic particularly with sorghum in the system. Resistance to glyphosate is potentially a huge sleeper issue. Cotton picking – there are a range of issues around picking stemming from compaction and CTF incompatibility, costs and labour availability. Logistics and timing - Overlap between sowing cotton and winter crop harvest, then harvest cotton when you are planting winter crop. Plus there is no time for leisure. Low residue crops in the system (cotton and chickpea) means low stubble cover and low fallow efficiency.

Location	Challenges imposed by the farming system
	Weather forecasting is not reliable for a crop like cotton Hormone drift management and contamination challenges – specific to cotton.
Dalby	Summer weeds particularly feather topped Rhodes grass are increasingly difficult to control particularly due to tolerance to glyphosate. There is also an overreliance on glyphosate potentially reducing its longevity in the system as an effective knockdown. Rain forecasting reliability is considered to be very poor regardless of the source. Despite planting into good stubble, getting cotton established is difficult. Conflict between moisture seeking during planting and planting the seed too deep. It could be that the focus of breeding programs has been on yield at the cost of seedling vigour. Spray drift killing cotton – it is a social issue Intermittent pest pressures – particularly around summer crop establishment pests such as earwigs and wireworm. Scarabs have also been a problem in the grains part of the system in some areas. Forecasting likely insect pressure would assist getting prepared. Cotton is an expensive and difficult plant to kill with herbicides. Controlling ratoons and volunteers in fallows represents a significant cost. There is a threat of new growers not using best practices to control cotton during this time. Availability of cotton equipment at the right time, cost of contractor and how the gear matches up with grain crop row spacing in the system. The picking operation causes by far the most soil compaction, however the new stripper (just released) may reduce the extent of compaction as it weighs less. Millet establishment as a cover crop is challenging, particularly on box country.
Moree	In the lead out after cotton and chickpeas there is no cover. This can be a problem in sloping country (mainly east of Newell) leaving it prone to erosion. Cotton varieties which have high turnout have no coleoptile strength to push Through from deeper planting thus resulting in poor plant establishment. 2,4D drift is a major issue across the district due to ignorance of some users, cultural dynamics and the ability to control drift. Resistance to Glyphosate is a challenge. Tactics such as tillage and other herbicides are buying time but could be creating new problems down the track or just delaying the inevitable. Cotton itself is becoming a weed. Cotton requires specific equipment (or you use contractors) that can't be offset by growing other crops. Similarly with controlled traffic there are +ve/-ves with configurations between crop types. The associated tradeoffs with 1. early planting Cotton and the ability to double crop afterwards, and 2. Gearing the crop sequence for cotton as a pillar crop or using it opportunistically. The opportunity cost associated with lead in and out times around growing cotton to accumulate moisture should be quantified. Some growers have moved away from cotton as the pillar crop due to gross margin of other crops catching up, others move in and out of cotton when the price is right. No enough local information on row spacing impact on discounts and yield in the local region. Managing nutrition across the system has traditionally been easy. Growers are beginning to get responses to N in cotton which means the previous crop (mainly wheat) will need to be well fertilised to preserve stubble leading into cotton which may or may not work in its favour (blow the crop up and have N tied up in stubble). In crop application of N is considered risky from the perspective of losses and getting it into the root zone. P&D sheet for cotton is a problem. If you price cotton ahead of picking you are at the mercy of the discounts rather than selling bales after classing where you might be able to find a better market. Micronaire and Staple length are real issues due to the seasonal conditions in which it is grown. Cotton operations can often clash with winter crop operations (machinery, labour, management etc).

Table 5 Emerging issues, limits to expansion of the industry or problems constraining Dryland Cotton in the farming system?

Location	Issues constraining DC in the farming system
Quirindi	Neighbours to cotton farmers perceive they need to 'modify' their sequences because of 2,4-D drift. In a short fallow, 2,4-D gives good efficacy, compared with other more expensive chemicals, where a double knock is required therefore it remains a popular choice. However, the chemical is volatile and cotton is extremely susceptible. In many cases 2,4D is not used correctly, due to lack of knowledge – lack of chemical awareness and impact. Hormone damage in cotton has significantly reduced yield for some new growers and the risk of damage prevents growers trying DC.

Location	Issues constraining DC in the farming system
	In a system that is largely characterised by being no till with an opportunistic cropping program, in crop herbicide selections are critically important for system flexibility and continuity. If weeds become resistant to roundup (from over use in cotton), this will limit its use in fallow. Whilst there are other double knock opportunities in other crops but again these are more expensive. Growing a new crop for the first time is always daunting and cotton requires significant investment in capital and agronomic planning before planting and after harvest. Cotton will disappear from the Liverpool plains farming system if; the price falls below $350 /bale Roundup resistance occurs in weeds the exposure to one crop (risky at that) is considered too great year round workload becomes too great picker availability compromises realising yield potential (on top of the already short daily windows to actually pick) ratoon cotton cannot be managed effectively pupae busting gear is not available suitable dryland varieties that alleviate establishment issues aren't developed planting opportunities become less frequent due to climate constraints Period between Jan – Feb has lower rainfall reliability which can coincide with peak boll filling for cotton affecting yield and/or quality. Soil Temperatures are often too low at the time when sowing needs to occur (October).
Boggabri - Mullaley	Growers are constrained by the quantity of moisture available in the profile. It fits well after durum wheat as the stubble provides good moisture interception and retention. Similarly farm size and the current rotation prohibits an expansion in the dryland cotton area sown. Can't grow cotton on sloping country as it is a high erosion risk post cotton picking. Machinery and contractor limitations. Scale of production is really important for profitability. Perception of risk. Including the cost outlay required to grow cotton and the agronomy required (requiring a high degree of precision). Also, the vulnerability of having to use contractors may be viewed by some as too high risk. Cotton will disappear from the system if price is below $450/bale. Once sorghum gets over $220/t with average yields 5-6 t/ha the GM is ahead of cotton. Getting labour over Christmas is tough. Many forced to use a plane for spraying operations.
Goondiwindi	Growing dryland cotton may become cost prohibitive if <$300 bale. Dryland costs including Monsanto levy ($50/bale or $350/ha), picker cost ($290/ha (irrig) compared with $230/ha (dryland)), and the cost of compaction from pickers not on tramlines. Overcoming establishment issues including; - Inappropriate dryland varieties - Planter technology. This is an area of difficulty for many growers. Many growers make do with what is on hand as investing in purpose built equipment that might alleviate problems during certain conditions is cost prohibitive. An investment in this space would be able to be better justified if growers had greater confidence in knowing which setups are likely to succeed under marginal conditions. This is a bit of a "black box" set of issues for people. Holding moisture to the surface for longer. This is a significant issue for the Goondiwindi region. Due to soil types and hot days the surface can dry out rapidly even though PAWC is still good. This combined with low vigour of new varieties greatly limits moisture seeking cotton seed when planting thus limiting the overall planting opportunity to particular soil types or smaller areas. Dryland cotton is a risky crop to forward sell. Industry would benefit from better marketing arrangements for DC that balance risk vs rewards such as pool arrangements. Cotton is a low residue crop which predispose land to erosion decreasing farm fertility. Transitioning to a high stubble crop is not always possibly particularly after pupae busting. There are not enough strippers in the country. Stripping capacity would be of significant benefit to dryland growers.

Location	Issues constraining DC in the farming system
Dalby	Expansion of the cotton area is likely constrained by capital and infrastructure (set up for grain), suitable land area, financial backing and a reluctance by some growers to use contractors. Also many growers won't grow cotton as they have certain beliefs, have had bad experiences or are die hard zero till. Prior planning is critical (stubble, fallow management etc) to growing cotton. It isn't an opportunity crop. Some growers often fail with cotton when they don't 'fit' cotton into their system. It requires significant paddock preparation on top of a reasonably fertile, deep profile that can hold upwards of 150mm PAWC. Cotton benefits from grain farmers in the Darling Downs region as they create important diversity. However this does present some issues with herbicide drift. Managing chemical options (cheap options) v's managing risk to neighbours growing cotton. 2,4D issues are a big concern. New grower's compliance to the RMP. No audit of cleaning up ratoon cotton. Also there is a risk that good IPM practices are being forgotten by newer growers and generational shifts. Compaction is the sleeper issue for DC and system viability going forward into the future. The issues around picking are significant and with much of the industry reliant on contractors it is impossible to tramline pickers.
Moree	Rotations and the farming system that already exists is a product of the soil types and rainfall so DC is already at equilibrium Limited planting opportunities for cotton and having soil moisture (for planting) available at the right time, although the extended window goes someway to reducing this constraint. The issue can be exacerbated by limited capacity to plant e.g. 5-7 day window after rainfall, where there is appropriate surface soil moisture. This can be a constraint for planting larger areas. Whilst the risk and occurrence of hormone damage to cotton is real for many existing growers, this risk as perceived by non-cotton growers is a big impediment to trying DC. It is a risk that may be above the level they are prepared to take. There is significant expenditure and risk associated with having a LF lead in to a DC crop that may not be able to be sown when the time comes. The reliability of getting DC crop sown needs to be weighed up with opportunity costs of the preceding fallow. Cotton doesn't have a fit on all soil types and topography. Crops such as maize and sorghum are important crops for sloping country. Similarly, where set rotations exist the scale of the farm often dictates when cotton can be grown again. Livestock in the farming system can be a real impediment to having DC as crop residues can't be grazed and spraying is a perceived risk. The gross margins in DC are not as good as they were. Commodity price is becoming a bigger driver of cropping choices, with cotton not stacking up against grains and pulses, as well as it used to, especially considering discounts. Also, unlike some grains and pulses, DC is difficult to niche market. Variable cost of contract picking, in big years you pay a lot in quiet years it is cheap. DC growers generally click with the big years so picking can be expensive e.g. Supply vs Demand Perception issue with cotton e.g. spraying, transgenics, water use.

Table 6 Opportunities for dryland cotton efficiencies and industry expansion

Location	Future opportunities
Quirindi	A focus on cotton varieties that perform well in southern specific conditions (larger seed, shorter season length, emerges in colder soil temps). With Bollgard 3 and the changes to pupae busting there is potential to return to a zero-till system thus increasing cropping frequency – particularly after cotton. However managing ratoon cotton with root cutting and cover cropping should be investigated. Also need to understand trade-offs between managing crops for maturity by 31st March compared with letting crops grow for longer as conditions dictate with that of gains elsewhere in the system. Perceived opportunities for expansion which are specific to Bollgard 3 cotton variety traits: Reduced risk of Helicoverpa resistance Reduced refuge area Reduced cost of operation (not as many passes required) The expense at the end of the season is considerable (picking and crop destruction). Growers would be more interested in DC if these expenses were somehow more spread out during the season. Cotton in the system provides an opportunity to do strategic tillage and deep P and K placement.

	Tap rooted crops have the advantage of being able to access deeper parts of the profile during a dry finish. This benefit as it becomes more widely recognised by growers on the liver pool plains may see an increase in DC adoption. Flex cotton reduces the reliance from the traditionally applied soil herbicides and generally has a good fit for integrated weed management. Similarly, cotton has a good fit in providing a production break and rotational benefit for cereal diseases.
Goondiwindi	In addition to minimum tillage, increased stubble, and decreasing frequency of low residue crops, develop a product that retains surface moisture (e.g terasorb) to extend the length of planting opportunities. In terms of the cotton plant; - varieties with bigger seed, early vigour, shorter staple length - Perennial cotton which is multi –trait (insect, disease and pest resistant) - Annual cotton which is self-determinant and contains a gene that destructs the herbicide tolerance rendering the plant susceptible. - cotton which is GM for drought tolerance - Gene competition (more companies involved). 12m fast robotic picker on permanent tracks, that gins cotton and puts out cotton yarn!! Greater use of Automation/Robotics - general crop scouting - plant mapping - Real time sensing to manage Pix application(deals with variability) - automate picking operations (modules currently have this) Intercropping (mixed sward) leading to soil microbiological biodiversity and ground cover. Use of residual chemistry to address volunteers via weed seeker/drone spot sprayer. An alternative to mulching and slashing within a month of picking. Development of some sort of insurance for those growing dryland cotton that could help to average out production variability
Dalby	20 years from now Synthetic fibres will replace cotton Dryland cotton will supersede irrigated cotton as irrigation water is allocated to higher value food crops. Robotic pickers and equipment
Moree/Bellata	Need moisture seeking planting technologies that allow seeds with poor coleoptile strength to emerge. New technology with robotics to address weeds. Better integration of technologies eg. Satellite mapping integrating with ground rigs including booms and ploughs.

Testing water injection and the addition of the polyacrylamide product SE14 to improve cotton emergence under marginal moisture conditions

Summary

Water injection has been advocated as a potential mechanism to improve cotton establishment under marginal planting soil moisture conditions. These experiments aimed to compare the efficacy of water injection with drier than optimal soil conditions and to examine whether or not the addition of the moisture attracting product SE14 would further aid establishment. SE14 was recently registered by Sacoa Pty Ltd as an aid for improving the germination and establishment of wheat and canola in hydrophobic soils in Western Australia.

The results from several pilot experiments were inconclusive. The first test under marginal soil moisture conditions showed improved establishment with both water injection and application of SE14. Subsequent tests however had no impact compared to the control with field factors over-riding any potential treatment effects. At one site where conditions were very dry (and the grower had ceased planting 36 hours prior) the addition of water or SE14 showed no benefit. Soil conditions for when the positive result was achieved could be best described as being close to adequate for establishment suggesting that a narrow window of opportunity for when water injection or SE14 might offer the potential to extend the planting window by several days depending on ambient conditions.

Introduction

Placement of water into the seeding trench (water injection) during the cotton planting operation has been occasionally put into practice by growers over the last 30 years but has not become and enduring practice. The premise of water injecting is to hasten the seed imbibing process immediately after planting and to limit the drying back of the seed trench due to soil disturbance and exposure to the air during the planting operation.

The driver for conducting experiments to examine water injection and the addition of the moisture attractant SE14 was due to the reported successful usage of this technique by 2016 grower of the year award recipients Ian and Harry Carter of Connamara situated on the Liverpool Plains. The Carters reported excellent success with the use of water injection for improving crop establishment during marginal moisture planting conditions over several seasons. On this farm, water is injected directly on top of the seed in the planting trench just prior to it being closed at a rate of 340 L/ha or the equivalent of approximately 50 mL/linear metre of crop row. To achieve these application rates their Kinsey planter was modified to incorporate two separate sets of plumbing that enabled the injection of starter nutrition and water from different tanks. Given the considerable volumes of water involved, a large carrier tank for the water complete with its own pumping system is trailed behind the planter. Whilst this is an efficient set up, water injecting still slows down the planting operation.

SE14 is an experimental product that has been under development by Sacoa Australia and is designed to be used with water injection enabling much lower rates of water to be applied in other crops such as canola and wheat in Western Australia's grain belt. The potential for SE14 to be used with water injection for cotton is unknown and was the focus of this pilot study. Two detailed experiments were conducted at Connamara taking advantage of the twin tank set up owned by Ian and Harry Carter. Two other basic tests were also conducted at Biniguy and 30 km north east of Wee Waa.

Pilot Experiments

Test 1 – 'Connamara' January 2016

A simple split plot design experiment was implemented utilising three rates of water injection with and without SE14 as a split plot. Treatment plots were 12 rows by 50 m, replicated four times along the length of the field in a randomised complete block experiment. The split plots were not randomly allocated: SE14 was applied to the same half of all of the plots to negate the need to double traffic the field area. This was done due to some field limitations and the out of season planting window used for the experiment. This experiment was planted late because the traditional planting window had been very wet and therefore the testing of moisture attractants and water injection was considered inappropriate for that season. By January conditions had changed to being dry, and whilst it was hotter than the normal planting window conditions, it was considered to be an opportunity to test a new product.

The experiment was planted in a recently harvested wheat field with fresh heavy stubble cover that was slashed just prior to sowing. The planter was calibrated to plant approximately nine seeds of Sicot 71RF per linear metre on 60 inch row spacing (at about 8-9 km/hr). Nutristart 32 and insecticide were applied during the planting operation. The water and water + SE14 treatments were:

1. Water only at standard rate (340 L/ha)

2. Water only at reduced rate (170 L/ha)

3. No Water injected

1b. Water only at standard rate (340 L/ha) + SE14 (4 L/ha)

2b. Water only at reduced rate (170 L/ha) + SE14 (4 L/ha)

3b. No Water injected + SE14 (4 L/ha)

Planting depth was set so that the seeds were placed within the top 1.5 cm of underlying soil moisture which was approximately 4-5 cm below the surface. The water only side of the split plots were sown first. SE14 was then added to the nutrition tank so that it could be applied during the second pass for the SE14 side of the split plots. The SE14 is compatible with the Nutristart product and was added at a ratio of 4 L SE14 for every 30 L of nustart 32, equating to an application rate of 4 L/ha. The soil type at the site was a high quality self-mulching black clay soil with excellent ped structure.

The different water rates were achieved by reducing the application pressure during planting. These were calibrated prior to planting.

The treatments were sown on 12 January 2017. 3 mm of rainfall was recorded within 12 hours of planting. A further 30 mm of rainfall occurred 8 days later on 20 January.

Results

Establishment success was measured on 24 January 2017. This date allowed sufficient time for the full emergence of each treatment and was soon enough to avoid the emergence of any dry seeds that may have germinated from the 30 mm rainfall event on 20 January. Heavy stubble cover directly impeded the establishment of cotton on some rows. Given the variability across the site, four rows were selected for making establishment assessments for every plot. The best row and an 'average' row within each split was chosen for the assessments. The 'best' row selected had much less overlying slashed stubble. Five metres were randomly chosen on each of the four rows in each treatment plot (20 m in total) and counts made of the emerged cotton seedlings.

The emergence of cotton in the trial was adversely influenced by the heavy stubble present and the lack of randomisation within the split plots. The high variability between rows meant that the comparison of water vs water + SE14 was compromised. However, the comparison of the three water only and the three SE14 treatments was valid. The results are presented below for each row and then as a final combined figure (all treatment rows averaged with a standard error).

The results indicate a trend for improved seedling establishment with water injection compared to no water applied (Figure 1). The result is less clear however for rows with heavy stubble cover (row 2). A similar trend is present for the SE14 treatments and the applied water rates (Figure 2). The combined data set (Figure 3) would suggest a potential improvement with the addition of SE14 although the trial layout and general impact of the stubble (which contributed to within trial variability) prevent a fair comparison.

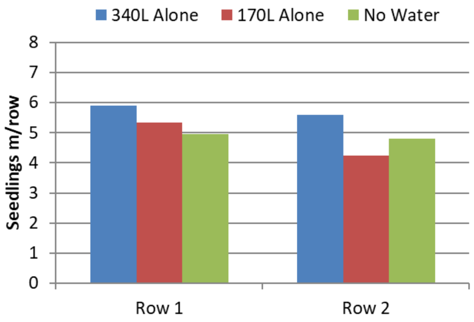

Figure 1. Sample rows for water injection alone. Row 1 was the best row and row 2 was an 'average' row.

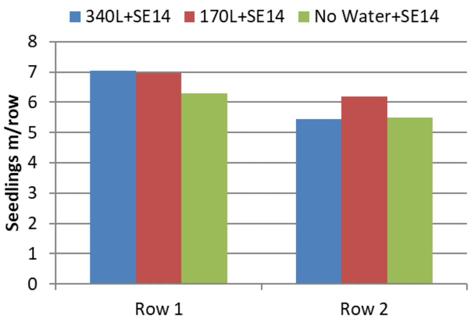

Figure 2. Sample rows for water injection with SE14. Row 1 was the best row and row 2 was an 'average' row.

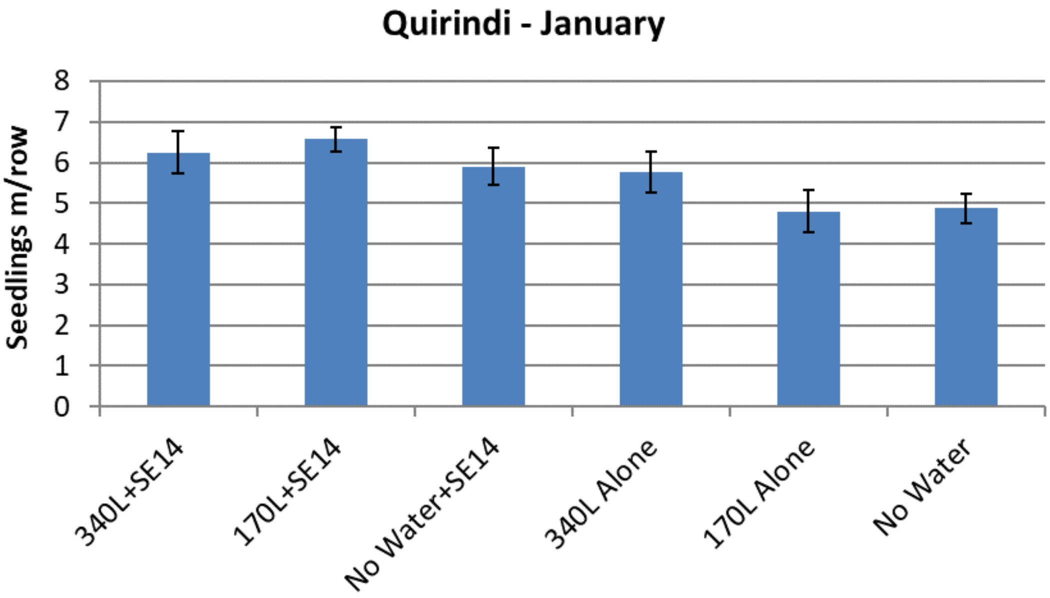

Figure 3. All of the rows and treatments combined. Bars denote standard error. Note that a comparison between the SE14 and water only treatments is compromised by the split plot design.

Test 2 – 'Romaka' October 2016

This experiment was conducted near Biniguy on a property farmed by Broughton Boydell. A simplified version of the first experiment was implemented because the planting equipment on this farm did not lend itself to the application of SE14 separately to the applied water. The treatments implemented were:

1. Water only at standard rate (150 L/ha)
2. Water only at reduced rate (300 L/ha)
3. SE14 @ 5L/ha and water at (150 L/ha)
4. SE14 A 5L/ha and water at (300 L/ha)
5. No Water

These treatments were planted in three replicated strips a planter width wide by field length and recorded on the farm's GIS system. In total 6.96 ha was sown dry, 8.67 ha with water at 150 L/ha and 4.83 ha with water at 300 L/ha. The SE 14 treatments were applied as a split plot to half of each water sown section.

The planter was a John Deere maxi emerge planter with disc openers that was calibrated to plant approximately nine seeds of Sicot 71RF per linear metre on single skip row spacing (at about 8-9 km/hr). The crop was sown on 18 October 2016 into standing cereal stubble that had been long fallowed for 12 months. The field site consisted of a variable soil type that was predominantly a lighter red clay soil type that could potentially hard set under certain conditions and readily dries out at the surface after rain.

Five hours after planting, 10 mm of un-forecast rain fell very gently on the trial over a several hour period. This rainfall did not cause any crusting but rendered the assessment of water injection ineffective as it completely re-wet the surface profile.

Seedling counts on 3 metre sections of row 10 days after planting confirmed uniform establishment across the trial area with no discernible treatment differences in plant size or density. No further measurements were taken from the trial area.

Test 3 – 'Connamara' October 2017

A second experiment was planted at Connamara near Quirindi. The field conditions at the time of commercial planting were not genuinely marginal although were considered to be sufficiently dry by the grower to water inject all cotton being planted on the farm.

A more detailed experimental design was implemented at the site to avoid some of the compromises made with the previous year's split plot trial design. Six treatments were again implemented but on this occasion a lower rate of SE14 was utilised according to advice from Sacoa. The SE14 was applied at (700 mL/ha) which was a much lower rate than that used in the previous pilot experiments. The treatments were:

1. Water only at standard rate (340L/ha)
2. Water only at reduced rate (170L/ha)
3. No Water injected
4. Water only at standard rate (340L/ha) + SE14 (0.7L/ha)
5. Water only at reduced rate (170L/ha) + SE14 (0.7L/ha)
6. No Water injected + SE14 (0.7L/ha)

These treatments were replicated 6 times in a randomly designed latin square experimental design and sown into a field that had been long fallowed since a previous cereal crop on 16 October. Treatment plots were 6 rows wide by 80 m in length. Sicot 714B3RF was sown throughout the trial area at a rate of eight seeds per linear metre. The Kinsey planter utilised was set up to inject both water and chemical separately (two plumbing lines and tanks) with fluid being delivered to the bottom of the seed trench. The first assessment of the experiment conducted two weeks after planting. Four x 10 m row transects were assessed for seedling number and appearance in each plot. No discernible differences between treatments could be observed indicating that soil moisture was adequate in the controls and therefore no further improvements could be gained (Figure 4.).

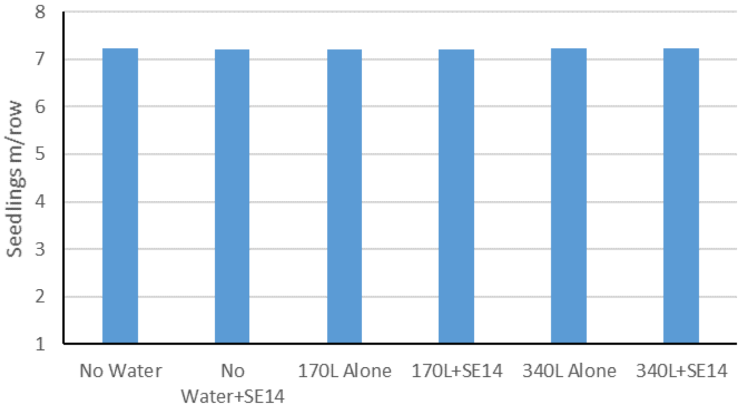

Figure 4. Seedling establishment results from Connamara 2017. No differences were observed between treatments.

Test 4 – Bellata November 2017

A fourth basic test planting was conducted at the property of Byron Birch west of Bellata on 2 November. This site had genuinely marginal planting conditions with the grower having ceased commercial planting 36 hours prior due to rapidly drying out soil moisture conditions caused by hot weather. Trial design was simplified at this site due to equipment constraints with a treatment structure of:

1. a control (no water or ameliorants)
2. water only injection (263 L/ha)
3. water injection (273 L/ha) and SE14 (0.7 L/ha)
4. water injection (273 L/ha) and a higher rate of SE14 (1.4 L/ha)

Trial plots were the width of the planter and field length (approx. 1.4 km long). Due to the size of the field each treatment occupied a single field length strip as the exercise was likely to be a potential waste of seed and resources. The seed was sown to a depth of 3-4 cm which situated the seed on the very edge of the underlying moisture.

A site inspection 3 weeks after sowing to conduct emergence counts found that very few seedlings had established irrespective of the treatment. Sections of row 20-30 m in length were found to have no plants at all punctuated by small sections (1-2 metres in length) where some seedlings had established. This test failed to provide any evidence of a benefit from either the water injection or addition of SE14.

Inspection of cotton adjoining the trial area that had been planted two days earlier had a suitable plant stand (5-7 plants/metre) showing that the window for adequate soil moisture had been surpassed by the time the trial was sown.

Conclusions

The basic tests conducted with water injection with and without SE14 suggest limited potential for these technologies to overcome unsuitable planting conditions. In two of the experiments moisture conditions were adequate and consequently both water injection and SE14 provided no additional benefit. During the first pilot test, field moisture was marginal but could still be engaged with careful planter set up to place seeds into about 0.5-1cm of moist soil without burying it too deep. For this scenario it is possible to envisage that within another 24-48 hours the available moisture would have become insufficient. This was the only test where a positive improvement in seedling establishment was achieved with both water injection and water and SE14. In the last test which was conducted only 2 days after the grower decided that conditions were becoming too dry. The addition of either water or water with SE14 was insufficient to overcome dry soil constraints.

Whilst each of the tests only had a basic design, conducting the tests under commercial conditions suggest that the addition of water during planting is only likely to make a difference during a very narrow window of opportunity. Injecting water into the furrow when soil moisture was adequate made no difference to the rate of establishment and therefore would only slow the planting operation down. When conditions were to dry, water injection could not turn back the clock and restore emergence rates achieved when compared to a crop sown 2 days earlier. The positive result that was achieved occurred under marginal planting conditions (soil moisture that was only just adequate for planting). Despite the improvement in establishment, an adequate stand was still achieved in the controls without water injection suggesting that the window for improvement is narrow indeed. Given the logistics required for growers to water inject during planting, it is difficult to advocate this practice as a remedy for marginal soil moisture conditions.

Pilot study to examine efficacy of AquaTill for crop destruction root cutting and herbicide application

Summary

The stem-cutting potential of AquaTill technology was investigated as an alternative method to mechanical root cutting to enable zero tillage end of season cotton crop destruction. The option of injecting herbicide into the stem below the cotyledon nodes with Aquatill was also examined.

A ground engagement tool was constructed that allowed a jet of ultra-high water pressure perpendicular to the main stem to be directed against the base of the plants. Initial stem cutting with AquaTill using a single nozzle assembly was found to be ineffective. In each test instance (irrespective of applied water volume or pressure) the water jet could not fully cut through the main stem. A portion of remaining intact stem bark on the opposing side was sufficient to allow cotton stub regrowth. A follow-up test utilising a different engagement tool design with two opposing nozzles (enabling cutting from each side) successfully severed the stems but required a high volume (>300 L/ha) of water.

Applying fluroxypyr with AquaTill to the main stem was found to be highly efficacious for crop destruction. An initial test of 1 L/ha fluroxypyr applied with 130 L/ha of water (carrier) achieved 100% control of treated stub cotton. A second experiment using fluroxypyr at 0.5 and 1.0 L/ha and three water rates (31, 63 & 113 L/ha) was also highly effective, with 99-100% control of cotton plants. In each test the retardation of regrowth was immediate. However, it should be noted that in each test circumstance that sufficient soil water was present to allow rapid regrowth to occur, a scenario that might vary considerably from the typical finishing circumstances of many dryland cotton crops.

This research suggests potential for the use of AquaTill technology as an herbicide delivery technique for end of season crop destruction. Realising this potential would require:

1. significant engineering development work to:
    a. refine the engagement technique to ensure accurate placement of herbicide
    b. ensure that the design is suitable for broad acre application
    c. ensure that efficacy is replicable across a range of field conditions (dry vs wet, time of season etc.)
2. testing of efficacy across a range of cotton crops that have finished under varying soil moisture conditions
3. development of an appropriate data package for candidate herbicides to support label registration by the APVMA. Ideally this should be done with the support of relevant herbicide registrants so that any potential label changes are supported by the registrant.

Introduction

Ultra-High Pressure (UHP) Water Jet technology has a number of industrial applications in product manufacturing. The technology uses water pumped through specialised nozzles at ultra-high pressures (50,000-60,000 psi) to create a high powered jet that can be used to cut very accurately through a broad range of materials ranging from carrots to steel. Researchers from the South Australian No Till Farmers Association (SANTFA) have been investigating the potential for this UHP Water Jet technology, termed AquaTill, to be retro-fitted to planting equipment for the purpose of cutting through fallen stubble that would otherwise obstruct the passage of the planting tynes through the soil surface. Compared to a standard cutting disc fitted to many planters for this purpose, AquaTill provides the advantage of cleanly cutting through stubble, eliminating the occurrence of trash 'hair pinning' during the planting operation.

Demonstrations of AquaTill in northern NSW by the SANTFA at field days during 2016 piqued the curiosity of a number of cotton growers who expressed an interest in seeing this technology tested for its potential to be used as an alternative method for traditional root cutting.

Root cutting is a commonly deployed crop destruction technique whereby two opposing and overlapping discs are drawn at ground level through the crop and used to cut through the main stem below the cotyledon nodes. Ineffective root cutting can occur when equipment is either not well set up or when in-field conditions are variable (un-even ground or stones), resulting in a percentage of plants that are not severed below the cotyledons and consequently grow back as ratoons, presenting a significant challenge for farm hygiene.

The use of AquaTill technology to cut through the main stem at ground level offers an alternative method to the use of metal discs. The addition of herbicide might also provide a technology fail-safe in that any plants not effectively severed below the cotyledons might still be destroyed.

To test the potential application of AquaTill technology as an alternative technique for root cutting, proof of concept experimentation was undertaken at 'Keytah' west of Moree. This work was a joint effort by Mr Greg Butler – SANTFA and Mr Darren Hart of Keytah with financial and intellectual support provided by the Queensland Department of Agriculture and Fisheries (DAF) through this project.

Methods

Equipment setup

A Flow International Hyplex pump capable of delivering 55,000 psi of liquid pressure was modified for AquaTill by fitting a 3-point linkage frame and a drive shaft compatible with a tractor power take off (PTO).

A 12V priming pump draws liquid from a standard agricultural spray tank and feeds it into the Hyplex UHP pump, where it is pressurised and pushed out to specialised nozzles via a stainless steel delivery pipeline.

A basic ground/plant engagement tool was constructed from sheet metal for the purpose of mounting the AquaTill nozzle assembly and holding it in place perpendicular to the plant stem just above ground level. The tool funnelled the plants into a narrow slot whereby the proximity of the nozzle against the main stem could be controlled. A picture of the mounting assembly is given in Photo 1.

Photo 1. Shows the sheet metal engagement tool which held the AquaTill nozzle in place and funnelled the plant stems through for controlled contact with the cutting jet.

Base stem cutting

The initial test of AquaTill for root cutting was conducted in a small test area of cotton crop at Keytah that was mulched at the early boll opening stage to simulate a crop that had been mulched after picking.

A range of nozzle types were fitted to the engagement tool and passed over single rows of mulched cotton to test the cutting efficacy of the AquaTill cutting jet on 12 March 2017.

Several engagement tool designs and nozzle configurations were tested:

- A) A single nozzle delivering a cutting jet at 55,000 psi mounted in a single sided engagement tool drawn at 3 km/hr
- B) A twin nozzle cutting jet at 40,000 psi mounted in an engagement tool drawn at 3 km/hr
- C) A single nozzle cutting jet at 50,000 psi mounted in an engagement tool (metal guides on both sides) drawn at 3 km/hr
- D) A single nozzle cutting jet at 50,000 psi mounted in an engagement tool (metal guides on both sides) drawn at 6 km/hr

Table 1. Initial AquaTill configurations

Treatment	Nozzle	Jet pressure (psi)	Metal guides	Speed (km/hr)
A	single	55,000	Single	3
B	twin	40,000	both sides	3
C	single	50,000	both sides	3
D	single	50,000	both sides	6

None of the above combinations tested (that varied pressure, water volume or the engagement tool) were observed to completely sever the main stem on the majority of plants subject to treatment. The water jet would typically sever the majority of the main stem but leave a small section of bark intact on the opposite side irrespective of the stem thickness.

The treated sections of row were marked and left for a period of 4 weeks to at which point treatment efficacy was assessed.

A second experiment was conducted on 22 May 2017 in a field of cotton that had been picked and mulched at Keytah to test a configuration where two opposing cutting nozzles were mounted on an engagement tool so that the main stem would be cut from both sides, thus eliminating the problem of the main stem being incompletely cut through. This technique was successful but required over 300 L/ha to be delivered to the plant line.

Ultra-high pressure water injection for herbicide delivery

The other mechanism tested was whether AquaTill technology could be used to stem inject cotton plants with herbicide to achieve crop destruction. Fluroxypyr was chosen as previous work with herbicides for ratoon control as part of DAQ1502 had shown this product to be effective when applied at 1 L/ha.

The first test was conducted on 12 March 2017 with the ski engagement tool delivering a jet of water at 50,000 psi and drawn over the row at 6 km/hr (delivering approximately 136 L/ha). At this application rate and speed, the water jet penetrated the main stem of the cotton plants by approximately 30-40% of the stem's diameter. A fifty metre section of row was used for each treatment:

1. water only
2. Comet 400® herbicide added to the supply tank to provide an equivalent application rate of 1 L/ha
3. A variation using the nozzle mounted over the top of the plant row to inject the herbicide mixture down the centre of the stub cotton plants (at the same application rate).

Control efficacy was assessed approximately 4 weeks after treatments were enacted.

A second experiment was conducted on 22 May 2017 to further test the efficacy for using AquaTill technology to deliver herbicide to stub cotton. A range of treatments were included (applied at 50,000 psi to randomly assigned single row plots of stub cotton) to assess the relative effectiveness of varied herbicide and water rates:

1. 1L Comet 400® and 113 L water/ha
2. 1L Comet 400® and 63 L water/ha
3. 0.5L Comet 400® and 113 L water/ha
4. 0.5L Comet 400® and 63 L water/ha
5. 0.5L Comet 400® and 31 L water/ha
6. Control (no treatment)

Each treatment was replicated 4 times. As the trial was conducted in late autumn, the plots were left until spring for assessment with final efficacy being assessed on 28/11/17. Initial inspections in August and early October indicated that some plants were showing signs of regrowth and could not be conclusively assessed.

Any surviving plants during the November assessment were pulled from the ground to determine whether or not the plant had been stem injected. Due to the basic nature of the ground engagement tool and the presence of volunteer plants just outside of the plant row, a small percentage of plants were "missed" by the basic engagement tool. The surviving plants that had no signs of having been stem injected were excluded from the final assessment counts.

Results

Base stem cutting

The first test of stem cutting failed to reliably fully cut through the main stem of the treated plants with a large proportion of plants remaining attached to the root system by a sliver of bark. Subsequent inspection of these plants demonstrated that this was sufficient to allow regrowth of ratoons (Photo 2). For instances where plants were completely cut through, control was effective.

For the second test utilising opposing nozzles, complete cut through of the main stem was achieved, providing effective control when this occurred below the cotyledons. This approach however required a slow travel speed (3-6 km/hr) and high water volumes (above 300 L/ha), which is commercially unviable.

Photo 2. Cotton plants cut with high pressure water only showing the typical pattern where a small section of bark remained intact post-application allowing regrowth to occur.

AquaTill injection for herbicide delivery

The pilot test of Comet 400® applied at 1 L/ha either to the side stem below the cotyledon nodes or injected down the centre from over the top gave 100% control of all treated plants. Photo 3 clearly shows the herbicide treated row beside rows treated with water-only (either side) that failed to provide control. The control provided was also rapid with plants showing no regrowth prior to death.

Photo 3. AquaTill injected fluroxypyr treated row with water-only treated rows on adjacent sides. Control of the stub plants in the herbicide row was 100%.

In the second experiment, the application of Comet® 400 at a 1.0 L and 0.5 L per ha with a range of water volumes gave excellent control of ratoon cotton (Figure 1). The two 1 L/ha Comet® 400 treatments gave complete control of all plants in each plot whilst very minor survival (<1%) was recorded across the three 0.5 L/ha Comet® treatments. Survival of plants in the control was also very low at just over 6%. The site was subject to rainfall soon after enactment of the treatments, which led to significant regrowth of the control treatments. However, severe frost events throughout July and into August resulted in significant plant death during winter.

In comparison, the fluroxypyr treatments exhibited no regrowth during this period suggesting that treatment suppressed growth until mortality occurred. With such low survival rates it is not possible to define differences between fluroxypyr or water volume treatments other than to say efficacy was very high.

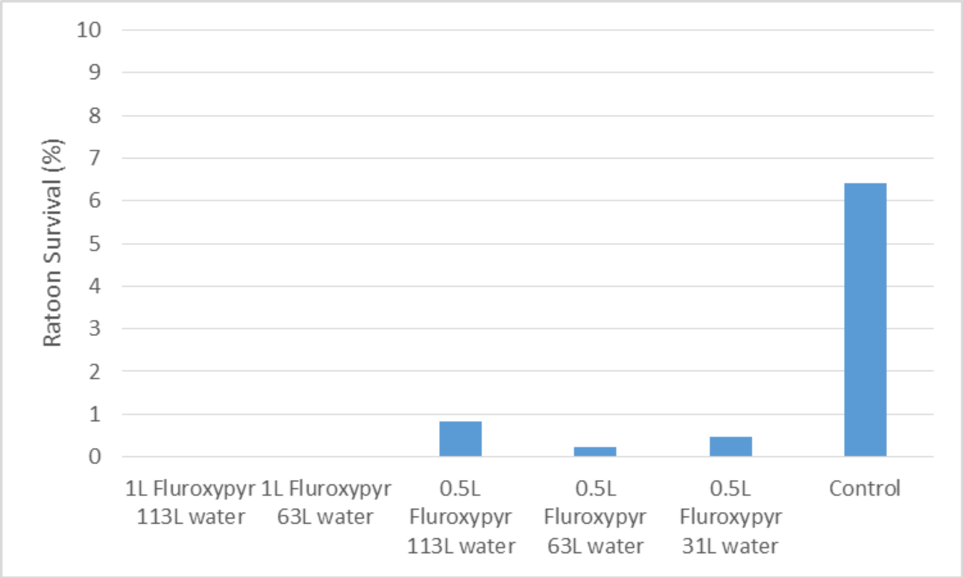

Figure 1. Percentage survival of cotton plants post treatment from the second field test with a range of water volume and fluroxypyr (Comet 400®) combination treatments.

Interestingly the trial area was situated within a larger field that had been subject to standard root cutting. Despite the effective deployment of the mechanical root cutting technique, the number of surviving ratoons was high (Photos 4 and 5). Closer inspection of surviving plants showed that they were able to re-emerge from the production of meristematic tissue that built up just above the root system giving rise to a new shoot (Photo 6). Surviving plants in the experiment showed the same ratooning mechanism.

In the case of the root cut field (that visually had much greater survival than the controls in the experiment) it would appear that root cutting prevented the plant from being exposed to cool weather during winter (as the remaining plant was under the soil surface) and that with warmer temperatures and rainfall a new shoot was able to emerge in spring.

A general observation was that all of the treatments in the second experiment provided better control of stub cotton than the root cutting operation conducted in the remaining field area beside the experiment.

Photo 4. A high number of ratoons have grown back after traditional root cutting (left) compared to the trial area on the right.

Photo 5. A newly emerging ratoon even though the plant had been effectively root cut below the cotyledons

Photo 6. Tissue build-up that has given rise to a new terminal at the base of the plant. This process was observed on all of the survivors recorded.

Conclusions

The application of AquaTill technology has shown promise for end of season crop destruction, particularly when used to deliver stem injected herbicide.

The use of AquaTill for cutting alone had design challenges and limitations associated with the high volumes of water required, achieving adequate ground speed, and ensuring control of the jet to maintain the correct cutting height. The use of a modified ground engagement tool with two opposing nozzles achieved successful main stem abscission. However, this technique required increased water volumes required (300 L/ha), and therefore is unlikely to be commercially viable.

The use of AquaTill supplemented with herbicide showed excellent promise for further development as a bona fide end of season crop destruction tactic. Progressing this concept will require specific agricultural engineering to ensure reliable engagement with the crop post-harvest so that product can be delivered accurately and reliably. Engineering will also be required to fit this technology to equipment that allows broad acre deployment. A data package will be required for any suitable herbicide deployed using AquaTill technology. This data package will need to address the variables of rate, timing, placement on the plant main stem, and performance on crops with different finishing conditions. The development of a data package should be done with the support of a potential registrant from the outset so that the work is conducted in a way that would enable the registrant to register label changes.

Acknowledgements

This research was undertaken due to the generous contribution made by Mr Darren Hart and the Sundown Pastoral Company's 'Keytah' cotton operation. This contribution entailed instigating, supporting and hosting the trial work.

Acknowledgement is also given to Mr Gregory Butler and his team from South Australian No Till Farmers Association (SANTFA) who travelled on several occasions to Moree to implement the AquaTill tests.

Outcomes

Describe how the project's outputs will contribute to the planned outcomes identified in the project application. Describe the planned outcomes achieved to date.

The grower workshops and literature review provide an up to date perspective of research gaps and the extent to which previous research has been conducted. This review will be valuable for planning future dryland cotton farming systems RD&E.

The potential to utilise Aquatill has been demonstrated by the pilot study conducted during this project. With growers looking for minimum tillage methods to successfully implement crop destruction further investment in the development and testing of the Aquatill concept could be warranted.

Crop establishment under marginal soil conditions will remain a significant issue for dryland cotton growers in some seasons. As outlined in the review, the solutions for this challenge are likely to be found by taking an integrated approach that considers planter design and function combined with a farming system that sequences crop options to optimise soil surface structure and stubble cover. Tactics such as water injection or use of ameliorants such as SE14 are unlikely to provide a widely applicable solution for the challenge of cotton emergence.

At the review stage of this project after year 1, it was concluded in consultation with CRDC and the DCRA that the best way forward would be the cessation of this project in its current form with DAF contracted to provide service delivery as the clear majority of identified research objectives and extension needs were required on the ground in the Gwydir, Namoi and Liverpool Plains NSW regions.

Please describe any:-

a) **technical advances achieved (eg commercially significant developments, patents applied for or granted licenses, etc.);**
b) **other information developed from research (eg discoveries in methodology, equipment design, etc.); and**
c) **required changes to the Intellectual Property register.**

N/A

Conclusion

Provide an assessment of the likely impact of the results and conclusions of the research project for the cotton industry. What are the take home messages?

This project was brought to a close soon after the completion of the first year for which the primary milestone was the delivery of a grower consultation process and literature review for the purpose of identifying future RD&E needs.

After determining grower feedback and advice on current farming system issues, a comprehensive literature review was undertaken so that RD&E needs related to these topics could be identified. Potential gaps included:

1. Determining the systems implications that may arise with changes to pupae busting requirements for the dryland cotton farming system.
2. The need to develop effective crop destruction tactics in the absence of pupae busting tillage.
3. The opportunity to utilise modelling combined with structured research and validation as a way of assessing the longer term impacts of changes made to the farming system.
4. The need to target weed species across the entire farming system not just in particular crops.
5. The existence of a very large body of information regarding crop establishment, row spacing, crop rotations, varieties and nutrition, which would provide an excellent foundation for a development extension campaign, particularly in newer dryland cotton production areas.

Effective extension and localised validation of existing information could play a very important part in supporting the dryland cotton industry.

The other impact that this project may have for the cotton industry has been the preliminary assessment of AquaTill for end of season crop destruction. This research has shown that this technology holds promise to be developed as a mechanism to apply herbicide as a zero-tillage crop destruction technique. To realise this potential will require significant agricultural engineering to ensure effective plant engagement, testing and registration of potential herbicides and testing of the technology across a range of crop finishing conditions to ensure reliability.

6. A. List the publications arising from the research project and/or a publication plan. (NB: Where possible, please provide a copy of any publication/s)

N/A

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

No.

Part 4 – Final Report Executive Summary

This project was undertaken to investigate how dryland cotton production and its place in the farming system could be improved, particularly with the release of Bollgard® 3 varieties. Changes to the Resistance Management Plan (RMP) for Bollgard 3 with the relaxation of planting windows and pupae busting requirements offer the potential for greater flexibility in how growers might utilise cotton within the dryland farming system.

The project commenced with a series of workshops to engage with dryland cotton growers from across the northern region to better understand the strengths and limitations of the overall farming system and dryland cotton's place within it for the purpose of identifying opportunities for where RD&E could have the greatest impact. The topics, concerns and opportunities raised at the workshops were then subject to a broad-based review to determine where RD&E could best be targeted for the betterment of the dryland cotton industry. The review identified a number of R&D gaps around the:

- implications for changes to pupae busting on the farming system
- need to develop effective zero-tillage crop destruction tactics
- opportunity to combine modelling with farming systems research to answer some of the more difficult crop sequencing questions raised by growers
- need to ensure that weed management practices extend across the system and are not carried out in isolation within each commodity
- potential to better extend a large body of existing R&D together with local validation to answer the many questions that growers have in expanding dryland cotton regions (e.g. the Liverpool Plains).

The grower workshops and review identified that it was regions with more marginal dryland cotton production prospects (lower rainfall and/or duplex soils) or areas where dryland cotton has been recently expanding (Liverpool Plains) that would potentially see the greatest benefits from new RD or E.

At the same time that the review was undertaken, a number of pilot studies were also conducted to examine the potential to overcome marginal soil moisture conditions with water injection and to test the use of the ultra-high pressure water jet cutting technology AquaTill for end of season crop destruction. Water injection both alone and with the addition of the moisture attractant SE14 (Sacoa Pty Ltd) was found to have limited potential to aid crop establishment under marginal soil moisture conditions. The use of AquaTill for the delivery of herbicide to post harvest stub cotton showed promise as a zero tillage crop destruction technique. This technique will be further developed by the Dryland Cotton Research Association in cooperation with the South Australian No Tillage Farming Association.

A conclusion of this project was the region spanning the border at Goondiwindi to Rowena and east to Quirindi in NSW represented some of the areas that would most benefit from targeted RD&E. The Queensland-based Department of Agriculture as the lead agency was not ideally placed to deliver on the identified needs of this region and therefore the project was concluded after the completion of the review so that a localised delivery model could be developed.