An impact assessment framework for harvesting technologies in cotton

Management considerations for the John Deere 7760

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Acknowledgements

Contents

List of publications

What follows is a list of current publications stemming from this work. Note well, further scientific peer reviewed journal publications will be made from this work over time and will be searchable by author from University of Southern Queensland ePrints <click here>.

1. Antille, D. L., Bennett, J. M., & Jensen, T. A. (2016). Soil compaction and controlled traffic considerations in Australian cotton-farming systems. *Crop and Pasture Science,* **67**(1), 1-28. doi: http://dx.doi.org/10.1071/CP15097
2. Antille, D. Bennett, J.McL., Roberton, S., Jensen, T. (2015) Low tyre pressure to reduce soil compaction from cotton pickers. *Australian Cotton Grower*, **36**:7, 17–22
3. Antille, D. L., Bennett, J. McL., Woodhouse, N. P., Jensen, & T. A., Keller, T. (2014) *Assessment of soil compaction caused by cotton pickers*. Paper presented at the 17th Australian Cotton Conference, Gold Coast, Queensland.
4. Bennett, J. M., Woodhouse, N. P., Keller, T., Jensen, T. A., & Antille, D. L. (2015). Advances in Cotton Harvesting Technology: a Review and Implications for the John Deere Round Baler Cotton Picker. *Journal of Cotton Science,* **19**(2), 225-249.
5. Bennett, J. M., Antille, D. L., & Jensen, T. A. (2015). *Highlighting the importance of CTF for heavy cotton harvest machinery*. Paper presented at the International Controlled Traffic Farming conference, Prague.
6. Bennett, J.McL., Antille, D., Jensen, J. (2015) The impact of pickers on soil compaction. *Australian Cotton Grower*, **36**:4, 24-28
7. Bennett, J. M., Lei, J., & de Vetten, L. (2015). *Diagnosing traffic based soil compaction with an EM38*. Paper presented at the Measuring soil water using EM38 technology, Toowoomba.
8. Bennett, J. M., Jensen, T. A., Antille, D. L., & Woodhouse, N. P. (2014). *Understanding the JD7760 round module picker impacts*. Paper presented at the 17th Australian Cotton Conference, Gold Coast, Queensland.
9. Bennett, J. M. (2013). Harvesting. In Roth Rural (Ed.), *Cotton growing practices 2013: Findings of CRDC's survey of cotton growers* (pp. 34-39). Narrabri: Cotton Research and Development Corporation.
10. Bennett, J. M., Antille, D. L., & Raine, S. R. (2013). Technological and integrated approaches for practical and rapid assessment of compaction in agricultural soils. Toowoomba: USQ.

Executive summary

Introduction

Since its inception in 2008, the adoption of the John Deere 7760 (JD7760) cotton picking system has exceeded all expectations, with more than 80% of Australia's cotton crop now being picked with said equipment. The primary driver being the perceived improvement in the farming system's efficiency, rather than immediate productivity gains. Upon reflection, the specific major adoption drivers were: (1) increased safety on farm, (2) improved effective capacity, and (3) reduced labour requirements coupled with decreased management-related stresses. Transport and ginning procedures, were all identified as issues, but were rapidly addressed.

The overarching **aim** of the project was to assess the impacts of the JD7760 on the farming system and develop strategies to optimise operating potential, with a further objective of developing a framework to help assess potential impacts of an innovation prior to its adoption.

Results found

The JD7760 is a heavy machine (upwards of 36 Mg) with a much greater potential to cause soil compaction compared to the previous basket picker systems (a little over 20 Mg). This project has found that the dual wheel front axle configuration of the JD7760 significantly influences compaction within the major root zone of cotton and influences soil structural arrangement. Importantly, both the inner and outer dual wheel were shown to have similar impact, effectively creating a compaction pan. The following rear tyre with its cyclical loading due to bale formation and the practise of carrying one on the tailgate should not be forgotten, although did not resulting in further significant compaction. In essence, the rear wheels traffic already severely compacted soil (i.e. a second pass) without further significant consequence. Potential for greater depth of compaction exists, but was not tested below 0.8 m

In the six Vertosol soils studied, there was significant occurrence of soil compaction beneath all wheels. Significant compaction was further observed to 0.8 m depth for 50% of the soils, with density conducive to long-term formation of a compaction pan beneath the tillage zone. Furthermore, the average increase in density was 10.9%, which represents a significant reduction in macroporosity most likely affecting future infiltration and plant available water. Given the load applied to the soil by the JD7760, to minimise risk the advice is that soil moisture is as close to permanent wilting point as possible within the rooting depth (deficit of ≈177 mm/ 0.9 m soil depth).

Farmers are taking the approach of investing in a lot of diesel via cultivation, in an effort to maintain soil water storage and function, with some using over 50 litres/hectare to mitigate compaction. Although showing dividends in the short term, concerns should be raised about the long term cumulative effects of using big heavy machinery on wet soil. Performing heavy tillage below 30 cm is a very costly exercise, and with increased compaction evident at 80 cm, remediation may not be economically possible, or if economically possible result in further long-term soil function consequences.

Controlled Traffic Farming (CTF) is one efficient way of dealing with the compaction problem by constraining to defined tracks through the field. CTF faces significant challenges in moving toward adoption due to perceived costs and perceived yield reductions. The timeframe that the cost of conversion could reasonably be recovered was investigated. If fields are virgin, or being converted

from previous basket picking systems, then the cost could reasonably be recovered within one cotton season. However, if converting from a standard dual-wheel JD7760 system, the conversion costs were conservatively estimated to be recovered in 2–3 years.

On yield reductions, a CTF approach using a converted CTF JD7760 and 1.5 m row spacing was shown to provide comparative yield to the conventional 1.0 m system after two cotton seasons and one traffic pass of the JD7760. A subsequent wheat crop designed for bio-ripping more effectively accessed water in the CTF system and out yielded the conventional system by ≈60%. It is concluded that a CTF approach provides better protection of the soil resource than the conventional system and will likely have greater productivity in the long-term.

Segment picking of this trial revealed that the majority of the fruit from the 1.0 m cotton was from fruiting positions 1-8, while the majority of the lint yield for 1.5 m cotton originated from vegetative branches. This suggests that the 1.5 m row spacing cotton matures more slowly, which led to stronger and long cotton fibres on average for the 1.5 m row spacing system, with an overall better fibre quality than the 1.0 m row spacing system. The use of 1.5 m row-spacing cotton appears to be best suited to water limited environments based on its ability to enhance WUE.

Other possible approaches

Other possible compaction mitigation approaches were investigated. Evaporation and evapotranspiration were both shown as effective in reducing soil compaction due to cotton picker traffic in the 0–0.3 m soil depth, via wet-dry cycling of shrink-swell clays. However, for adequate regeneration comparable to the control, between 12 and 24 months of wet-dry cycling was required for the JD9976 basket picker and under a JD7760, much greater. Using the crop to dry soil down to well below plastic limit prior to harvest in an irrigated cotton-grain rotation should be investigated as a potential management strategy for soil compaction due to heavy machinery (axle load > 10 Mg).

Another approach was to delay the defoliation of a cotton in high risk weather conditions to reduce the soil compaction risk at harvest via moisture drawdown from cotton transpiring. The conclusions drawn from the study indicated that the proposed management strategy of delayed defoliation was effective in reducing soil moisture and thus the resulting soil compaction risk at cotton harvest. However, the comparative difference in compaction for use of this method did not necessarily warrant it as one to protect the soil resource verbatim. Differences in resulting compaction were small and did not adequately address subsoil compaction concerns. Additionally, growers must way up the potential risk of cotton fibre implications against the cultivation requirement cost (to alleviate compaction to the same extent observed) to determine viability of approach.

Reducing tyre inflation pressure to 50% of the recommended pressure showed some advantages in terms of compaction alleviation compared with tyres operated at the standard pressure, albeit not significantly alleviating subsoil compaction risk. The main advantages were reduced soil disturbance (cross sectional area of rut) and reduced soil strength, particularly at relatively shallow depths (<30 cm). The practical and safety aspects of operating tyres at lower than the pressure recommended by manufacturers still need to be observed; the pressures used in this investigation were well outside tyre limitations and highly dangerous at an operation scale. Combining lowered pressures along with crop drawdown provided a greater degree of machine floatation that was achieved with only a small reduction in field moisture; although the effects of compaction are still evident in such conditions.

This is not advised as a viable management method with conventional tyres, but near-future advances in low ground pressure tyre systems may increase the viability of this approach.

Modelling of cotton planting between middle of October and early to middle of November indicates plant timing as likely to minimise the risk of soil compaction at harvest due to occurrence of unforeseen rainfall at harvest, without a significant compromise on crop yield. However, further assessment of this as a probabilistic approach to risk reduction for the industry should be undertaken.

Use of an EM38 to diagnose compaction has merit and should provide a more cost effective way by which to demonstrate graphically the effect of machine traffic on the soil resource. The Geonics EM38 MKII has proven capable of diagnosing soil compaction in high clay content soils at a moisture range of 38–22% gravimetric soil moisture. Importantly, this work has highlighted that wheel tracks appear wetter under the investigated conditions, meaning wheel tracks should not be used for soil moisture budgeting.

Recommendations
From this work comes the following recommendations;

- Traffic of Vertosols near, or above, the plastic limit should be avoided with the JD7760 in dual wheel configuration. Traffic should only occur well below the plastic limit.
- Timeliness of operations does not always facilitate avoidance as an option. Thus controlled traffic should be considered the best management practice for limiting soil compaction, increasing yield potential and decreasing environmental cost.
- Further controlled traffic investigations in the cotton industry are required to justify conversion time and cost, as well as other row spacing configurations (e.g. ultra-narrow). Further investigations include:
    - o Multiple side-by-side CTF Vs. Non-CTF sites throughout cotton regions and climatic regions where row spacing is co-investigated with soil compaction to provide economic rationale
    - o Economic investigations and social strategy formulation to provide impetus and means to convert a critical mass of the industry to CTF; in order to address issues associated with providing/receiving contractor services
    - o Cultivation regimes and bio-ripping (evapotranspiration wet-dry cycles) should be investigated as interacting factors with controlled traffic and best management practices developed on this basis
    - o Improvement in cultivation, and other traffic process, fuel use for cotton systems (up to 50% reduction in fuel requirement has been obtained in CTF grain systems)
    - o Optimal design of traffic lanes (length, slope), particularly within irrigated systems to reduce concentration of runoff potentially leading to increased erosion risk.
- Natural regeneration of soil structure via bio-ripping shows some potential, but is limited where the JD7760 is used in dual wheel configuration. Further investigation of long-term effects on a number of sites should be assessed against deep cultivation and in conjunction with CTF to provide a proper economic comparison – information concerning the economic

viability of bio-ripping as a compaction management method, and CTF augmenting factor is lacking.

- Collection of precision agriculture data (yield, elevation, fuel use, irrigation etc.) is essential to spatially understand production relationships, and should be collected

- Spatial fuel use is a generic measure that integrates the remediation of compaction. Using fuel use in a range of tillage impact trials would allow visualisation of the impact of compaction.

- The compaction implications on yield may not become evident for several years due to seasonal influences and so trials should be at least medium term (5-10 years).

- There is merit in further investigating tillage to greater depths and at multiple sites over multiple years, if not only to dispel the myth that deep tillage can be economic, but also to understand long-term structural implications, and nutrient dynamics.
  - The requirement for further investigation into the relationship between cultivation depth, cost and cotton yield was also identified.

- Further work including associated effects on energy use in tillage repair treatments, long-term effects on crop yield, and soil sustainability merits a research priority.

- With a need for farming enterprises to maximise profitability, the adoption of an innovation framework will allow cotton businesses to identify weaknesses within the enterprise and adopt the innovation required. Further financial systems research is required to understand the long term effects of heavy machinery on our soils. This identifies a need for growers to be provided with a tool to help make informed decisions and to prompt consideration of potential pitfalls prior to purchase. The framework produced in this work requires facilitation by an independent party to provide maximum usefulness. To remove this requirement, greater complexity and automation is needed, which lends itself to a digital, rather than analogue approach. Incorporating Bayesian Belief Networks, or some other automated computational approach, into the existing structure would be advantageous.

1. Introduction

Technological innovations in the cotton industry are advancing mechanisation and seeking to create improved efficiencies of labour and energy inputs. These innovations are often adopted rapidly without specific knowledge to support the adoption. That is to say, innovations are often adopted on the face value of a proclaimed efficiency. Thus, the farming system impact of these innovations is not well understood in the majority of cases. While the cotton industry has developed and endeavours to use best management practices (BMPs) for farming system components (including soils and water), an impact assessment framework for evaluating the impacts of these new technologies on the whole farming system does not exist. The rapid adoption of the John Deere 7760 on-board-module-builder cotton picking system (JD7760) presents an opportunity to investigate the specific effects of this new technology, and in doing so, inform development of an impact assessment framework applicable to other technological innovations for cotton.

Of particular concern is the potential for delayed impact of the JD7760 on sustainable management and production, particularly from a soils perspective. These machines are designed to provide energy/labour efficiencies (the current driving force), but impacts such as increased compaction resulting in increased soil-bed preparation costs may emerge in subsequent seasons. The major impact of heavy machinery on the soil is compaction, and not surprisingly 'SOILpak for Cotton Growers' declares compaction as a yield limiting factor in cotton production. Compaction has historically been managed through various techniques, such as controlled traffic farming (CTF) and minimum tillage. In the case of the JD7760, these machines eliminate the need for the boll buggy by preparing round bales on-the-go, but the trade-off is an increase in total machine weight. This raises concerns for increased soil compaction, especially under moist soil conditions generally experienced in irrigated fields, or during wet cotton seasons. The ability of the soil to carry the increased weight under marginal traction conditions may narrow the harvest window. Furthermore, given the adoption rate, it is unlikely that optimisation of machine performance within individual farming systems has occurred. The potential to provide further impact-offset capability is real and should be optimised. The question is then raised: "*Is this machine being utilised optimally and do the economic efficiencies offset potential field impacts?*"

As the uptake of the JD7760 has been widespread and rapid, it is not a matter of whether or not the industry should adopt this technology, rather a process of determining its impacts, evaluating impacts against previous harvesting systems, and developing strategies to optimise operating performance. By engaging the industry in discussion and reviewing current information on harvesting system implementation and performance, this project sought to determine a series of considerations to assess field impacts and machine performance. In doing so, the basis of an impact assessment framework was constructed and refined over three years.

The overarching **aim** of the project was to:

Assess the impacts of the RB picker on the farming system and develop strategies to optimise operating potential.

To achieve this aim, the following specific **objectives** were identified:

- Identify potential impacts of RB harvesting on the farming system
- Measure and assess the impacts of round bale harvesting on the farming system
- Develop and evaluate strategies to minimise the impacts of round bale harvesting systems
- Recommend BMP for harvesting systems and impact assessment frameworks appropriate for use with other cotton farming technologies

Based on initial findings from literature and field observations, the project direction primarily focussed on soil resource impact and mitigation of this. This focus was warranted, and somewhat expected, given the fact that supply chain impacts were quickly self-addressed by industry and rectified in majority prior to this project commencing.

2. Australian perspectives on John Deere 7760 integration

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Introduction

With the inception of the on-board-module-building system has followed rapid adoption of the John Deere 7760 round module picker (JD7760). This adoption pattern commenced in 2008 and by 2013 the majority of cotton growers either owned or used the JD7760 with capacity of the reported sales of machines able to pick greater than 100% of the annual Australian cotton crop (Pers Comm. Broughton Boydell, John Deere Australia, 2013).

Adoption of technology occurs best when the perceived benefit of the technology is clear in comparison to the process it is designed to replace/augment (Guerin and Guerin 1994), and when the technology is simple or, if complex, is clearly explained in terms of incorporation/use (Diallo 1983). The JD7760 replaces multiple personnel, and contracts the cotton picking process from multiple machines to the one JD7760 unit. Additionally, the technological innovation uses a familiar platform in the cotton picker, with the only major technological change being the addition of the on-board-module building unit where the basket would previously have been. Thus the concerns of Guerin and Guerin (1994) and Diallo (1983) appear to have been addressed. However, initial capital outlay in terms of farming system changes, and more specifically machinery costs, have been shown as significant barriers to adoption of technology (Bennett and Cattle 2014; Guerin 1999). In the case of the JD7760 the cost of the machine during peak adoption (2008–2013) was approximately AUD$750K based on a weak USD; with a normalised USD the JD7760 would cost in the order of AUD$1.2M. Irrespective of highly substantial initial capital outlay, these machines were rapidly adopted.

A potential consequence of such rapid adoption is that due consideration to potential latent impacts is not afforded; i.e. adoption lag does not occur thus the majority of growers suffer the impact of any unforeseen impacts, rather than learning from the early adopters as would occur in a slower adoption cycle. Therefore, this chapter seeks to specifically understand the driving motivation to use and/ or purchase a JD7760, the perceived impacts of the technology and the attitudes associated with its use. It follows up on soil compaction as an impact and presents controlled traffic farming as a potential management solution. Grower perspectives and attitudes are further presented on this management approach.

Methodology

An initial perspective on the JD7760 from Australian cotton growers was obtained through administering a number of discussion forums and a mail based survey. Follow up discussion forums were held to present findings on soil compaction and to discuss potential management options.

Initial data collection

Emphasis was placed on collection of "rich" data (Kelly et al., 2009) through a series of five face-to-face discussion forums held throughout the Australian cotton industry including New South Wales (Hillston, Warren, and Narrabri), and Queensland (Dalby and Goondiwindi). These forums focused on four key discussion points: (1) technology uptake, (2) incorporation of technology to the farming system, (3) perceived and evident impacts of technology, and (4) technical support and

communication. The forums were attended by growers, industry representatives, and extensionists who provided industry perspective. A summary of the grower perspectives is shown in Table 1.

To augment these rich data, growers provided information on their on-farm integration of, and attitudes towards, the JD7760 via the annual Cotton Research and Development Corporation (CRDC) growers survey in 2013 (Roth Rural 2013). The JD7760-specific questions were incorporated into the survey to provide information to this project. The survey was mailed to an effective grower population of 837 with a response of 362 (43% response rate) completed surveys and 134 (16% effective response) completing the cotton harvest section to some extent. The total response represented 23% and 27% of the Australian irrigated and dryland cotton crops, respectively, with regional representation within this ranging from 12 to 30%. Given the magnitude of response to the survey in full, non-response was not assessed. The full dataset and survey implement are available from CRDC (http://www.crdc.com.au/) upon request.

Soil compaction management data collection
Soil compaction management was the focus of these forums of the basis of JD7760 impact on the soil resource, detailed in following chapters. The major outcome of the work being that soil moisture is the most important factor for a specific machine mass (32–38 Mg for the JD7760). Given the nature of Vertosols in relation to water holding capacity and clay content (both high), avoidance of compaction is the most reliable method, thus controlled traffic farming (CTF) was identified as the most suitable system. However, SOILpak for Cotton Growers (Daniells and Larsen 1991; McKenzie 1998) also recommended a CTF approach to the cotton system, but this has not been adopted despite nearly 30 years of scientific recommendation. Thus, it is pertinent to understand and document why.

Again, emphasis was placed on the collection of rich data through a series of discussion forums held in Goondiwindi, Undabri Station, Jimbour, and Aubigny (all in QLD). Additionally, the CTF management option was presented at the 2015 Cotton Collective in Narrabri (NSW) and one-on-one follow up discussions were held with growers as time permitted. For Goondiwindi and Undabri Station forums, the forum was part of a larger industry event and discussions were not recorded during limited question/discussion time, but followed up post event.

A thematic approach to forums was used, whereby presentation of JD7760 impact on the soil resource was undertaken and then compared to a JD7760 CTF system, including cultivation energy requirements of the standard JD7760 system. Attendees were asked to form their own opinions on the approach and discussion was facilitated via basic prompting on their initial thoughts as to whether or not compaction was an issue for the cotton industry. Conversation was then allowed to flow freely. In this approach data suggesting compaction is an issue was presented, but this was not deemed as confounding the ensuing discussion. The fact is these machines cause compaction, the objective was then to understand why some may believe this not to be an issue for their management. Emerging themes from discussions were then identified by region and collated.

Results and discussion

Adoption rate of the John Deere 7760
Grower estimation of adoption by 2013 is in excess of 80% across all cotton-producing areas, except for Dalby (Queensland, Australia), where growers were uncertain of adoption rate. This agrees with the proportion of the 2013 cotton crops picked by JD7760 machines (approximately 82%), although

survey response indicated 70% of growers owned a JD7760 (Figure 1 and Figure 2). Additionally, the proportion of crop picked by a JD7760 machine based on survey response is supported by ginning data that take into account the proportion of the seasonal cotton pick arriving at the gin in round module form (Table 2).

Table 1. Summary of emerging themes for discussion forums held in the Australian cotton industry ordered in terms of key discussion points. Total participants for the five forums were twelve. JD7760 is the John Deere 7760. For frequency of response use N = 12. For number of forums representing view use N = 5

Emerging theme	Frequency of response (%)	No. of forums representing view
Technology adoption		
Adoption of JD7760 influenced by contractors	33	4
Harvest cost reduction is not an adoption driver	92	5
Increased safety	100	5
Management stress is reduced by the JD7760	42	4
The CASE IH Module Express did not meet the needs compared with the JD7760	100	5
Incorporation of technology to the farming system		
Cost of wrap per ha is reducing bottom-line	67	3
Skilled operators are required	33	2
Need to be more careful with module moisture	25	3
Parts can be hard to source	58	2
The 2012 JD7760 model accumulator is too small	75	3
Easy control of moisture allowing higher moisture pick (Vomax moisture sensor is a key support tool)	42	3
Machine electronics can cause downtime and frustration	75	4
Perceived and evident impacts of the technology		
Increased effective capacity	67	5
Reduced need for seasonal workforce	50	3
Increased tillage requirement post-harvest	25	3
Soil compaction is an issue	50	5
Decreased workplace health and safety risk	100	5
Increased contamination of modules	33	2
Technical support and communication for the technology		
Technical support provided by dealers is adequate	42	5
John Deere link system	33	3
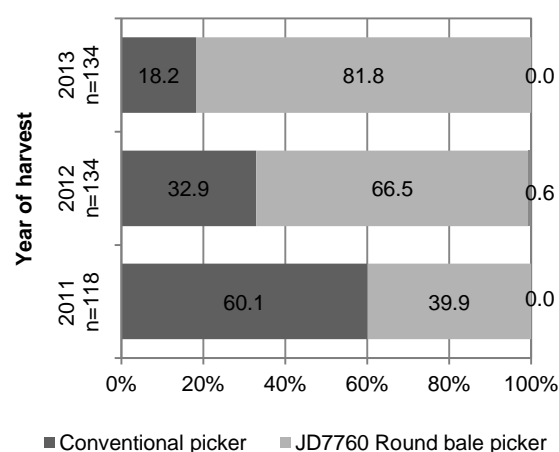
Figure 1. Cotton area picked using the various technologies for 2010-2011 through 2012-2013 seasons. Results are presented as a percentage of the harvested area allocated to each technology for each season by respondents. Values within bars are percentages.
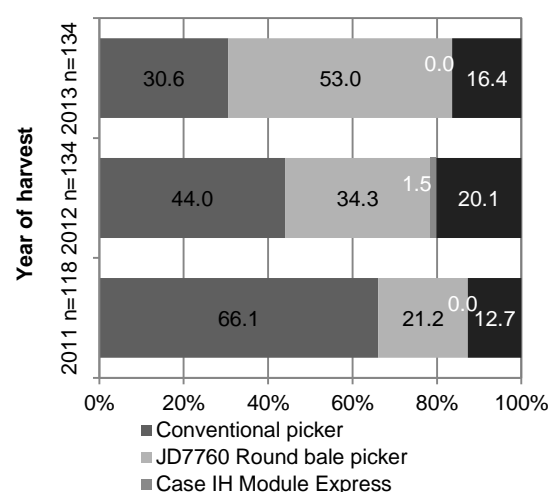
Figure 2. Percentage of growers indicating use of the various picking technologies for 2010-2011 through 2012-2013 seasons. Values within bars are percentages.

Adoption drivers

The decision to adopt the JD7760 appears to have been made at an individual grower level, with the majority of survey respondents considering "Discussion with John Deere dealers" and "Discussion with other cotton growers using round module pickers" as low motivations to adopt. This reinforces that the machine benefits and use of existing machine platform were highly transparent, not requiring involved demonstration or convincing (Guerin and Guerin 1994; Diallo 1983).

Initial insights into adoption drivers suggest that the JD7760 has been adopted due to perceived improvements in farming system efficiency, rather than immediate productivity gains, the latter often regarded as primary driver of adoption (Kelly et al., 2009). The JD7760 represents a substantial investment (market price at the time this work was undertaken was approximately AUD$750K), which might be considered as a barrier to technology adoption (Bennett and Cattle, 2014). However, Australian cotton growers clearly do not appear to see this level of capital investment as a barrier for adoption of the JD7760 (Figure 4 and Figure 5). This is explained by the fact that John Deere has elucidated the benefits of the machine to the agricultural system in a way that reduced the perceived risk of investment to growers.

The forums identified major adoption drivers as: (1) increased safety on farm, (2) improved effective capacity, and (3) reduced labor requirements coupled with decreased management-related stresses, which is supported by survey data (Figure 3). The vast majority of survey respondents (70%) considered the JD7760 picking system to be on par, or potentially more expensive, than the basket picking system. Furthermore, the survey forum also revealed that 92% of growers agree that increased productivity, which is cost reduction in harvesting operations (crop return considered to be equal irrespective of harvest system utilized), did not drive adoption. This finding supports the finding that growers consider, primarily, the overall benefits to the agricultural system in the decision-making process for technology uptake. In addition, issues with availability of parts and access to qualified mechanical expertise were of concern to 58% of growers in Warren and Hillston (New South Wales, Australia). In Warren, growers indicated that this was due to qualified personnel being relocated away from the region, whereas those in Hillston are more geographically displaced from the center of the cotton industry and might find access to services limited. These aspects also featured heavily in prepurchase considerations.

When looking at the number of survey respondents reporting the use of the various picking technologies, it can be seen that fewer JD7760 machines, as a percentage of respondents, are required to pick the same area as the conventional system. This supports two interrelated notions:

- The conventional system is generally being retained by smaller operators
- The JD7760 is capable of a faster pick (further supported by Figure 3 and Figure 5)

For example, in the 2012-2013 season, 81.8% of the reported area was picked using a JD7760 and 69.4% of growers reported using a JD7760, while 47% of growers reported using the conventional system to pick 18.2% of the reported area. On this basis, from the 2010/2011 through 2012/2013 seasons, it is apparent that JD7760 picking has become more efficient improving from 1.17 (ratio of JD7760 picked area and JD7760 reported use) to 1.27 area/use.

During the 2011/2012 season two growers reported using the CIH625 on board module picker. Anecdotal discussions with growers and dealers suggest that there are no CIH625 machines

commercially operating in Australia. It might be that this use represented a trial of the technology as the total area reportedly picked by the CIH625 was 591 ha. From discussion forums it was found that all participants believed that the CIH625 did not meet their requirements. When asked to explain what these requirements were the major reason given related to module formation and subsequent transport in field; the CIH625 did not allow the ability to carry one module whilst forming a second, which the JD7760 did. This was apparently not in relation to the cotton contained within the respective modules, but mainly to do with planning the dumping of CIH625 modules and subsequent removal of these from the paddock. This is a highly important finding, as adoption of the JD7760 required that transport and ginning techniques change (transfer from larger rectangular modules to small round ones), whilst the CIH625 did not. This indicates that clear benefits of technology can even supersede ease of logistic management.
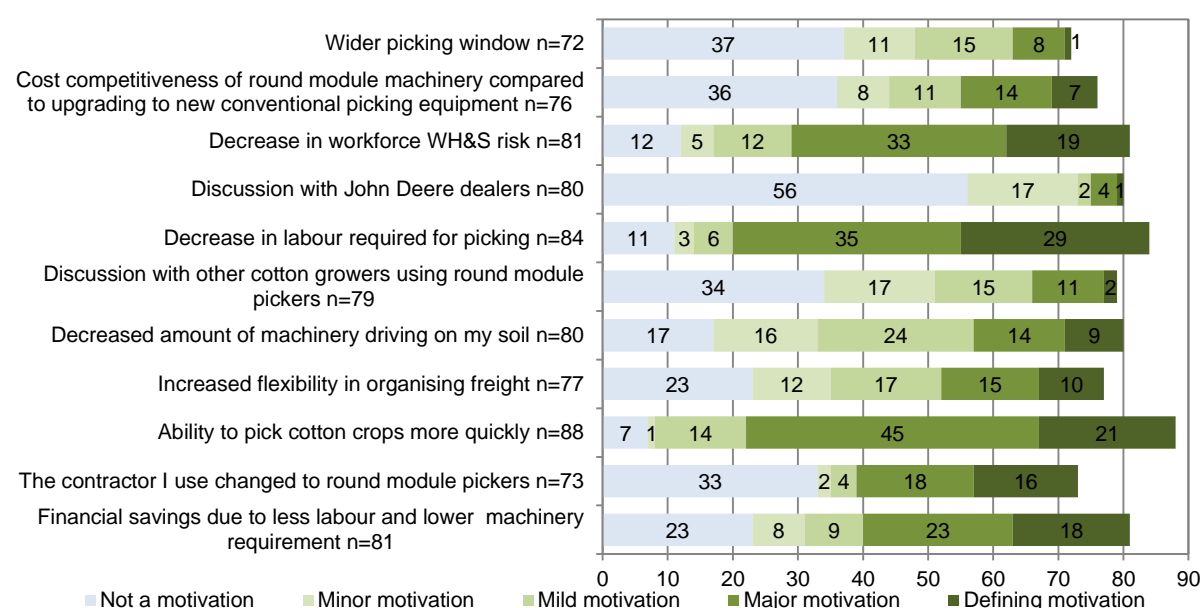
Figure 3. Initial motivation to use the JD7760 picker whether using a purchased machine or contract harvest. Data is presented as stacked frequencies. Values within bars represent the number of respondents for each category (the total summing to n).

Interestingly, "Financial savings due to less labour and machinery requirement" is relatively evenly split between low and high motivation (Figure 3), with a slight majority leaning towards it being a driving motivation (combination of Major and Defining motivation categories). One grower commented that *"Round bale cost a lot more $ overall!!"*, while another suggested that *"It is not true that there are financial savings in labour and machinery from changing to round module pickers."* The cost of the boll-basket and JD7760 systems has been considered on par by the industry (Bennett *et al.* 2015). However, it is apparent that irrespective of any actual financial savings that the prospect of a financial saving did act as a driver for adoption for a large proportion of responding growers.

Location of gin	Round bales ginned at season finish (%)				
Year	2008	2009	2010	2011	2012
MacIntyre	0	0	0	41	62
Mungindi	0	0	26	29	73
Ashley	24	40	39	48	75
Wathagar	0	0	0	20	45
Moomin	0	0	0	28	69
Yarraman	0	0	0	0	26
Merah	0	0	0	0	34
Boaggabri	0	0	0	24	38
Trangie	0	0	0	0	65
Hillston	0	0	0	57	74

Considerations during adoption decision making process

Growers were asked to indicate to what degree the considerations listed in Figure 6 featured in the purchasing/ leasing decision making process. This question differs to the data presented in Figure 3 in that is relates to purchasing considerations, rather than motivations, or impetus, to use the machine. That is to say, one might be motivated to use a machine by a defining impetus, but the decision to buy a machine is governed by a decision making process with various characteristics. This question seeks to understand those characteristics. This question also excludes those who only use contract JD7760 harvesting.

Interestingly, there was no single overriding defining consideration identified by responding growers. The major considerations in purchasing related to the ability to have the machine serviced, the cost of module wrap, the availability of parts, the transport of round modules and the transport of the machine itself. Consumption of fuel and lubricants were generally not important considerations.

The cost of plastic wrap is seen as a latent impact because growers can source it from only one manufacturer, which was echoed in forum responses. The general consent from forums is that this issue will be addressed and that an alternate source of wrap will be developed, ideally within Australia. Prior to purchase, machine and module transport were major considerations for 33% and 44% of growers, respectively. Approximately 25% of forum participants found the machine difficult to transport, but the large majority (99%) expressed no problems in transporting round modules. This reflects the fact that transport infrastructure does not continue to constitute an impediment post-purchase, possibly due to capacity of fleet and road infrastructure, and a concerted effort by the cotton industry to address interstate regulations concerning transport of modules and pickers (Houlahan, 2012) and the fact that this was a consideration prior to purchase.

Approximately, a third of participants agreed that the use of JD7760s has increased contamination compared with the traditional module, which agrees with observations made in earlier studies (e.g., Krajewski and Gordon, 2010).

The machine weight and potential for soil compaction were cursory considerations with the majority of response in the Minor and Mild categories. The machines ability to be incorporated into a controlled traffic system was even less of a consideration. Approximately three quarters of growers responding to the survey identified that soil compaction was not a major consideration prior to purchase of a

JD7760. However, 48% agreed it had increased soil compaction (Figure 6). Also, 50% of participants indicated that soil compaction was a problem associated with the JD7760 cotton picker. In Warren, cotton has only been reinstated in the rotation since 2012, due to drought, which means that the use of the JD7760 in that region was only recent. These participants indicated that soil conditions during harvest were rather dry, and therefore, significant damage due to compaction was not observed in 2012. If participants from Warren were removed from the survey, about 80% of responses linked increased soil compaction at harvest with the JD7760 cotton picker. Overall weight of machine was a relatively greater consideration than soil compaction prior to purchase (Table 3), which is presumably related to road traffic and freight considerations.

This appears to suggest three possible thought processes: 1) soil compaction is not perceived as an important consideration for grower's farming systems; 2) that growers felt that at the time of purchase they were able to sufficiently manage soil compaction that would occur due to JD7760 use; and/or 3) that the benefits of the JD7760 in terms of in-field and management efficiency outweighed the potential soil compaction impact. Given the weight of the front axle exceeds the suggested 20 t limit identified by Soane et al. (1979, 1982), and the rear axle approaches this value, the potential risk of compaction due to JD7760 use should be viewed as high. Furthermore, compaction is regarded as one of the main causes of soil degradation worldwide (Hamza and Anderson, 2005), and it is clearly raised as a major concern for the Australian cotton system in industry grower support tools (SOILpak 2nd and 3rd Edn, Daniells and Larsen 1991; McKenzie 1998, respectively). So, it might reasonably be expected that compaction be an important consideration of Australian growers, even though it clearly wasn't, indicating a dire extension requirement given what is known about the load of these machines and impact on the soil resource.

When analysing the considerations and their apparent importance against the notions of Guerin and Guerin (1994), that potential benefits must be easily identifiable as better than those of the current option (that designed to be replaced), it is observed that immediate supply chain considerations rate highly. This is in keeping with easily identifiable issues rating highly. Module wrap was a major consideration when asked in 2013, but discussion forums revealed that this was somewhat of a hidden cost for those adopting earlier, who did expect some financial saving due to JD7760 inception. On the other hand, soil compaction is a production consideration, rather than a direct supply chain consideration, and a misconception that significant wheel ruts must be observed for compaction to occur exists, meaning unobservable subsoil soil compaction continues to be ignored by approximately half the industry.

Trends in John Deere 7760 use

During the 2012/13 season, the majority of JD7760 use was through contract harvesting (60.3%) (Figure 4), but where machines were purchased (47.3% of growers), the vast majority of picking was performed by one picker (Figure 5). In the 2013/14 season the average cotton picked by an owned/ leased JD7760 machine was 650.36 ha (*n*=37). In three cases during this season, growers reported that a single machine was picking almost twice the average area for the season (1000–1100 ha), which indicates that individual machines may be being underutilised in terms of their true capacity.

Furthermore, cotton that was picked exclusively by machines that were owned/ leased (39.8%, Figure 4) represented 54% of the total cotton area picked by JD7760 machines and 44% of all cotton picked

in the season. So, while more people using JD7760 machines were utilising a contractor for harvest, the area of cotton picked was less.

This might indicate a potential saturation of JD7760 machines in the Australian market, which is a concern for capital repayment models based on factoring contract harvest as a significant supplementary income. This raises an important consideration that was not able to be quantified as a part of this work, but needs to be considered by a grower when purchasing, which is: How will borrowed capital investment be repaid if contract harvesting is not a realistic option?

Figure 4. Percent of growers indicating the use of a JD7760 in 2013 who purchased/ leased a machine, contract harvested, or both (n=93).

Grower attitudes toward incorporating the John Deere 7760 into a farming system

Growers who had purchased/ leased their JD7760 were asked to what extent they agreed/ disagreed with the attitudinal statements in Figure 7 in terms of utilising their picker within the farming system. These questions were split into those relating to soil compaction, attitudes towards paying the machine off, and machine performance. Responding growers clearly thought that harvesting cotton was more important than causing soil compaction, but conversely were not inclined to pick at higher soil moisture content just because the machine could. This suggests that if climatic conditions

Figure 5. Number of JD7760 machines purchased/ leased by growers in 2013 as a percentage of those indicating they purchased/ leased a machine in Figure 4 (n=37).

and external circumstances require cotton be picked at detrimental soil moisture, then it will be, but all conditions/situation allowing growers will attempt to avoid traffic at detrimental soil moisture.

On the other hand, while many did consider the machine weight in their purchasing process, they were not overly inclined to consider a controlled traffic regime as being any more important than with their previous system. The ability to modify a JD7760 to pick on an 8 row frontage allows those using skip-row cotton systems to harvest more quickly by ensuring that all 6 heads are picking rather than running in skip rows. While the number of growers considering this was not assessed, it appears that the ability to do this does not cause growers to be any more inclined to do so.

In regards to paying off the JD7760 picker, growers favoured using their picker for contract harvesting over growing back to back cotton. Given the data presented earlier that might suggest that the Australian market for JD7760 pickers is becoming saturated and pickers are not necessarily picking at capacity. The fact growers are considering contract harvesting as a method to pay off their machine could be a pressure on the contract harvesting market and therefore the future ready availability of

contract pickers. Although those using contract pickers agreed that their crop was more reliably picked when it was ready to be picked (Figure 8), this statement, in terms of contractors, pertains to picker availability; we interpret increased availability as inactivity rather than overall better access.

Growers tended to agree that the JD7760 was more reliable at picking than previous systems.

Similarly, growers who had used a contractor with a JD7760 were asked to what extent they agreed/ disagreed with the attitudinal statements in Figure 7 in terms of utilising that contractor within the farming system.

While removing cotton from the field was still a clear priority as compared to avoiding soil compaction for growers using contractors, encouragingly, they indicated that they did not feel more inclined to pick at high soil moisture just because the ,machine could, but may feel pressured to do so slightly (split between disagree and agree) depending on contractor availability. Similarly, growers using contractors were no more inclined to use controlled traffic than those purchasing/ leasing their machines. This also means that they were generally no less inclined to use controlled traffic systems as a result of contract picking with a JD7760.

Growers also did not feel pressured to pick at higher lint moisture to keep the contractor on the farm. This once again highlights that factors directly affecting profitability in the short-term are of high consideration, but those indirectly affecting profitability over the longer-term are not held in as high regard.
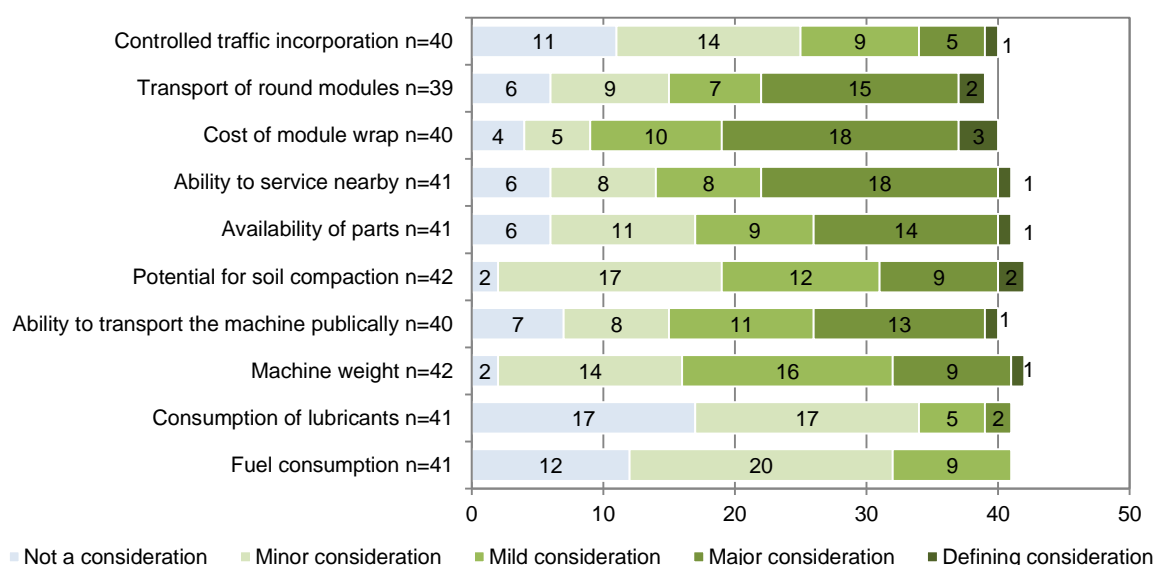
Figure 6. Considerations made by growers during the purchase/ lease process of the JD7760. Data is presented as stacked frequencies. Values within bars represent the number of respondents for each category (the total summing to n).
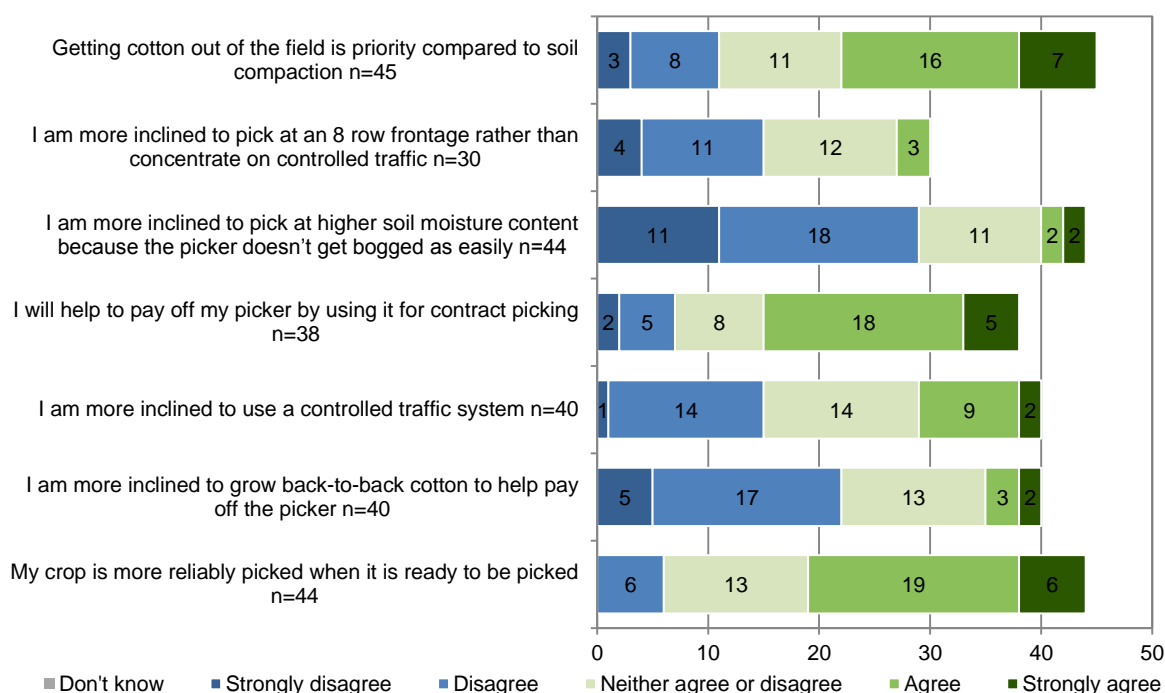
Figure 7. Grower attitudes towards the use of an owned/ leased JD7760 picker in their farming system. Data is presented as stacked frequencies. Values within bars represent the number of respondents for each category (the total summing to n).
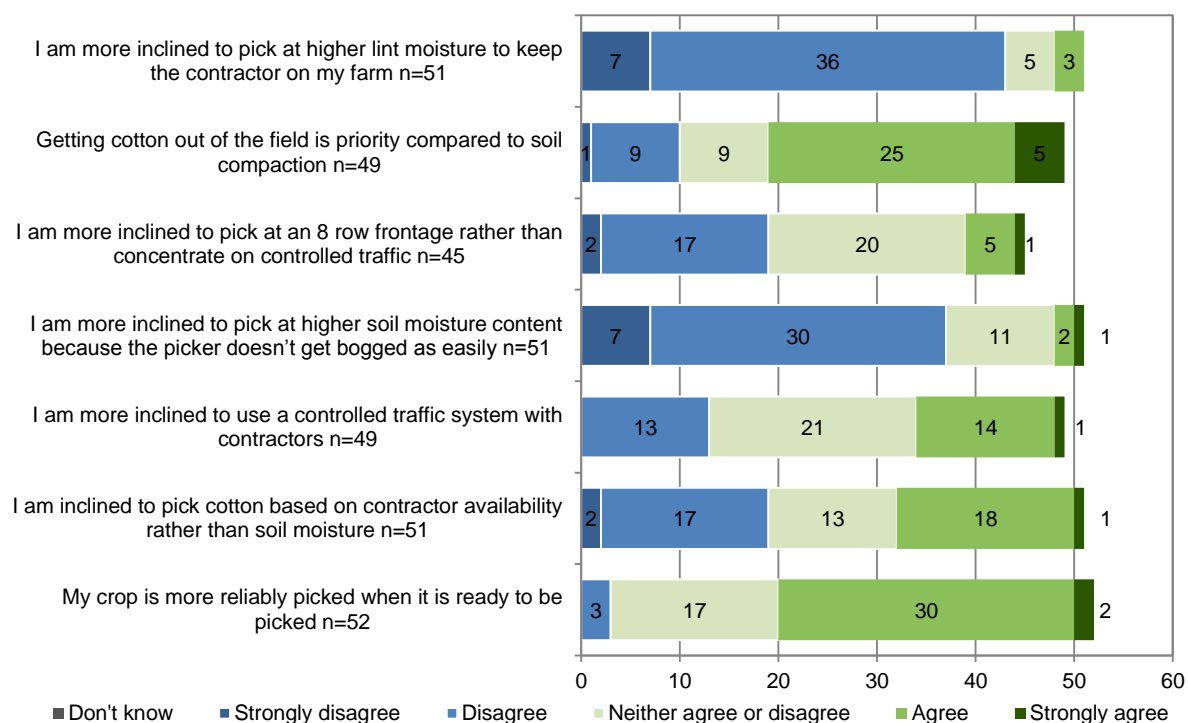
Figure 8. Grower attitudes towards the use of a contractor with a JD7760 picker in their farming system. Data is presented as stacked frequencies. Values within bars represent the number of respondents for each category (the total summing to n).

Views on soil compaction and its management

In 2015 growers were asked their views on compaction as an issue and how this might be managed, with controlled traffic farming presented as the better method in terms of long-term productivity (based on previous industry advice and the current findings); a summary of major emerging themes is presented in Table 3. In 2013 the majority of growers indicated that soil compaction did not feature as a concern when purchasing the JD7760 with a further ~50% indicating it had increased soil compaction. By 2015 this had increased to 81% of growers indicating that it caused a significant impact on their production system. Whilst this value is likely influenced by the fact a presentation on impact of theJD7760 on soil compaction was shown prior to discussion, of more interest is that 19% of growers thought the impact was not significant even in the face of scientifically collected information suggesting the JD7760 had significant impact.

A further 7% (3 growers) indicated that soil compaction was not a concern at all, explaining that they had seen no yield impact. Further discussion revealed that these three growers, 2 different forums, had highly uncontrolled traffic systems where multiple machine passes occurred with mismatched wheel spacing ranging from 2–4 m track width. These growers had GPS guidance systems, but also did not always use them, or construct cropping-hills in exactly the same spot. In this case, it is possible that soil compaction was already impacting the system, so introduction of the JD7760 did little in terms of detectable impact.

Whilst not an emerging discussion theme, it was clearly evident in all discussion forums that growers expected significant rut formation to need to occur in order to cause soil compaction. This confuses flotation and compaction. Rut formation usually results in compaction, but where soil is sufficiently dry at the surface and adequately plastic in the subsurface, compaction can occur without rut formation. This indicates there is further requirement to communicate the incidence, mechanisms and ideal conditions for soil compaction to occur.

Table 3. Summary of emerging themes for compaction management discussion forums held in the Australian cotton industry in 2015. For frequency of response use N=43. For number of forums representing view use N=5

Emerging theme	Frequency of response (%)	No. of forums representing view
Soil compaction as an issue		
Soil compaction is a significant* issue since using the JD7760	81	5
Soil compaction is not a concern in my farming system	7	2
Controlled traffic farming as a management option		
Will only work if majority of industry changes (contracting)	78	5
The cost of conversion is too high	88	5
Available row-spacing won't work in my system	45	4
More CTF-row-spacing information is required for regions	83	5
Would convert in the short-term	13	5
Would convert if short-term profitability benefits clearly are demonstrated	59	5
Cultivation to maintain yield		
Basic** cultivation is sufficient management	67	5
Deep ripping will protect/increase yield	50	3
More information on yield and cultivation depth (inc. cost)	25	3

* Significance was described as affecting production inputs or outputs
** Basic was defined as not deep ripping where a bull-dozer or equivalent horsepower machine is require (<20 cm)

Controlled traffic as the optimal approach to compaction impact limitation and protection of long-term productivity was generally well received, but discussion tended to focus on why this would be too hard to implement rather than the benefits of converting. Such discussion is useful in identifying

barriers to adoption and formulating plans to counter these. The major impediments to adoption, in order of importance, that emerged were: 1) cost of conversion; 2) alternate cotton row-spacing information availability; and 3) rate of industry adoption. The cost of CTF conversion for a JD7760 is ~AUD $68K (Pers. Comm. Vanderfields, 2015), which is not a substantial cost in the scheme of the capital investment made. However, there is doubt around cost to convert other machinery and implements, due to no agreed CTF standard track width and little track width option available directly from manufacturers (Tullberg 2010; Tullberg *et al.* 2007). Cost benefit analysis of conversion will be required in convincing the industry to adopt CTF within the cotton industry. Furthermore, whilst the cost to convert completely to CTF might still be relatively low in terms of matching equipment to a 3 m track (current popular track for grain harvesting equipment), the uncertainty around time to recover this cost remains.

Closely coupled to the discussion around requirement for cost-benefit analysis of CTF was row spacing. A 1.5 m CTF row-spacing case-study was presented at each forum, along with a concept for a 1.0 m system at 3.0 m track width picking a five row frontage. There was an apparent concern that current high performing cotton cultivars are specifically bred with a 1.0 m system in mind and that changing to any other row-spacing would reduce yield. The 1.5 m spacing did reduce total yield, but also reduced input costs. Interestingly, the term "Yield is king" was used multiple times at multiple forums when discussing the 1.5 m system and the reduction in green hectares. This again highlights the need to portray yield in terms of system comparative gross margin and in terms of water use efficiency. Ultra-narrow row-spacing is a potential option, but no publically available information concerning system performance when incorporated with a JD7760 could be found. This should be provided greater attention and future row spacing research should include the traffic system as an important variable.

Only 13% of growers indicated they would convert in the short-term with the majority of these at Jimbour (strong CTF culture) and Goondiwindi events. If the profitability of a CTF system could be clearly explained, this only resulted in 59% of growers indicating they would seek to convert (includes the 13% short-term converters), which is substantially less than the 81% who thought it was a significant issue. Whilst this can be partially explained by row-spacing uncertainty, there was genuine concern that ability to get a contractor on-farm or the ability to go contracting to supplement income would be hampered is there was not a high level of regional CTF adoption. Row-spacing information can be collected and presented with time, but on-farm gains from CTF would need to offset current contracting income to facilitate slow adoption. Alternatively, the discussion indicated that a critical mass of early adoption will be required to convince the majority of growers to adopt.

Interestingly, 67% of growers considered that current basic cultivation practices were sufficient in managing compaction, with 50% believing that deep ripping could protect/increase yield. This was evident at Aubigny, Goondiwindi and Narrabri and appeared to stem from industry anecdotal evidence of high yield (14-15 bales/ha) where deep ripping had occurred. This was in keeping with cultivation results presented at the forums (detailed in subsequent chapters), whereby increased cultivation depth resulted in increased yield. All forums raised, unprompted, in discussion that further information on cultivation depth and the subsequent cost-benefit should made available.

Conclusion

Adoption of the JD7760 since inception in 2008 was approximately 82% in 2013, and was primarily driven by perceived improvements in farming system efficiency, rather than immediate productivity gains. Specific major adoption drivers were: (1) increased safety on farm, (2) improved effective capacity, and (3) reduced labor requirements coupled with decreased management-related stresses. Transport of the machine and round modules, along with ability to gin round modules, were all identified as issues, but were rapidly addressed by the industry, presumably as they directly affected the supply chain. Latent impacts of the JD7760 were identified as the cost of module wrap and soil compaction, although the industry had faith that module wrap cost would be rectified in the short-term. Additionally, survey data suggests that the JD7760 is not being utilized to its full capacity throughout the industry, which suggests saturation of the market and raises some concerns where supplementary income relies on contract harvesting.

The JD7760 is identified as a heavy machine with potential to cause soil compaction beyond previous systems. It also has greater horsepower than previous systems. Generally, the attitude towards protection of the soil resource in terms of traffic in moist conditions was positive, even though the machine was capable of traversing the conditions. However, there was clear tension between harvesting yield (risk of loss) and avoiding soil compaction. Controlled traffic farming is the most efficient way of dealing with this tension, but significant challenges in moving toward adoption were present in insufficient cotton row-spacing information relating to compaction and yield, and hesitance to convert unless a regional critical mass converted within a short timeframe. The later was primarily linked to contractor availability, and ability to supplement income through contract harvesting. The cost of conversion was also raised as an issue, highlighting the importance of detailing actual costs and the timeframe these could reasonably be recovered in. The requirement for further investigation into the relationship between cultivation depth, cost and cotton yield was also identified.

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3. Impact analysis

This section builds on the outcomes of the Australian perspective on integrating the JD7760 into the farming system by directly analysing a number of impacts. The analysis is done from an engineering, biophysical and economic point of view, with the social impacts detailed in the previous section.

Initial impact assessment of the John Deere 7760 on-board-module-builder for the Australian cotton industry

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Introduction

Since the inception of machine-based cotton pickers having on-board module building, the time required to pick a bale of cotton (weight range: 2-2.5 Mg) has decreased from approximately 50–70 man-hours (hand-picking) down to eight minutes (Narayanan, 2005; Wattonville, 2008; Willcutt et al., 2009). This reduction is due to mechanisation and continued innovation of the cotton picking platform. The John Deere 7760 (JD7760) was introduced to the Australian market in 2008 and since then has undergone rapid adoption, probably the most rapid innovation adoption in the Australian cotton industry history.

Such a rapid change can have impact on the farming system that was duly perceived, as well as more latent impacts. Additionally, perceived positive impacts are sometimes not realised to the extent initially perceived. Hence, this chapter undertakes an impact analysis of the JD7760 with regard to the Australian cotton industry. Focus is placed on the machine itself, how it came to be and what this means for the Australian industry. An impact assessment for the JD7760 is presented and the major impacts discussed.

Advances in cotton picking techniques and technology uptake

Innovation and automation in cotton picking technology are often regarded as key drivers for a successful and competitive industry. However, mechanization of cotton harvesting brought about contrasting effects; for example, increased picking rates, ability to manage greater land areas, and lower labour requirements, but also resulted in gin downtime and safety issues (Fragar and Temperley, 2011; Holley, 2000; Key, 1985). In mechanized agriculture, higher capacity machines have contributed to reduce risk associated with climate uncertainty (timeliness), improve harvest rates and overall system efficiency but, often, at the expense of increased weight of farm equipment. Cotton production systems are no exception; cotton pickers feature more design constraints than other systems because of the picking action of the spindle. Maximizing picking efficiency, that is the percent of cotton picked from the crop, requires plants to pass through the spindle mechanism (Willcutt et al., 2010). Consequently, the direction of travel must be the same for that of planting. Because the majority of Australian cotton growers (approximately 80%) utilize furrow irrigation (Roth et al., 2013; Silburn et al., 2013), picking must be conducted in the same direction as the furrows in any location in the field. Other crops such as winter cereals do not have this limitation because the plants can be cut at any position relative to the front of the machine by harvesting first. Hence, the direction of harvest can change from the planting direction, allowing for increases of turning space. Conversely, furrow-irrigated cotton fields in Australia are characterized by "dead space" at the head ditch reserved for turning machinery, which cannot be increased by harvesting first. Therefore, the turning circle has to be small to minimize turning time, which is enabled by maintaining a short wheel-base and a relatively narrow, rear track-gauge width (Deutsch et al., 2001).

The latest cotton pickers manufactured by John Deere (e.g., JD7760 and CP690), commonly referred to as round balers, utilize on-board module building (OBMB), as opposed to the conventional boll-basket picker (BP), which requires external module building and additional in-field equipment support to operate (Deere and Company, 2014; Willcutt, 2011). The weight of the JD7760 is approximately 36 Mg fully loaded, with a rear axle load reaching 16.5 Mg; this represents a weight increase of about 50% compared with the BP (Deere and Company 2012). This has several engineering design implications for the JD7760, including: (1) increased dimensions of rear tires, (2) repositioning of engine, and (3) raised chassis. The increase in the overall weight of the machine has resulted in increased risk of soil damage due to compaction, which is recognized in several studies to be one of the main causes of soil degradation in cotton-based systems in Australia (e.g., Bennett et al., 2014; Braunack and Johnston, 2014). Estimates for Australia indicate that the cost of soil compaction, determined as equivalent agricultural production loss, is approximately AUD$850 million per year (Walsh, 2002). The incidence of soil compaction has brought about increased discussion on the maximum acceptable axle load for agricultural machinery with large physical footprints (Mosaddeghi et al., 2007). Despite this, the Australian cotton industry has seen a rapid adoption of the JD7760, with approximately 80% of the cotton area harvested in the 2012/2013 season picked by JD7760 pickers (Chapter 2). Further, 36% of JD7760 owners have more than one JD7760 picker (Chapter 2). The JD7760 picker has been labelled as a revolution in cotton picking (Wattonville, 2008); however, improved understanding of its potential impacts on the cotton production system is required.

Overview of efficiency gains.

Harvest rates of cotton pickers have increased with the increase in harvest frontage width from approximately 0.35 ha h^{-1} for a two-row cotton picker to 3.5 ha h^{-1} for the six-row JD7760 picker (Key, 1985; Willcutt et al., 2009). This is shown in Figure 1(d) based on several studies (Chen and Baillie, 2009; Kocher et al., 1989; Kulkarni et al., 2008; Parvin and Martin, 2005; Wanjura et al., 2013; Wilcutt, 2011). Field efficiency has remained close to constant for the BP system using baskets for uncompressed boll capture, whereas field efficieicny of an OBMB is greater by approximately 75%. Effective capacity is derived from field efficiency and forward speed, and appears to be the parameter upon which mechanization had the greatest effect.

The increase in cotton picking rate indicated in Figure 1 has not translated into increased fuel, which has remained close to constant despite the operating capacity gains. Three main constraints on field machinery operations that affect the theoretical capacity (TC) are: (1) operational, (2) power- and machine-related, and (3) weather-related (Gao and Hunt, 1985). Therefore, the actual or effective capacity (EC) is somewhat less than TC. The EC depends on field efficiency (FE), which considers the total effect of the following factors contributing to non-productive use of time (Edwards and Boehlje, 1980; Gao and Hunt, 1985): (1) non-operating turns, (2) less than full-width operation, and (3) stopped time (e.g., refuelling, machine adjustments). The FE is therefore the ratio of time effectively used to total time spent processing an area, that is, the ratio of effective to theoretical field capacity (Gao and Hunt, 1985). This relationships is shown in the following equation:

$$EC = TC \times FE$$

where: EC is effective capacity, TC is theoretical capacity, and FE is field efficiency.

Effective capacity appears to be the main factor underlying machine innovation and technology uptake. The need for increased EC has influenced cotton production systems in several ways. In the 1940s, on the high-yielding West Coast of the U.S., the cotton spindle picker rapidly replaced hand-picking (Heinicke and Grove, 2008). As a result of technology uptake, farm incomes, farm size, and productivity increased, which are perceived benefits of increased EC.
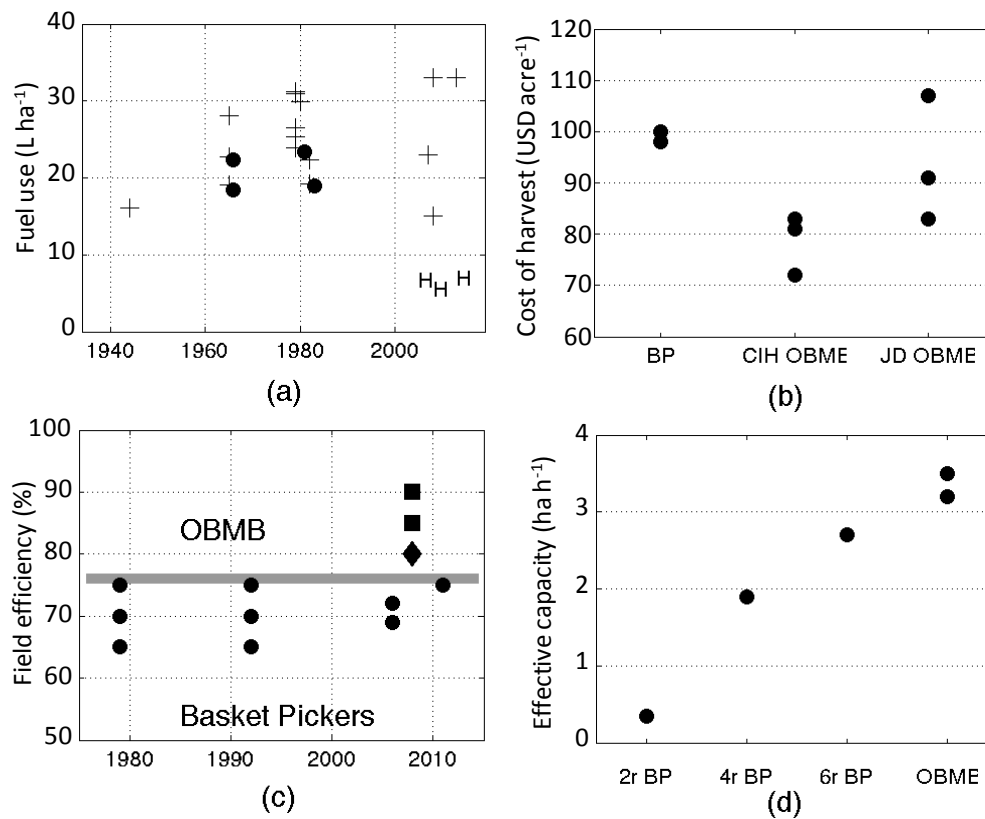
Figure 1. (a) Fuel use during first (+) and second picking (●), and the handling system (H); (b) Cost of harvest for basket pickers (BP), CASE IH 625 OBMB, and the JD 7760 OBMB; (c) Field efficiency over time for basket pickers (●), CASE IH 625 OBMB (♦), and the JD 7760 OBMB (■); (d) Effective capacity for two- (2r), four- (4r) and six-row (6r) basket pickers, and the OBMB.

Between 1955 and 1965, adoption of mechanized cotton pickers in the U.S. increased from 12 to 100%, which made it difficult for ginners to process the influx of machine-picked cotton (Anthony and Mayfield, 1995). Gins became the bottleneck in the cotton production system, which led to farmers dumping cotton at the ends of rows to enable picking to continue (Anthony and Mayfield, 1995). In the late 1960s, the caddy and the ricker became the first devices to form a free-standing stack of cotton (Anthony and Mayfield, 1995). However, these free-standing stacks were inefficient in comparison to the conventional system developed later by Cotton Incorporated known as the module building (MB) system (Jones and Wilkes, 1973). Complete adoption of the MB system did not happen until four-row cotton pickers increased field efficiency in the 1980s. Although the MB system was successful in removing the gin as the main impedance, from an occupational health and safety perspective, it significantly increased the risk of injury (Willcutt et al., 2009). In Australia, from the 1997/1998 to the 2005/2006 seasons, the MB system was responsible for 723 workers compensation claims and claimed four lives (Fragar and Temperley, 2011). Clearly, the inception of an OBMB alleviates the requirement for the MB to be used, which provides less labour requirement and removes the work place health and safety concern.

Overview of cotton-picking systems in Australia.

The growing conditions and yields for cotton in Australia are similar to those in the western U.S. (USDA, 2015). Both regions have seen similar rates of adoption of novel picking technology (Chapter 2; Musoke and Olmstead, 1982). Differences between the JD7760 and BP system fronts are minimal; however, the former machine does not require stopping to unload into boll buggies, which is the main gain in terms of improved efficiency (Willcutt et al., 2009). On average, one boll buggy and one MB are required for every six rows of cotton harvest, meaning that the OBMB demands approximately the equivalent of 2.5 tractors per 1000 ha (Parvin and Martin, 2005).

Relatively high yields per hectare in Australia, as compared to the U.S., result in an approximate requirement for 1.5 boll buggies or 2.5 module builders per 1000 ha of cotton picked at six rows. Consequently, labor requirement was reduced by eight people every 1000 ha. Another effect identified with the use of OBMB, particularly the JD7760, is that cotton presents larger moisture variation to ginners in a ginning run, due to a mixture of cotton bales picked at different times during the day (Houlahan, 2012). There is less mixing of cotton in the JD7760 system compared to the BP, which stores cotton in a basket and is subsequently transferred either into a boll buggy or a MB, then receiving multiple compressions (Willcutt et al., 2010). In the JD7760, cotton is compressed only once following picking, which reduces the opportunities for airing (Willcutt et al., 2010). This increases variation at the gin, as round modules reflect field variation, although are internally homogeneous and arrive at the gin often not in sequence, whereas conventional modules builders homogenize field variability into larger modules and are sequenced easily, meaning less variability at the gin (Willcutt et al., 2010). Several studies (e.g., Houlahan, 2012; Vanderstok, 2012) highlighted additional costs associated with the JD7760 system such as the wrap and increased cost of transport due to weight and size of harvesting equipment.

To increase EC, machine efficiency and process automation are the main requirements. Direct benefits on productivity also carry latent effects on the system, such as those relating to decreased workforce availability, health and safety-related issues, and potential impacts on social capital at the regional scale. The Australian cotton industry is characterized by its resilience and responsiveness to technological changes; for example, by strengthening production and processing systems. This process has been acknowledged as ad-hoc and reactive, rather than structured and mitigative. Early identification of likely technological effects on cotton production and processing systems would enable systems optimization prior to significant technology uptake across the industry.

Implications of increased effective capacity.

Initial concepts to compress cotton on-board began in the early 1920s with an all-in-one picking and ginning machine, and continued in the 1950s and 1960s (Nickla, 1968; Silverthorne, 1919; Wagnon, 1956). However, the physical properties of cotton have presented machinery designers with challenges, which led to the development of augers to compact cotton on harvesters (Deutsch, 1989). Subsequently, this concept led to the design of the first OBMB in the 1980s consisting of an auger 1.5 m in diameter and two module chambers (Fachini and Orsborn, 1985). The first OBMB was developed by John Deere and CASE IH in the early 2000s (Covington et al., 2003). John Deere combined the cotton picker with design and principles applied to hay balers, whereas CASE IH used proven concepts of the MB (Gola et al., 2000; Viaud, 1990). Due to the automation of the module-forming process, both John Deere and CASE IH developments improved overall occupational health and safety aspects of cotton harvest (Fragar and Temperley, 2011). However, the focus on improving EC also resulted in increased

overall machinery weight compared with conventional BP. The increase from two- to four-row pickers revealed a number of design constraints such as the relationship between spindle size and forward speed of the machine (Figure 2).

When forward speed is increased, the speed of the row of spindles needs to be increased to maintain a zero velocity relative to the cotton plant. The rotational speed of the surface of the spindle also needs to be increased so that the barb can continue to attach to the cotton fibre and be removed from the plant (Baker et al., 2015). This problem can be overcome by increasing the revolutions per minute of the spindle or by increasing its diameter (Baker et al., 2015). The latter solution results in increased weight of the spindle and cost of material; hence, increased rotational speed is the preferred option. The drawback is that higher revolutions per minute might decrease lint quality through higher counts of short fibre and tiny knots (neps), suggested to double the occurrence for every 1000 rpm increase (Armijo et al., 2006; Baker et al., 2010).

In Figure 4, the starting weight includes the weight contribution of fluids, five rolls of wrap, dual wheels, and six-row PRO-16™ picking units. During the formation of the initial round bale, the front axle load remains relatively constant at approximately 21.5 Mg. Subsequently, it decreases to slightly less than 20 Mg as the bale moves to the rear platform. The load on the rear axle is more dynamic compared with the front axle having an initial

Figure 2. Constraints and possible engineering solutions to optimize forward speed, speed of spindles relative to the ground, speed of the surface of the spindle, which enables the attachment of cotton, and rotational speed, which can potentially tangle cotton.

weight of approximately 10.6 Mg when the machine is empty and increasing to 12.8 Mg after the first round bale is formed. Subsequently, the rear axle load changes from 14.5 Mg to 16.5 Mg when the second round bale is formed, which equates to approximately 45% of the total load of the machine. The absolute maximum (dynamic) weight of the machine fully loaded with cotton and assuming the weight of a round module to be 2.27 Mg (Deere and Company, 2012) is estimated to be 36.5 Mg. This analysis does not compute the weight of the cotton in the accumulator.

An increase in machine length could alleviate the significant increase in dynamic load on the rear axle but such a configuration could have a negative effect on turning efficiency. Tight turnings allow for reductions in turning times (Renoll, 1979). It also enables the machine to fit between the head ditch and the start of the row in situations where cotton is furrow-irrigated. Therefore, a short wheel base with high angle pivoting rear tires is critical (Wong, 2001). John Deere expressed difficulties in accommodating for larger wheels and maintaining a tight turning circle (Fox et al., 2009). This would necessitate repositioning and realignment of the engine, and raising the rear wheel cavity accordingly to create the required space (Fox et al., 2009). Tire dimensions for the JD7760 are 520/85R42 R1 (inflation pressure: 0.25 MPa) and 520/85R34 R1 (inflation pressure: 0.32 MPa) for the standard dual front and standard steering tires, respectively (Deere and Company, 2014). Increasing the wheelbase and track width requires sharper steering of the

Figure 3. Side drawing of the JD7760 cotton picker (after Deere and Company, 2012). Dimensions are: (A): 10.1 m, (B): 5.25 m, (C): 3.81 m, (D): 4.32 m, (E): 3.89 m, (F): 7.48 m.

Figure 4. Dynamic axle loads for front and rear axles of a JD7760 round baler cotton picker. The x-axis represents the time that takes to form a round bale. The space between these points is the transition phase as a bale is produced.

wheel to maintain the same turning circle (Wong, 2001). Constraints from the cotton production system and machine design characteristics have resulted in restrictions in all three dimensions: height (storage and transport), width (cost and weight of additional picking units), and length (turning circle radius). Space for the addition of the OBMB is limited, resulting in much of the excess weight positioned on the rear axle. The implications of increased axle load for agriculture are primarily concerned with soil compaction, with a secondary impact in terms of increased fuel consumption during tillage (increased draft force).

Potential compaction effects of the JD7760 cotton picker.

The JD 7760 has a six-row cotton frontage, which is compatible with a 12-m planting system common to cotton. Because the machine is fitted with dual tires on the front axle, the area traversed is larger compared to conventional four-row pickers. The dual wheels of the JD7760 increase the total area subjected to traffic compared to conventional pickers. The use of BP requires boll buggies, which enable machine downtime to be minimized by unloading a full basket into the boll buggy. Therefore, the picker can work continuously without the need to leave the field, although boll buggies are of less concern from the soil compaction perspective.

The positioning of machine transient load affects individual wheel loads in a nonuniform fashion. For this reason, Keller and Arvidsson (2004) suggested that wheel load is relatively more important than axle load when soil stresses are estimated, and that each wheel of the machine should be considered

independently. In this respect, Schjønning et al. (2012) proposed the 50:50 rule, which refers to the avoidance of traffic in soils with moisture contents near field capacity if soil stresses at 50 cm deep exceed 50 kPa. Other approaches based on critical soil moisture leve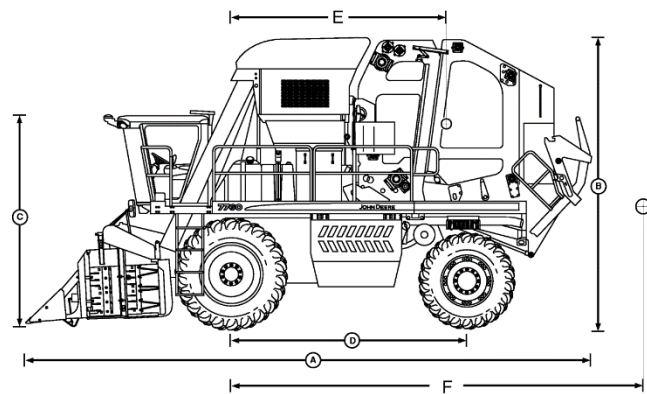ls for field traffic have been used satisfactorily (e.g., Earl, 1997; Ohu et al., 1989; Vero et al., 2014). For the JD7760, the dual wheel configuration results in an average wheel load of approximately 5.4 Mg on the front axle, which decreases to approximately 5 Mg as a round module is transferred to the rear haulage basket. The average load on each rear wheel increases from approximately 5.3 to 8.25 Mg, during the same process (Figure 4). The average wheel load of the JD7760 for all wheels, especially in the rear wheels, largely exceeds, the threshold load suggested by Danfors (1994; 3 Mg per wheel).

Further work by Braunack and Johnston (2014) showed that average soil strength (cone index) increased to a similar extent following traffic with conventional BP and RB pickers (depth range: 0-600 mm). However, traffic with the JD7760 caused increased strength (3000 kPa) at a slightly shallower depth (300 mm) compared with the conventional picker (400 mm). Soil strength greater than 2000 kPa causes significant root growth retardation in cotton (Coates 2000). A study by Kulkarni et al. (2010) showed that soil compaction increased progressively in the direction of travel due to the change in cyclic loading that is characteristic of harvesting equipment (gradual filling of harvest space with harvest). The JD7760 places the round module (weight: 2.3 Mg) on the ground as it travels, which commonly occurs in-field given the length of Australian cotton fields. A tractor then needs to remove the module from the field, which increases traffic intensity, albeit on the same tracks. This problem is sometimes overcome by attaching a trailer behind the picker, which is capable of carrying up to four bales, therefore enabling reduction in traffic intensity. The trailer also reduces the period of time in which the load of the rear axle is elevated to 8.25 Mg by distributing the load over tandem axles on the trailer. However, effects of the pass of the trailer over the same pass of the picker require investigation to determine whether additional compaction is created. Additionally, the turning circle of the machine is increased where a trailer is used, which may affect headland requirements.

The area affected by traffic when dual tires are used appears to be one of the main concerns associated with JD7760 cotton pickers. Innovative Australian growers have adapted their machines to suit true CTF system using single tire configurations both on the front and rear axles (e.g., 3-m wheel-spacing on 1-m row-plant spacing). However, such modifications void the machine warranty, which therefore discourages growers from adapting their equipment to make them compatible with CTF systems (Tullberg et al., 2007).

Towards an Informed Decision-Making Framework.
Although the decision to adopt the JD7760 cotton picking system is not in question, the rate of technology uptake has brought about concern over sustainability aspects of intensively managed agricultural soils. These sustainability aspects include potential long-term effects on crop productivity and energy use in tillage repair. Increasing harvest rates in cotton cropping via the range of innovations discussed has shown both positive and negative effects on the overall dynamics and efficiency of the system. To enable such effects to be determined prior to technology adoption and identify possible mitigation options, an initial impact assessment framework has been developed (Figure 5). This framework identifies potential impacts considered to be major, based on the information compiled in this work, to assist in informed decision-making.
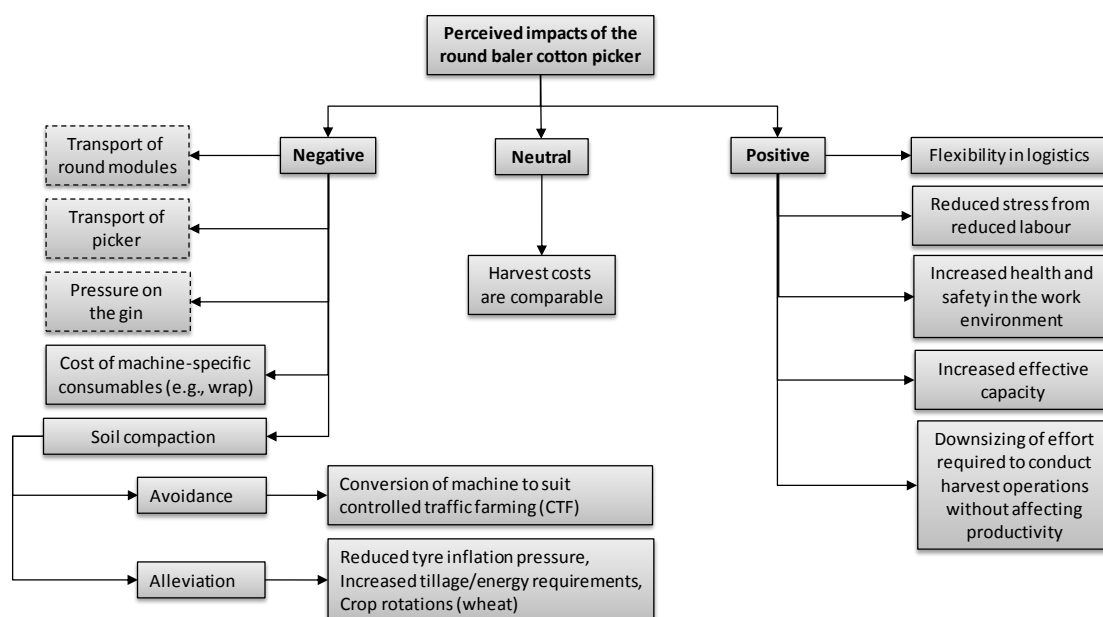
Figure 5. Summary of impacts identified following the introduction of the round baler picker into the Australian cotton system. Information drawn from the Australian perspective and the literature reviewed in this work. Dashed lines indicate that those issues are already dealt with by the industry.

As a result of initial analyses of literature and the Australian perspective of the JD7760 and farming system incorporation, it is clear that supply chain issues are quickly dealt with. The JD7760 itself is not something easily modifiable, and appears to be well suited to the Australian cotton system in terms of its operation, labour requirement, and effective capacity. However, the potential for soil compaction due to the increased weight, and significant increase in wheel load, is a very serious issue that requires further investigation for the Australian cotton industry. Typical soils (Vertosols) within the Australian industry have soil water holding capacity that is considered very high and retain relatively high water content at permanent wilting point for crops (−1500 kPa). This is due to the high clay content of such soils. As clay content increases, the forces that govern soil compaction shift from frictional to cohesive, and cohesion forces are highly affected by small changes in soil moisture. Thus, it is apparent that Australian cotton soils may present the perfect storm for soil compaction under heavy machinery. As such, the focus of this report is on soil compaction extent and management of this within the context of the farming system.

Conclusion

The bulk of impacts caused by the JD7760 cotton picker are perceived as positive. Despite this, the majority of growers picking cotton in regular seasons suggest that the use of the JD7760 has implications for soil compaction, which need to be considered in managing agricultural systems into the future. Further work including associated effects on energy use in tillage repair treatments, long-term effects on crop yield, and soil sustainability merits a research priority. Soil compaction research in grain cropping has shown that production loss, and soil, water, and energy conservation, are significant, and points towards increased adoption of CTF. However, there are perceived financial restraints to adopting CTF such as initial capital outlay and risk of loss of product warranty.

Even though the implications of the JD7760 for the cotton system in terms of transport and ginning have been rapidly identified and adjusted for, a desirable option would be for growers to identify these effects prior to adoption to have mitigation plans in place and minimize potential negative

impacts on the system. To enable this, decision support systems are required to assist in quantifying benefits as well as potential impacts and costs associated with those impacts. Such a framework could be applied to demonstrate the benefits of CTF and the feasibility for its adoption in cotton-based systems.

Technology uptake is largely driven by the need to improve EC with less labour and in a safe manner. However, technological advances and progressive increase in EC require that potential impacts associated with technology uptake are identified as early as possible in the adoption process. Australian cotton growers have embraced the JD7760 on the basis of clearly elucidated benefits to the harvesting system. John Deere's success in elucidating these benefits, highlights that large capital outlay can be overcome by clear communication. On the basis of understanding what the JD7760 offered the farming system, growers have actively worked with the industry to rapidly overcome associated issues within the cotton production system.

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Impact of the John Deere 7760 on compaction of Australian cotton soils

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Introduction

The cotton industry has recently undergone a revolution in harvesting technology whereby the requirement for multiple operations such as harvesting, chaser bins (boll buggies) and module building (compression of cotton for transport to processing plant) has been decreased to a single operation using an on-board-module-building (OBMB) system. John Deere (JD) has produced cotton harvesters that pick, accumulate and compress cotton into modules on-the-go (JD 7760). With the addition of the OBMB, the machine weight of the JD7760 ranges from 32 Mg (field ready starting weight) to 36.5 Mg (fully laden; i.e. carrying two modules), which is approximately a 50% increase in weight from the previous cotton harvest system. Additionally, as the machine creates a module on board, the weight over the rear axle increase from 10.6–12.8 Mg, and then from 14.5–16.5 Mg as it creates a second module and carries the first module in a basket at the rear of the machine. The front axle weight is more static at approximately 21.5 Mg. The front axle load is spread over four wheels in a dual wheel configuration, whilst the rear axle is spread over only two wheels that are slightly offset to the inner dual wheel of the front axle. This increase in machine weight and large traffic footprint present substantial concerns for soil compaction, as well as subsequent yield and tillage energy costs.

The JD7760 is simply following a trend in the past few decades toward the use and development of larger and more powerful agricultural machinery to increase the effective capacity of agricultural machinery. This trend will likely continue (Kutzbach, 2000). Increased machinery size has the drawback of increased axle loads, increasing subsoil stresses (Keller & Arvidsson 2004). In grain cropping, Chamen (2014), estimated an average 14-fold increase in subsoil stresses (from about 0.02 to 0.28 MPa at 400 mm deep) between 1930 (horse-ploughing) and 2010 (30 Mg combine harvesters), respectively. Despite the JD7760 cotton pickers being fitted with dual tires on the front axle, subsoil stresses are comparable to those reported by Chamen (2014) for commercially available combine harvesters. Consequently, the drive towards adoption of more efficient machines to reduce costs and increase work rates has brought about concern, due to the potentially negative effects of increased soil compaction and the associated need for tillage repair.

Therefore, this work aims to provide a broad industry assessment of soil compaction extent due to the inception of heavy cotton machinery, principally the JD7760. In doing this, both topsoil and subsoil compaction will be assessed in order to understand the risk of unchanged traffic management.

Methodology

Six experimental sites (Table 1) were utilised to assess soil compaction impact of the John Deere 7760 (JD7760). The sites came from the Macquarie Valley, Macintyre Valley and Darling Downs, but represented the major cotton growing soil, primarily Grey Vertosols and Black Vertosols. Sites were selected on the basis of traffic history so that a range of histories could be assessed. Due to the rapid adoption of the JD7760, choice of sites where it had not been used prior to 2012 were extremely limited. Auscott, and Kieli sites had never had a JD7760 traffic the experimental sites at the time of measurement. Whilst Kieli was a dryland farm, the soil was experimentally irrigated for Kieli. Hence,

at the time of traffic all sites were considered representative of irrigated soil; moisture content at time of traffic is reported.

Table 1. Experimental sites, region and location with traffic history prior to soil compaction assessment.

ID	Property	Region	Traffic history	Soil	Location
A	Auscott	Warren, NSW	24 yrs of traffic, bio-ripped, field reformed, no JD7760	Grey Vertosol	31°47'24.15"S, 147°44'4.68"E
B	Kalanga	Toobeah, QLD	11 yrs traffic, 2 yrs JD7760	Grey Vertosol	28°30'4.54"S, 149°45'37.23"E
C	Kieli	Jimbour, QLD	15 yrs no-traffic, no JD7760	Black Vertosol	26°57'35.26"S, 151° 7'4.46"E
D	Koarlo	Yelarbon, QLD	22 yrs traffic, 8 yrs ago traffic lines changed, and 5 yrs ago changed to 12 m system, 2 yrs JD7760	Grey Vertosol	28°37'26.62"S, 150°32'23.47"E
E	Yambacully	Goondiwindi, QLD	23 yrs of traffic, 2 yrs of JD7760	Grey Vertosol	28°27'39.00"S, 150°10'19.67"E
F	Yangullen	Aubigny, QLD	30 yrs of traffic, 4 yrs of JD7760	Black Vertosol	27°28'30.44"S, 151°37'41.27"E

Experimental design

The experiment was designed to provide a snapshot of the extent of impact the JD7760 has had since inception in the industry. From the six sites, two would provide a first impact assessment, whilst the other four provided a cumulative impact assessment. To achieve this, sampling was conducted before and after cotton picking traffic to determine changes in soil moisture content distribution and bulk density.. Figure 1 shows the wheel configuration of the machine corresponding to sampling approaches.
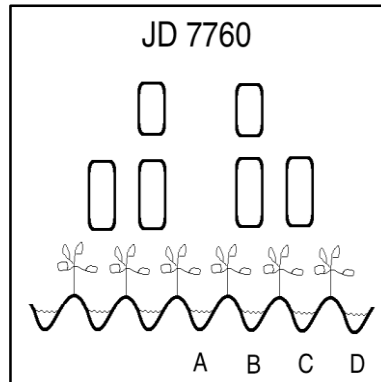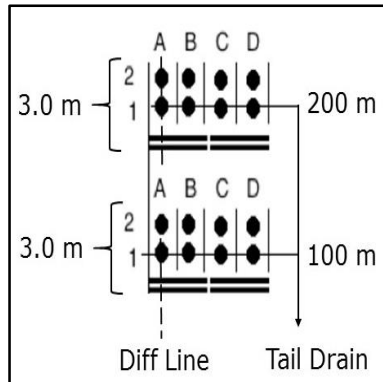
Figure 1. Experimental design where Left diagram shows positioning of soil cores (black circles) in furrows (A) centre furrow under machine differential (Diff), (B) inner-wheel/single-wheel, (C) outer-wheel (JD7760)/non-traffic furrow (Basket/CTF), and (D) non-traffic furrow with replicates 1 and 2 spaced 1 m apart. The Right diagram shows the furrow configuration for sampling under the John Deere 7760 (JD7760).

Whilst this approach only captured a small amount of information at numerous sites throughout three major cotton production valleys, it is valuable in confirming impact over a wider area. Given the rapid adoption of these machines and the dual wheel nature of them, the land mass affected is large, and a misconception is often that the dual wheels alleviate compaction to a tillage manageable depth. Hence, the experiment was designed to maximise the range of sites.

SoilFlex modelling

SoilFlex is an analytical model for simulation of soil compaction (Keller et al. 2007), and was used to simulate soil vertical stress distribution under the wheels of pickers. The model assumes that the soil profile is isotropic throughout, which is a limitation in terms of modelling subsequent expected compaction without adequate calibration. However, this does not affect stress state simulation, which is a property of the machine rather than the soil. Simulations were conducted assuming an elliptical contact area, standard tyres and inflation pressures.

Soil sampling

Soil sampling occurred at stations (Figure 1), before and after traffic. Sampling transects were constructed so that the furrow under the centre line of the machine (termed the diff furrow) through to the outer non-traffic furrow were investigated. Two replicates within 1.0 m of each other within the same furrow were taken at each station (Figure 1). Two stations were investigated for each property. The purpose of the work was to provide a snapshot of the machine induced soil compaction impact. Thus, sampling had to be minimised to ensure immediate before and after samples could be taken from the multiple properties within the same season. This approach maximised the sampling at a single property and allowed transition through the 1,200 km distance between properties for before and after sampling to be done with minimised time between sampling.

A total of 16 cores per sampling incidence were taken before and after traffic. The sampling depth was 0.8 m to coincide with the maximum depth of cone penetration resistance. Once sampled, cores were separated into 0.1 m subsamples, providing a total of 128 subsamples collected before and a further 128 collected after traffic. Subsamples were stored in sealed foil lined bags and placed in the shade prior to further measurement.

All sampling occurred within 200 m of the tail drain to accommodate manual sampling using a Christie's Engineering CHPD78 Post Driver. The post driver uses a slight, but highly repetitive, hammering action to push sampling tubes to depth. Manual sampling was required due to standing cotton. As the sampling method used a hammering action, soil core length was measured and the depth of the hole confirmed to ensure compaction had not occurred during sampling; this method did not cause compaction of samples.

Moisture content and soil bulk density

Soil samples were weighed as soon as possible after sampling to determine the field wet weight of each sample. Samples were then placed in an oven for at least 72 hours at 105°C and then weighed to determine the oven dry weight of the samples. By difference of the wet and oven dry weights, the sample moisture content was determined and reported gravimetrically (mass per mass) and volumetrically (volume per volume).

Soil bulk density was used to determine changes in compaction and inform volumetric moisture content. As the soil samples had very carefully been split into 10 cm lengths, this was used as the height dimension, along with the cross-sectional area of the soil core cutting tip to determine the volume of a 10 cm sample. The oven dry weight was used to calculate the bulk density of each sample and reported as mass per volume (g/cm^3).

Optimum moisture content

The optimum moisture content (OMC) of the soil for compaction was determined in the laboratory using the standard Proctor test, consistent with Australian Standard method AS1289.5.1.1, but modified to use 20 blows, rather than 25. Whilst this test is designed to determine suitability of construction foundations, the static load equivalent of the test was comparable with the calculated rear wheel load (maximum impact the soil is subject to) of the JD7760 at the surface, as reported by Bennett et al. (2015). The 20 blows provided an equivalent static load of 508 kPa (Raghavan & Ohu 1985). Hence, for the purpose of identifying the optimum moisture content, this method was considered adequate. Proctor test results are applicable to the 0–0.3 m depth, but the OMC can be

used to *inform* risk of compaction with greater depth. For uniform texture soils, such as Vertosols, the OMC with depth is likely to be similar, or slightly less.

Results

Stress state simulation

Vertical soil stress simulation using the SoilFlex model (Keller et al., 2007) was undertaken for the front and rear tyres of the JD7760 and JD9996 cotton pickers (Figure 2). Results suggest the dual tyres of the JD7760 caused vertical stresses of 100-200 kPa at 300 mm depth compared with 75-100 kPa under the JD9996 at the same depth in the profile (Figure 2a and c). Vertical stress caused by a single tyre (front axle) under the JD9996 are of similar magnitude compared to each of the dual tires under the JD7760 at 300 mm depth, despite that total contact area is approximately half (Figure 2 a and e). For the rear tyres, soil stresses at 300 mm depth are approximately double under the JD7760 compared with the JD9996.

Optimum moisture content

A standard proctor test was used to determine the optimum moisture content for compaction at ≈500 kPa, which are shown in Figure 3. The OMC ranged between 19.62 and 28.14% for the Vertosols measured. This results in an average OMC of 23.98%. Using this average to calculate departure from the maximum density provides an underestimation ranging from 0.01–7%. Accepting the underestimation as reasonable, all soils achieve compaction >93% of the maximum dry density using the average OMC.

Soil moisture and bulk density

Soil moisture at the time of traffic was generally within close proximity to the each soils respective OMC within the 0.3 m depth (Figure 4). The exception was Yangullen, which had GMC 15% greater than the OMC. Inferring potential risk at depth using the surface OMC suggested that all soils would be susceptible to soil compaction with depth. Once again, Yangullen had a soil moisture profile in excess of the OMC, with depth.

Comparative analysis for the inner and outer dual wheel in terms of impacting bulk density revealed that both wheels caused similar impact throughout the soil profile. There were no significant differences (α=0.1) between the inner and outer wheel at any depth of investigation. However, there was generally a trend that the inner wheel track have a higher bulk density than the outer; the inner wheel track accommodates both a front axle dual wheel and the rear wheel of the JD7760.

Bulk density was significantly increased by wheel traffic of the JD7760 at all experimental sites throughout the 0–0.3 m depth (Figure 5). The average increase in bulk density for this profile depth was, 10.2, 6.4, 17.1, 8.5, 11.4, and 11.7% for soils A (Auscott) through F (Yangullen), respectively. The total average increase in density for the six sites was 10.9% throughout the 0–0.3 m depth. Auscott, Kalanga and Yangullen exhibited significant (p<0.1) increase in soil bulk density throughout the entire soil profile depth investigated (0–0.8 m). Whilst the other sites generally did not provide significant increase in compaction with subsequent depth, this was most likely an issue of short-range spatial heterogeneity masking the effect. Examining the before and after traffic variance revealed that the variability in after samples was substantially less than before samples, indicating a JD7760 effect on soil structural arrangement (decreased variability).
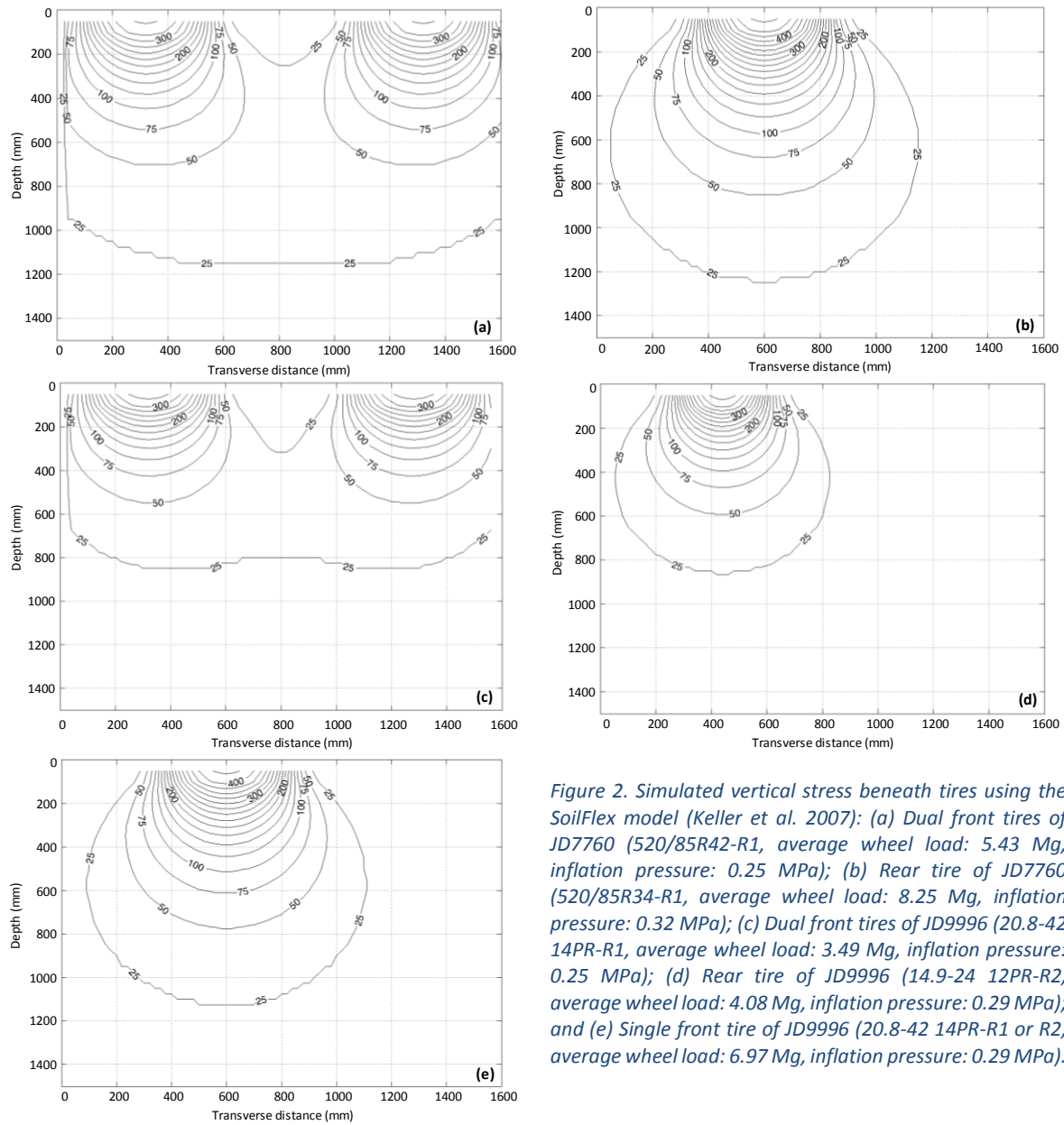
Figure 2. Simulated vertical stress beneath tires using the SoilFlex model (Keller et al. 2007): (a) Dual front tires of JD7760 (520/85R42-R1, average wheel load: 5.43 Mg, inflation pressure: 0.25 MPa); (b) Rear tire of JD7760 (520/85R34-R1, average wheel load: 8.25 Mg, inflation pressure: 0.32 MPa); (c) Dual front tires of JD9996 (20.8-42 14PR-R1, average wheel load: 3.49 Mg, inflation pressure: 0.25 MPa); (d) Rear tire of JD9996 (14.9-24 12PR-R2, average wheel load: 4.08 Mg, inflation pressure: 0.29 MPa); and (e) Single front tire of JD9996 (20.8-42 14PR-R1 or R2, average wheel load: 6.97 Mg, inflation pressure: 0.29 MPa).
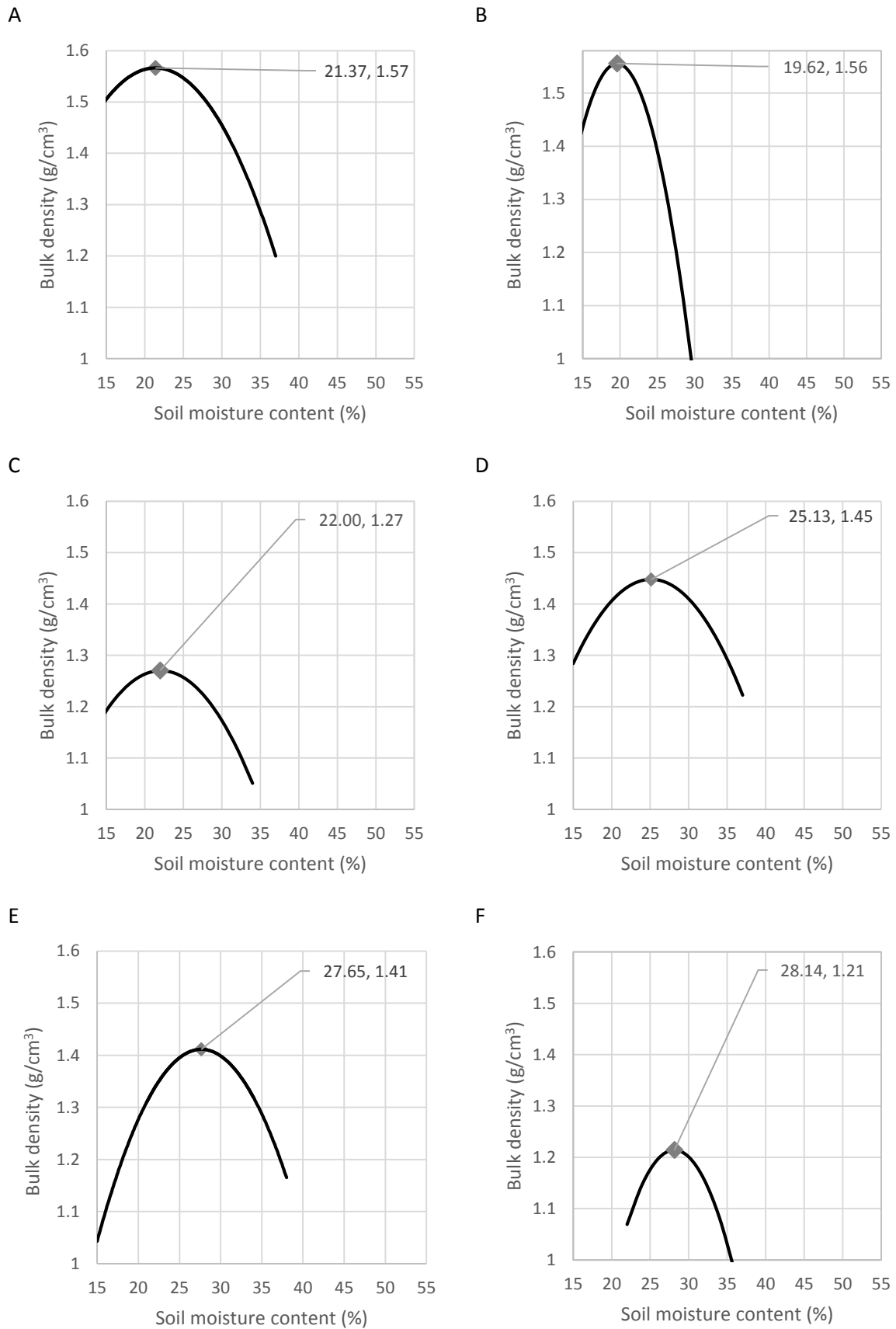
Figure 3. Dry density curves for the experimental sites in Table 1 obtained using a Stand Proctor test modified for 20 blows. Callouts detail the optimum moisture content (%) and maximum dry density (g/cm³) respectively.
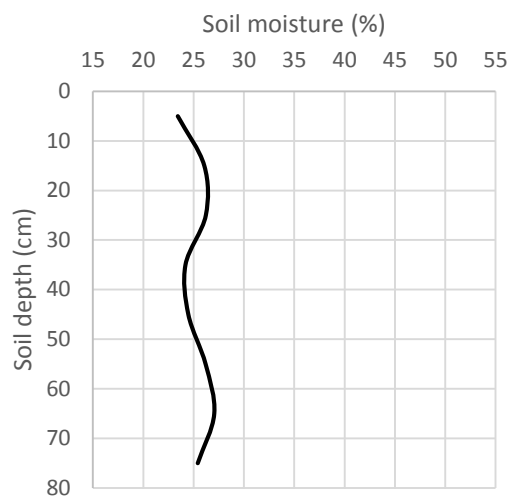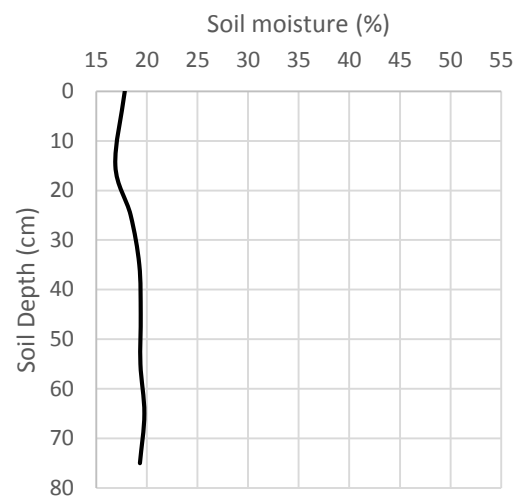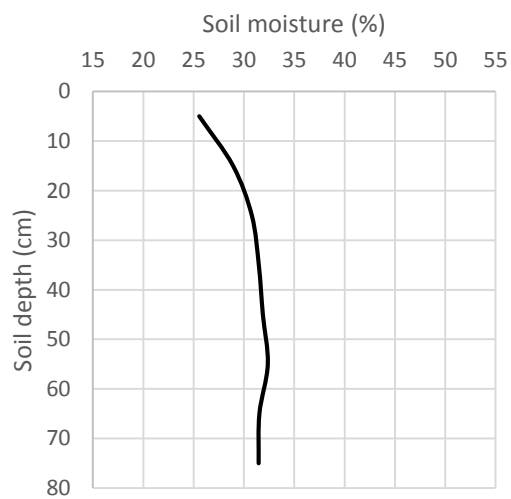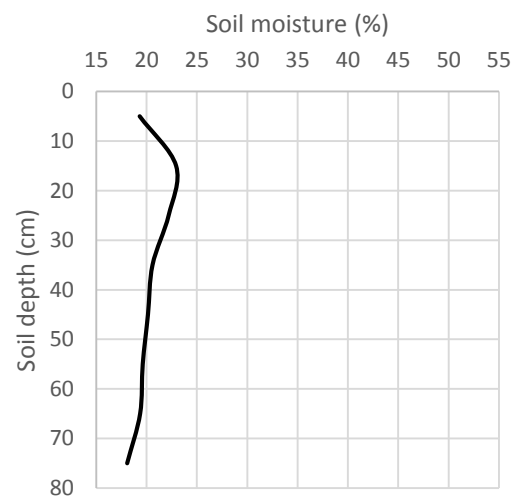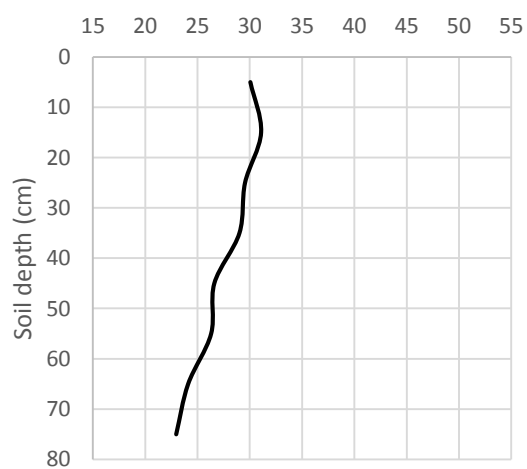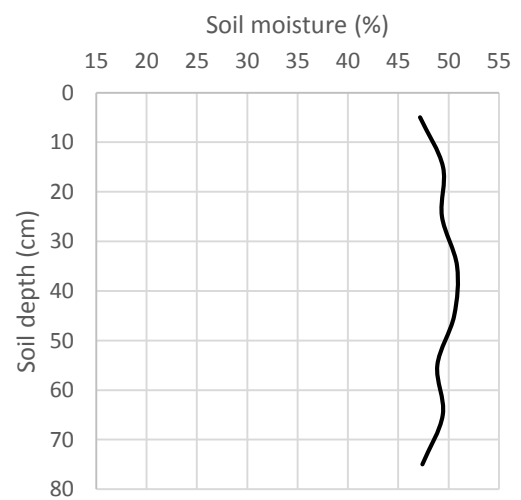
Figure 4. Soil gravimetric moisture content by depth for the experimental sites in Table 1 where moisture represents the profile immediately prior to traffic, as determined from non-traffic furrows between JD7760 frontages (i.e. not under the differential).
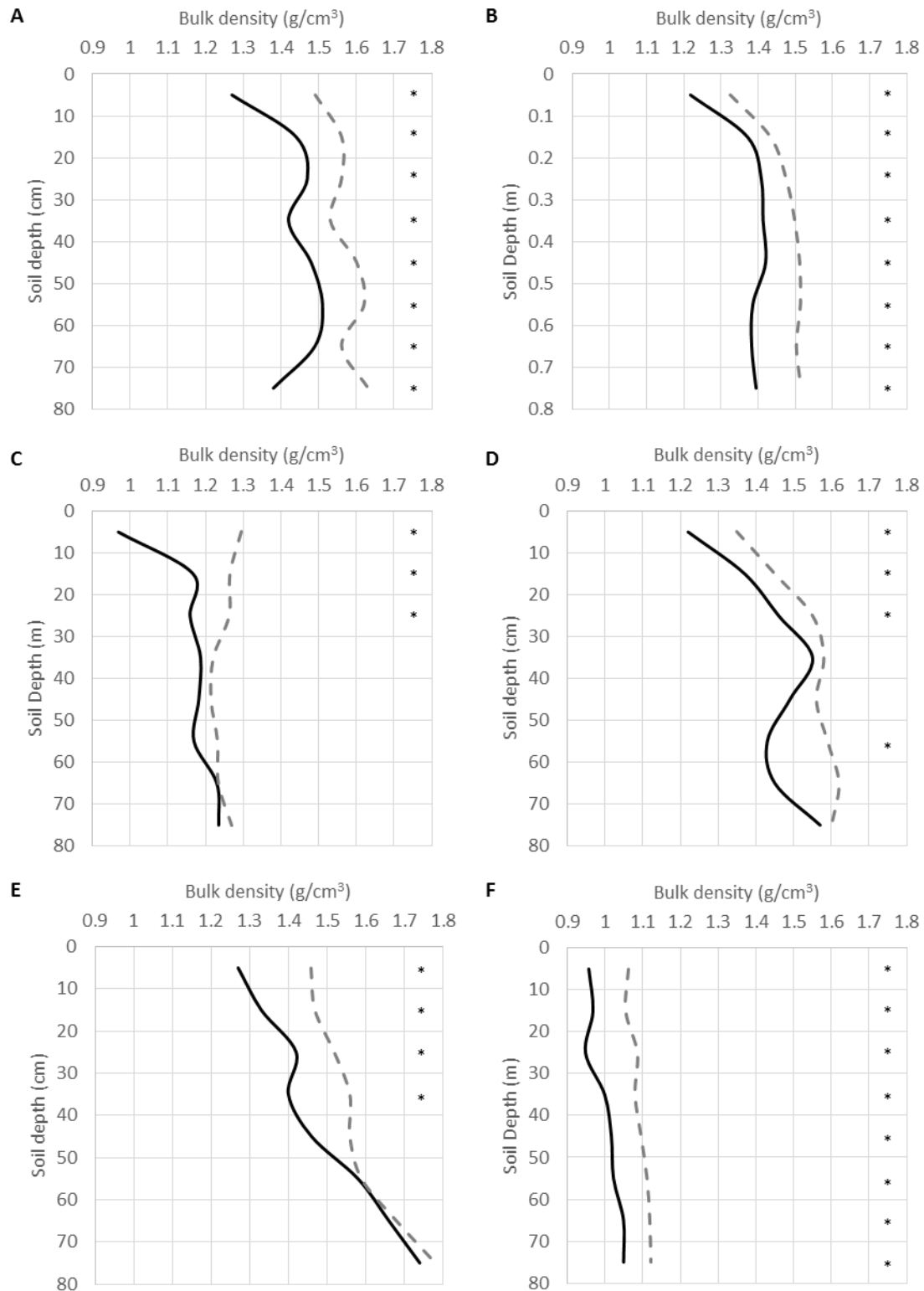
Figure 5. Bulk density by depth for the experimental sites in Table 1 where the solid line represents the before traffic conditions and the hashed line represents changes in density due to traffic under the wheel. There were no significant differences between bulk density under the inner and outer dual wheel on the JD7760, thus traffic furrows consist of data from both wheels. Significance ($p<0.1$) is represented by * at the respective depth.

Discussion

Risk of compaction incidence

It was found that >93% of potential compaction (at ≈500 kPa stress) for the investigated Vertosols occurred at a generalised OMC of 24%. Such a generalised value could be used to help determine maximum risk of traffic. Vero et al. (2013) have used soil moisture deficit with success to determine trafficability thresholds. Relating deficit to adequate moisture reduction of the generalised OMC ould be a useful approach to determining risk of impact. Hence, we used APSoil (Holzworth et al. 2014) to collate the depth of water at field capacity and permanent wilting point for 20 Vertosol soil profiles within the Australian cotton region (proximal to study sites). The average field capacity (0 mm deficit) was 402 mm with the average plant available depth of water at 177 mm (PAW, maximum deficit) in a 0.9 m soil depth (assumed effective rooting depth). The OMC therefore represented a water deficit of 134 mm. The difference between optimal moisture for compaction and that for safe bearing of traffic load is -43 mm (OMC-PAW). Therefore, it is advised for the JD7760 that traffic occur at a soil moisture deficit as close as possible to the permanent wilting point deficit of 177 mm (gravimetric moisture content of 20.15%) to minimise the risk of compaction.

Kirby (1991) measured critical state parameters of soil mechanics for regions in which the current work was undertaken. The generalised OMC is slightly less than the average plastic limit (24.15% GMC) for the same regions in Kirby's (1991) work, which is a reasonable relationship for high clay content, fine textured soils. On this basis, it is then practical to assume the precompression stress from Kirby (1991) would be similar as that for the current soils. Precompression stress defines the magnitude of stress a soil has been subject to prior to traffic and refers to the maximum stress the soil can undergo without any irreparable compression. On average, for Australian Vertosols, this value was found to be 99.3 kPa (Kirby 1991). This suggests that irreparable damage should be expected with the JD7760, and indeed smaller machines, which reconfirms the concerns of literature in limiting wheel loads (Alakukku et al. 2003; Keller & Arvidsson 2004; Soane, Dickson & Campbell 1982) and justifies the suggestion that the maximum load at the soil interface should be less much less than 200 kPa (Håkansson 1990).

Furthermore, plastic limit has been suggested as a useful metric for determining soil compaction risk, with the advice that traffic should occur below the plastic limit, or as close to it as possible (Braunack & Johnston 2014; Lamandé & Schjønning 2011). However, the results in this work show that the OMC calculated for the JD7760 machine contact stress is similar to the expected plastic limit. This suggests that traffic should occur at moisture contents much less than the plastic limit in order to limit compaction, although Braunack and Johnston (2014) advise that the soil profile will be above the plastic limit 75 and 14% of the time for irrigated and dryland operations, respectively. This suggests that soil is likely at risk of compaction unless significant drawdown occurs prior to harvest. In dryland systems the soil profile is exploited more fully as the soil water deficit cannot be managed approaching harvest. On the other hand, current industry irrigation practices manage for a low soil water deficit right up to defoliation, meaning sufficient moisture drawdown does not occur prior to harvest. To limit risk in irrigated agriculture to be similar to that in dryland agriculture will require a change in late season irrigation practices. Alternatively, it is suggested that avoidance of traffic is the best solution to limiting risk, which advocates controlled traffic farming approaches.

Implications of compaction extent

Both the inner and outer dual wheel of the front axle were observed to have similar effects throughout the soil depth irrespective of the rear wheel trailing the inner dual. Once again, considering the precomression stress of Vertosols (Kirby 1991), the front wheel traffic is highly likely to cause structural failure, nearly completely overcoming the elastic phase of the soil and severely limiting rebound of the soil volume (maximum compaction results). Thus, the immediate traffic of the rear wheel is now faced with a significantly greater precompression stress and a soil in a state of near complete failure, so that the subsequent traffic provides little noticeable increase in density. Keller and Arvidsson (2004) observed that axle load is less important than the individual wheel load, indicating that soil compaction is mainly a function of the stress on the soil surface and contact area. However, Ansorge and Godwin (2007), Antille et al. (2013) and Schjønning et al. (2012) have shown that contact stress has a relatively larger impact at shallower depths, whereas total wheel load is the controlling factor at greater depths. This helps to explain the similar impact at depth for both the inner and outer wheel traffic. All experimental fields were sufficiently short that the JD7760 was only ever in the process of forming one module, leaving this near the head or tail of the field. The exception was Kieli, where the JD7760 was completely empty. This meant that the front wheel load was ~5.8 Mg and the rear wheel load was ~6.0 Mg, on average.

The mean increase in bulk density for the cotton producing Vertosols was 10.9% throughout the top 0.3 m of the soil profile. Whilst this is not a large value, the effect on soil pore networks is likely to be vast. Kim et al. (2010) demonstrated that an 8% increase in soil bulk density decreased saturated hydraulic conductivity by 69%, due to decreasing macroporosity by 70%. Additionally, Awedat et al. (2012) showed that a 20% increase in bulk density (from 1.0 to 1.2 g/cm^3) resulted in an 84% reduction in saturated hydraulic conductivity for texturally similar soil to that of Kim et al (2010). It might be inferred that for a further 12% increase in bulk density beyond the 8% (i.e. 20% compaction increase) that this only represents 15% further reduction in hydraulic conductivity. These were not the same soils, only similar, but it serves to demonstrate the exponential decline in hydraulic conductivity as macropores decrease (Awedat 2014). Hence, it would be expected that hydraulic conductivity, and plant available water content, would be limited due to JD7760 traffic at these sites. Whilst some remediation of compaction in the surface layer could occur due to shrink-swell nature of Vertosols, this would require significant drying bellow the plastic limit and require multiple wet-dry cycles to affect hydraulic conductivity substantially (Pillai-McGarry & Collis-George 1990).

A cultivation regime is potentially able to remediate some of the compaction. However, all sites demonstrated significant increases in density to a depth of 0.3 m with detectable effect on soil structural arrangement, or significant increase in density, to depth (0.8 m). Conventional tillage regimes would not address the significant surface compaction, and certainly would not address the compaction with depth. Small increases in tillage depth cause significant gains in draught force. According to Godwin and O'Dogherty (2007), for a soil with clay content ~60% (reasonable for Vertosols), the draught force increases by 0.7 kN for every 0.1 m increase in tillage depth. Hence, use of the JD7760 is probable to result in increased tillage requirement and, subsequently, cost of in-field energy. Where increased density with depth is not addressed, and based on the fact that compaction was equivalent under all traffic furrows, it is likely that soil compaction pans will form under the full frontage of the JD7760. Braunack and Johnston (2014) showed that traffic with the JD7760 caused increased strength (3000 kPa) at a 300 mm, compared with the conventional picker 400 mm. Soil strength greater than 2000 kPa causes significant root growth retardation in cotton (Coates 2000),

which suggest that the increases in density and soil strength due to the JD7760 will limit root exploration also.

Yangullen

The soil at Yangullen demands some discussion given the moisture at traffic and the observed results. According to the OMC-MDD relationship (Figure 3) and the soil moisture profile (Figure 4), soil compaction should have been unlikely due to the soil being effectively saturated (47% GMC). However, significant increase in density was observed throughout the full profile. Soil pits were able to be dug at this site, which provided visual support for compaction depth (Figure 6) and allowed *in-situ* measurement of GMC.
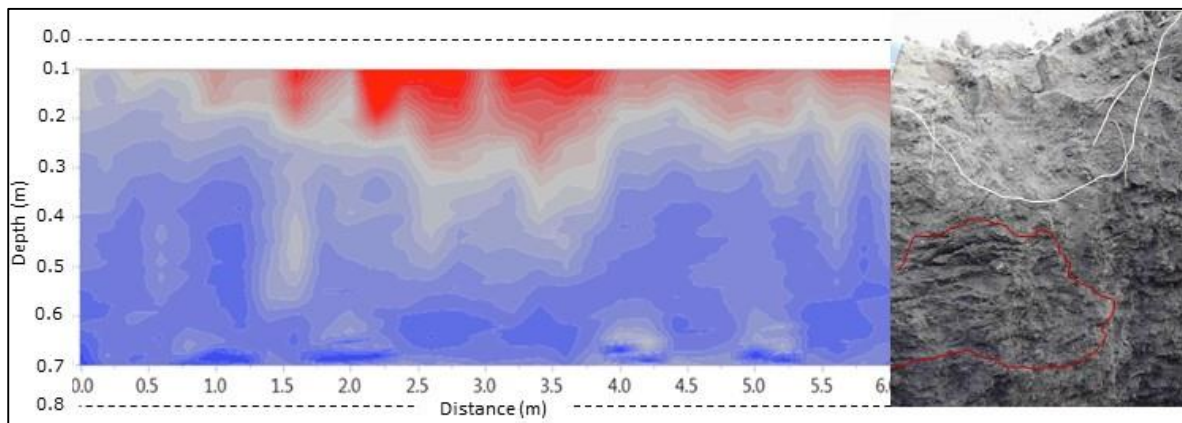
Figure 6. Soil penetration resistance and profile picture (to scale of graph) for Yangullen. Penetration resistance is in kPa and represents <500 kPa for dark blue, up to >5000 kPa for dark red. The white boundary on the image represents a change in soil structure from massive, dense pedolody caused by soil compaction, whilst internal to the red boundary indicates platy pedology synonymous with compaction.

As observed in the profile image for the Yangullen soil (Figure 6), significant rutting is not evident, as might have been expected with an ≈47% GMC; this image indicates that the JD7760 has achieved flotation. Soil compaction is evident in the form of dense, massive structure directly beneath the furrow, and as platy structure between 0.4 and 0.7 m, which is consistent with JD7760 traffic and bulk density changes. Of interest is the dark blue regions (1.0, 2.0, 4.0 and 5.0 m, Figure 6 x-axis) in the penetration resistance graph. These measurements correspond to directly beneath the wheels of the JD7760 and were substantially wetter than the soil in the profile above after traffic; indeed upon digging of pits moistures was observed to seep from these zones. This suggest that the surface contact area sufficient to achieve flotation has also caused mass convective downward movement of soil water as a result of the applied load. We suggest this explains the occurrence of density at a GMC very close to saturation prior to traffic. Hence, where tyre flotation at the soil surface is achieved at soil moisture content greater than the OMC, drainage within the profile and subsequent compaction should still be expected.

Conclusion

Traffic of six Vertosol soils, used for the production of cotton, with a JD7760 resulted in significant occurrence of soil compaction beneath all wheels. Significant compaction was further observed to depth (0.8 m) for 50% of the soils, whilst all other soils exhibited detriment to soil structural arrangement to depth in terms of reduced heterogeneity. Compaction trends beneath the full machine frontage and depth of effect on density are conducive to long-term formation of a

compaction pan beneath the tillage zone. Furthermore, the average increase in density was 10.9%, which represents a significant reduction in macroporosity most likely affecting future infiltration and plant available water.

The magnitude of stress applied to the soil when compared to industry precomression stress information for Vertosols suggests that the JD7760 will have irreparable effect on soil compaction, irrespective of soil moisture. This suggests that limiting the area trafficked by the machine is paramount to protecting the soil resource. Industry plastic limit values were found to be similar to the measured optimum moisture content for compaction with a JD7760. Hence, the advice to limit risk of compaction is that moisture content is significantly less than the plastic limit and as close to permanent wilting point as possible (water deficit of ≈177 mm/ 0.9 m).

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Cumulative traffic impact of heavy machinery and interseasonal repair of a black Vertosol

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Introduction

The John Deere 7760 on board module building picker (JD7760) provides an effective doubling in weight from the previous basket picking system. When forming a single module, and assuming all modules are dumped, rather than carried, wheel loads on the front and rear axle average 5.8 Mg and 6.0 Mg, respectively; if carrying a module, the rear load increases substantially, whilst the front load is decreased slightly (Bennett et al. 2015). This provides extensive contact stress at the soil surface, which results in soil compaction and modification of structural arrangement throughout the 0.8 m soil depth, as discussed in the previous section. Average increase in soil bulk density for six Australian Vertosols was 10.9% throughout the 0–0.3 m depth, which represents concern for infiltration, germination and subsequent root growth based on reduction of soil macroporosity. However, the shrink-swell nature of Vertosol soils may provide some natural remediation (Sarmah, Pillai-McGarry & McGarry 1996).

Laboratory investigations by Pillai-McGarry and Collis-George (Pillai-McGarry & Collis-George 1990) suggest that more than three wet-dry cycles are required to provide measureable repair, while Pillai-McGarry (1991) further state that three wet dry cycles is not sufficient to remediate compacted soil directly beneath wheel tracks. The latter finding highlights the misconception that a single season is sufficient to ameliorate wheel tracks. Furthermore, Sarmah et al. (1996) showed that reliance on evaporation alone, as would occur in fallow, only provides low to moderate remediation of soil compaction. In contrast, some success in remediating compaction to greater depths where crops are present has been demonstrated by Radford et al. (2001) and McHugh et al. (2009), although both studies still showed that substantially longer than a single season of wet-dry cycling was required to realise benefits of remediation, or measure differences.

In all cases, the above studies were not subject to soil stress of the magnitude the JD7760 supplies. Therefore, this experiment was designed to investigate capacity for natural interseasonal soil structural repair of JD7760 compacted soil and cumulative traffic impact. Additionally, the extent of repair that might be expected resulting from fallow (evaporation only) and rotation crops (evapotranspiration) was able to be assessed.

Methods

The experimental site, "Kendale", was located near Bongeen, Qld, 27°30'23.9"S 151°27'49.5"E and the soil was characterised as a black Vertosol. Prior to commencing the experiment the site had been used for agricultural production for approximately 30 years with no history of controlled traffic. Flooding during the summer of 2010/11 had resulted in filling the soil profile water holding capacity. The field was in fallow from that point in time up until the 2014/15 season where millet was grown. Hence, during the 2013/14 experimental period the soil profile was considered near field capacity, and subject to evaporation impacts in the 0–0.3 m approximate depth.

Experimental design

Given the requirement to determine bulk density directly after traffic did not allow standardisation of soil moisture, direct comparison of seasonal data was not appropriate. Hence, the experiment was designed to test cumulative traffic side by side at a single point in time. The traffic regime was as per Table 1, resulting in an experimental design consistent with Figure 1.

Table 1. Cumulative traffic by treatment for the three seasons of single-pass-traffic where JD9976 refers to the previous industry John Deere standard basket picker and JD7760 refers to the newer John Deere on-board-module-builder cotton picker. Both machines had dual wheels. Fallow refers to no traffic occurring as a result of the JD9976 being sold.

Treatment	Season 1	Season 2	Season 3
1	JD9976	Fallow	JD7760
2	JD9976	JD7760	JD7760
3	JD7760	JD7760	JD7760

The experimental area represented a 300 by 72 m area (2.16 ha) with each treatment replicate representing 6 by 300 m (0.18 ha). The 72 m width of the experimental area was sufficient to encompass the full farming traffic system 4 times. Hence, blocks A, B, C and D were used to ensure that treatments could be assigned randomly by block, but also ensure spray and grain harvester traffic was not unfairly represented within any one treatment.

Sampling along each transect immediately prior and post traffic allowed for direct impacts at a single point in time to be compared. Additionally, the before sampling provided indication of comparative soil bulk density repair from the traffic imposed in the previous season. This was assessed through treatment differences at each sampling period and was only applicable in season 2 and 3 representing repair from season 1 and 2, respectively.
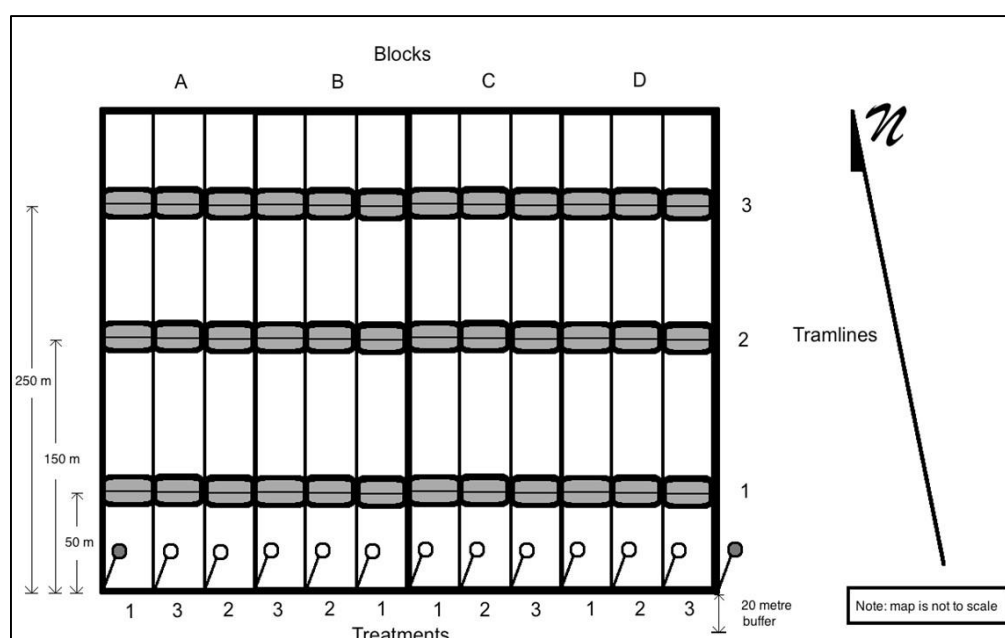
Figure 1. Experimental schematic showing treatment allocation by blocks (A, B, C and D). Transects 1 (50 m), 2 (150 m) and 3 (250 m) are represented by a single black line traversing the 72 m experimental area. The grey zone at each transect within each treatment represents a machine frontage of 6 m from where soil cores were taken at each meter of the frontage. Vertical lines within the experimental area represent treatment boundaries, with the point of traffic entry represented by pins at the base of the experimental area.

Measuring soil bulk density

Due to the shrink swell nature of Vertosols their dry bulk density changes with changes in moisture content related to the swelling nature of the 2:1 clay minerals. Recommended practice is to sample soil when it is in a swollen state and at a standardised moisture content (Håkansson & Lipiec 2000). However, in order to investigate harvest traffic impact it is necessary to investigate the changes in density directly after the traffic incident, which precludes the use of a standardised moisture content.

Hence, soil bulk density was sampled within two days of traffic using a hydraulic push core and careful manual partitioning of samples by depths accurate to +/− 0.001 m. The cross-sectional area was calculated using the internal diameter of the cutting tip and then multiplied by the sample length to determine its volume. The dry density was then determine as the oven dry mass of the sample at the specific volume.

Whilst this approach introduces some sampling error, it is rapid and allowed for a greater investigation of the farming system. Samples were taken in 0.1 m increments to a depth of 0.8 m, and this was repeated every 1.0 m along three 72.0 m transects. Bulk density cores were taken before and after traffic, resulting in a total of 432 soil cores and 3,456 bulk density samples per season. Gravimetric and volumetric water contents were determined in the process of each bulk density sample.

Penetration resistance

As machine traffic causes consolidation of soil solid particles, resulting in compaction, penetration resistance of an ASABE penetration cone was used to determine changes in soil strength, resulting from traffic. Penetration resistance is highly influenced by penetration velocity, soil moisture and soil bulk density. Velocity was controlled using a constant drive device. To understand the effects of moisture and bulk density these were measured directly in soil cores proximal to insertion points in furrows.

Penetration resistance was measured using a Rimik CP40ii Cone Penetrometer with a 100 kg load cell. The cone penetrometer was mounted to the constant drive device and penetration resistance measured every 0.2 m along each transect after traffic. In terms of depth, penetration resistance was measured every 0.01 m to an extent of 0.75 m, resulting in 10,950 measurements per transect.

Results and discussion

As might be expected, traffic resulted in increased bulk density within the major root zone in both 2014 and 2015 (Figure 2).The experiment was implemented in April 2013, but due to sampling difficulties the 2013 data is unable to be presented. However, sampling in 2014 allows assessment of 2013 JD9976 traffic legacy effect. The fallow treatment represents a single pass of a JD9976 basket picker in 2013, with subsequent fallow through to simulated harvest in 2015 (Figure 2B). Figure 2A shows that after 12 months since traffic with a JD9976 (Fallow) the average significant ($p<0.1$) increase in density throughout the 0–0.3 m depth, as compared to the control, is 11.6%. This is consistent with the findings of Pillai-McGarry (1991) and Pillai-McGarry and Collis-Geroge (1990), demonstrating that a single fallow season is insufficient to remediate the effects of traffic on soil compaction. After 18 months fallow (Figure 2B) and a single millet crop, the JD9976 trafficked soil bulk density has reverted to be consistent with the control, suggesting that the time for remediation under the previous basket system was greater than 12, but less than 24 months. This continues to support the requirement of greater than a single season to ameliorate changes in bulk density through shrink-swell processes

(McHugh, Tullberg & Freebairn 2009; Pillai-McGarry 1991; Pillai-McGarry & Collis-George 1990; Radford et al. 2001; Sarmah, Pillai-McGarry & McGarry 1996).

Figure 2. Changes in soil bulk density with depth due to traffic with either a JD7760 or JD9976 (fallow – traffic the previous year) at (A) post-traffic 2014; (B) before traffic 2015; and (C) post-traffic 2015; where treatments are as per Table 1. Lowercase letters refer to statistical differences (p<0.1) where letters differ with sequence of comparisons control>fallow>single>double,   or control>single>double>triple.

Traffic from the JD7760 produced significant ($p<0.1$) increase in soil bulk density for the 0–0.3 m depth. In 2014 an average increase in soil bulk density within this depth was 12.9 and 17.0% for a single and double pass of the JD7760 (Figure 2A). After a single season of millet, the double pass treatment reduced from a bulk density of 1.28 to 1.00 g/cm^3, while the single pass treatment reduced from 1.13 to 1.02 g/cm^3 in to 0–0.1 m depth, with reduction approximately half this magnitude in 0.1–0.3 m depth. Additionally, the 0.2–0.3 m depth was no longer significantly different to the control for either traffic treatment. Depths greater than 0.3 m tended to become more consistent with the control, although these were not significantly different prior to crop growth. This indicates that evapotranspiration has provided sufficient moisture drawdown to activate shrink-swell processes and alleviate soil compaction to some extent. However, it is noted that once again a single season was insufficient to revert conditions back to the control (Pillai-McGarry & Collis-George 1990). Furthermore, subsequent 2015 harvest traffic, at slightly higher soil strength than in 2014, results in bulk density increasing once again. Thus, it is deduced that evapotranspiration alone is not adequate to ameliorate traffic effects of the JD7760 in the root zone. Multiple seasons of JD7760 traffic result

in root zone soil density increase of 14.8–33, 4.8–12.3, and 3.0–5.7% in the 0–0.1, 0.1–0.2, and 0.2–0.3 m depths, respectively and comparative to the control. In all cases, the soil with the greatest number of passes produced the greatest increase in bulk density, suggesting that there is a cumulative impact of the JD7760. In this case the cumulative impact does not necessarily result in continuous increase in bulk density, but results in greater offset of any natural repair capacity.

Figure 3 and Figure 4 show penetration resistance for the soil in 2015 prior and post traffic. Figure 4 further details the traffic of harvest and spray rigs used during the millet season. This field had traditionally been a dryland field, but with flooding in 2011 the soil profile filled and the soil condition was considered representative of soil moisture conditions that an irrigated field might be subject to prior to harvest. Soil moisture was reduced in the top 0.3–0.4 m during 2013 to the time of planting millet. In comparison to the surface depth, the 0.4–0.8 m depth soil moisture remained relatively constant, even where millet had been planted, for the duration of the experiment, although some non-significant decrease in subsoil moisture was observed (data not shown). The penetration results generally concur with the bulk density data, although demonstrate penetration resistance prior to traffic was significantly less than after traffic in the 0.4–0.7 m depth (Figure 3), where grain harvest traffic had not occurred. This may suggest that the millet has provided some structural repair, although penetration resistance data prior to millet sowing is not available. There is a significant (p<0.05) increase in the average soil strength (3850 to 5970 kPa) in the subsoil after traffic, as compared to before, excluding grain harvester impact. Within the surface soil it is worthwhile noting that the soil prior to JD7760 traffic is at no time observed to have strength less than 1000 kPa, but that the majority of the soil profile throughout the 0–0.4 m depth has strength less than 2000 kPa, which has critical implications for root growth (McKenzie & McBratney 2001). Post traffic with the JD7760, this depth approaches a uniform strength interval of 2000 to 3000 kPa, whilst under the wheels the soil strength is increased to approximately 4500 kPa in the top 0.1 m (Figure 4).

The landowner reports no apparent loss in yield due to the introduction of the JD7760 module building picking system in comparison to the previous JD9976 basket picking system on soils proximal to the experimental site, despite an approximate doubling in machine weight. As discussed above, the starting conditions of this project were considered representative of an irrigated soil prior to harvest. However, without further subsequent irrigation, time was afforded between rainfall events for the soil to wet and dry to a greater extent than might have been expected in an irrigated field. Furthermore, whilst this field has a clear history of uncontrolled traffic (Figure 4), it will also have a long history of substantial moisture drawdown prior to traffic, by virtue of dryland cropping where the modelled probability of traffic conditions greater than plastic limit at harvest is approximately 14% chance (Braunack & Johnston 2014). This suggests that whilst soil structural repair due to wet-dry cycles was observed, the extent of effect may not be fair to expect in a true irrigated environment.

Thus, to receive maximum effect of wet-dry cycles in repairing potential compaction for irrigated soils the soil would need to be managed to:

- Have soil moisture content substantially less than the plastic limit prior to harvest; and
- Be subject to multiple wet-dry cycles prior to subsequent crops.

Both the incidence of grain harvester traffic and the JD7760 result in re-compaction of any potential repair from bio-ripping (wet-dry cycles due to evapotranspiration). Hence, as the traffic lanes of these are mismatched (Figure 4), it is postulated that sufficient time for bio-ripping to completely alleviate soil compaction for heavy machinery would never be allowed. Hence, this continues to advocate for a controlled traffic system as most the beneficial system in terms of maximising field inputs (water, energy and nutrients), or the requirement for an intensive tillage program (high energy and environmental cost).
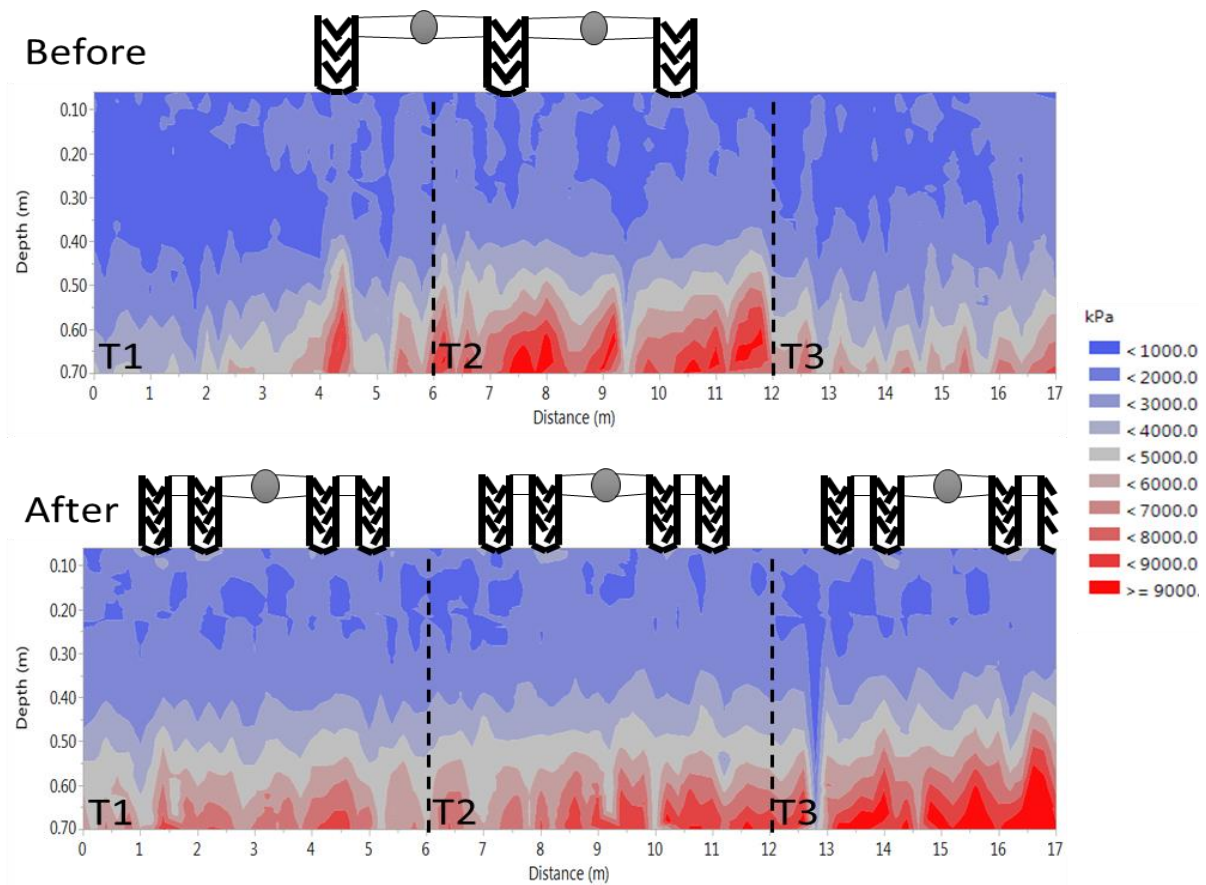
Figure 3. Penetration resistance measured in 2015 before and after JD7760 traffic for block 1. Before JD7760 traffic shows traffic lanes of 2014/15 millet crop harvest, while traffic lanes in after image represent the JD7760; T1= single JD7760 pass; T2=double JD7760 pass; T3=triple JD7760 pass; all traffic JD7760 passes were 12 months apart
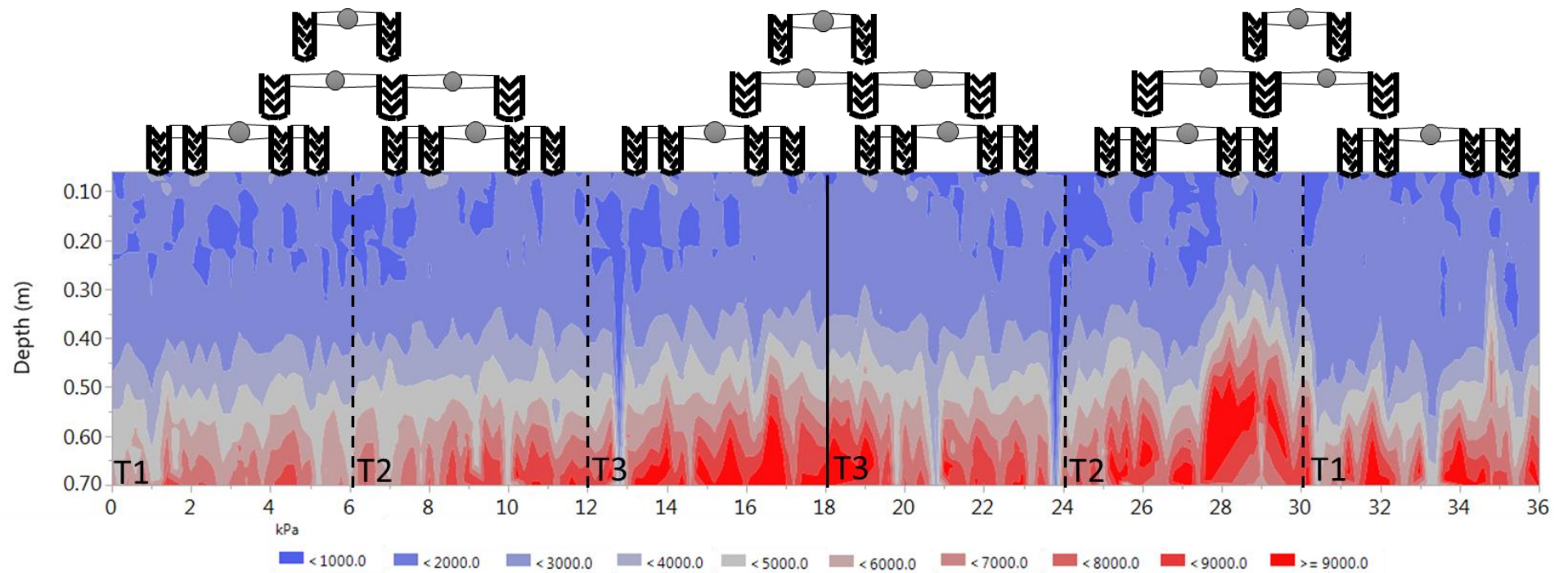
Figure 4. Penetration resistance following JD7760 traffic in 2015. JD7760 (2 m track) is represented by dual axle on the bottom tier, millet harvester (3 m track) is in the second traffic tier, and spray rig (2 m track) represents the top tier; T1= single JD7760 pass; T2=double JD7760 pass; T3=triple JD7760 pass; all traffic JD7760 passes were 12 months apart.

Conclusion

Evaporation and evapotranspiration were both shown as effective in reducing soil compaction due to cotton picker traffic in the 0–0.3 m soil depth. However, for adequate regeneration comparable to the control, between 12 and 24 months of wet-dry cycling was required for the JD9976 basket picker; for this result under a JD7760, greater, or similar, time would be required between JD7760 traffic incidences. To facilitate regular crop cultivation (continuous cropping, or short-fallow rotation) the time provided between seasons would be insufficient for bio-ripping to be a viable soil compaction control mechanism for this Vertosol. Using the crop to dry soil down to well below plastic limit prior to harvest in an irrigated cotton-grain rotation should be investigated as a potential management strategy for soil compaction due to heavy machinery (axle load >10 Mg).

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Energy considerations for management of heavy machinery traffic in cotton

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Introduction

As the uptake of the John Deere 7760 on-board-module-building picking system (JD7760) has been widespread and rapid, it is not a matter of whether or not the industry should adopt this technology, rather a process of determining its impacts, and developing strategies to optimise production. Other sections of this report deal with soil impact and economics. In this section, we will look at the fuel consumption of the new picker, along with the fuel consumption of tillage operations that are deemed necessary to 'keep the bucket the same size' (maintain adequate soil water infiltration and availability). We will also discuss the impact of such equipment on the soil.

Methodology

The experimental site was located at Norman Farming, [28°30'43.71"S 149°45'21.42"E](#), 191 m above sea level, situated 15 km SW@ of Toobeah, Qld. The soil was classified as a Grey Vertosol, typical of the cotton industry.

One of the major concerns for the Farm Manager was, in his words, to 'keep the bucket the same size', which was in reference to the amount of cotton accessible water the soil was able to hold and its ability to refill. Of importance to their farming system was the significant weight increase of the JD7760, as compared to the previous basket picking system (approximate doubling in weight), and potential ramifications on soil compaction; the ability of the soil to store water. Initially the farmer was using a Caterpillar Challenger (≈500 hp) to alleviate the compaction caused by the JD7760. In this case the farmer had accepted that compaction occurred and was putting counter measures in place to protect yield. Following discussion, a field was selected (see Figure 1) and a trial layout imposed following the 2013 pick using the JD7760.

The plot area, 216 metres by roughly 400 metres long, was divided into nine subplots to allow three replicates of three treatments (see Figure 2), with each tillage treatment consisted of 4 picker passes (24 m wide). The three different treatments represented three levels of tillage, and included tillage of hills and furrows across the whole machine frontage, as follows:

> 1. Low/Minimum tillage – the legal requirement for growing genetically modified cotton, a simple boll bust, with tillage occurring to 0.10 m depth.

> 2. Medium tillage – the traditional practice for busting, deeper than the minimum required and developed for the conventional system, with tillage occurring to 0.17 m depth.

> 3. High/Maximum tillage – the new regime adopted for dealing with compaction caused by the JD7760 involving either deeper tillage or double passes. This treatment was what the manager considered needed to be performed so that compaction was not compounding following the use of the JD7760; tillage occurring to 0.23 m depth
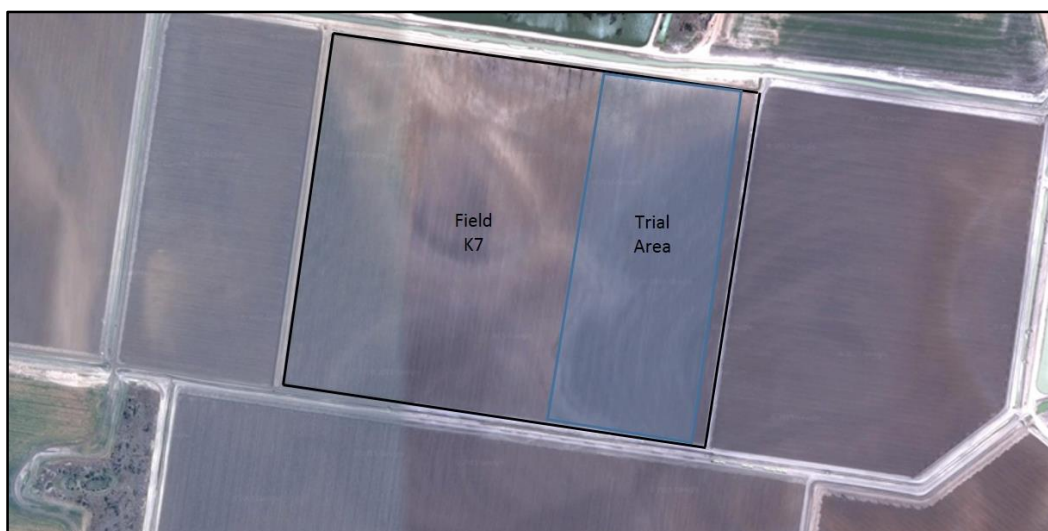
Figure 1 Field K7, Norman Farming, Toobeah.

The farming system used on the trial field utilised a JD7760 in standard configuration (dual-wheel front axle) picking 6 rows of 1 m cotton. During the pick in 2014, due to water limitations, the crop was planted in single skip configuration with picker heads 2 and 5 not picking cotton. Various tractors were used throughout the trial (see individual sections) and centre/side busting operations were carried out with Gessner tillage equipment (4 m wide – hence 4 picker passes equated to 6 tillage passes). The major production events during the life of the trial are detailed in Table 1.

There were 2 paths of investigation being undertaken at this site: 1) assessing the farming system from a production/energy perspective; and, 2) monitoring the soil resource from a soil science perspective. Prior to the tillage treatment being imposed in 2013, substantial soil quantification readings were taken in the form of soil penetration resistance and moisture/bulk density measurements. The soil sampling regime is shown in Figure 3.

Tillage treatments - 2013

For the first year, due to timing of the experiment, only one type of machine and implement were available for tillage so each treatment consisted of a different depth of tillage. The machine used was a John Deere 8320R, 240 kW tractor with a 4 metre, three point linkage tillage implement (see Figure 4 and Figure 5). The rows in each subplot were trafficked as per the schematic diagram in Figure 6. The order the subplots were trafficked were sequential from east to west:

T1R1 → T2R1 → T3R1 → T1R2 → … → T3R3

Due to equipment difficulties, only the surface penetrometer readings (0–0.4m) were valid but soil cores were more successful.
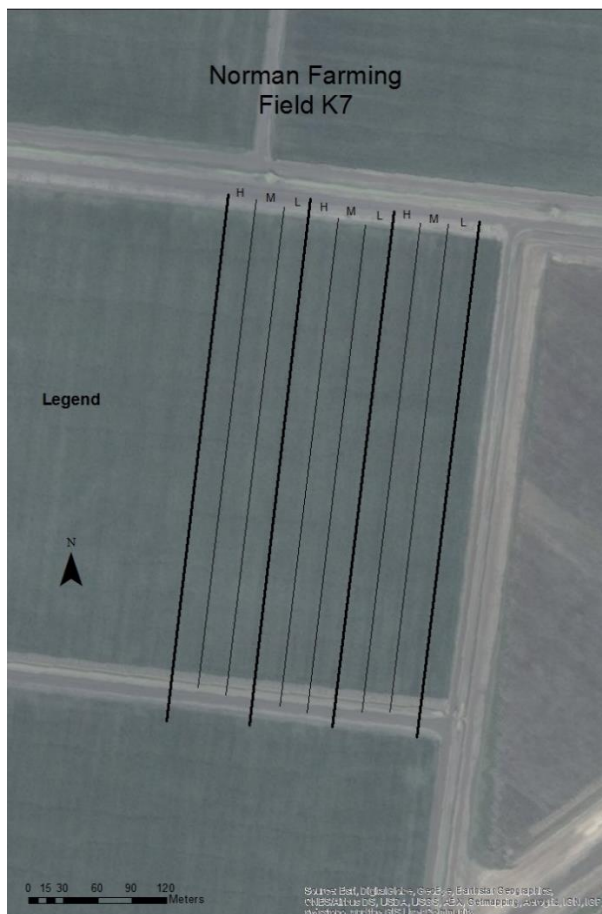
Figure 2 the tillage intensity treatments imposed (H-High, M-Medium, L-Low)

Table 1 Production Events in Field K7

Timing	Event
Before August 2013	Picking
Early August 2013	Soil coring and penetrometer insertions
Late August 2013	Tillage treatments applied
Late May 2014	Pre traffic cores and penetrometer insertions
Early June 2014	Picking
Mid June 2014	After traffic soil cores and penetrometer insertions
Mid to late July 2014	Tillage treatments applied
End 2014	Lack of water, no cotton planted
Early 2015	No cotton, cross ripped for chickpeas, treatments remediated
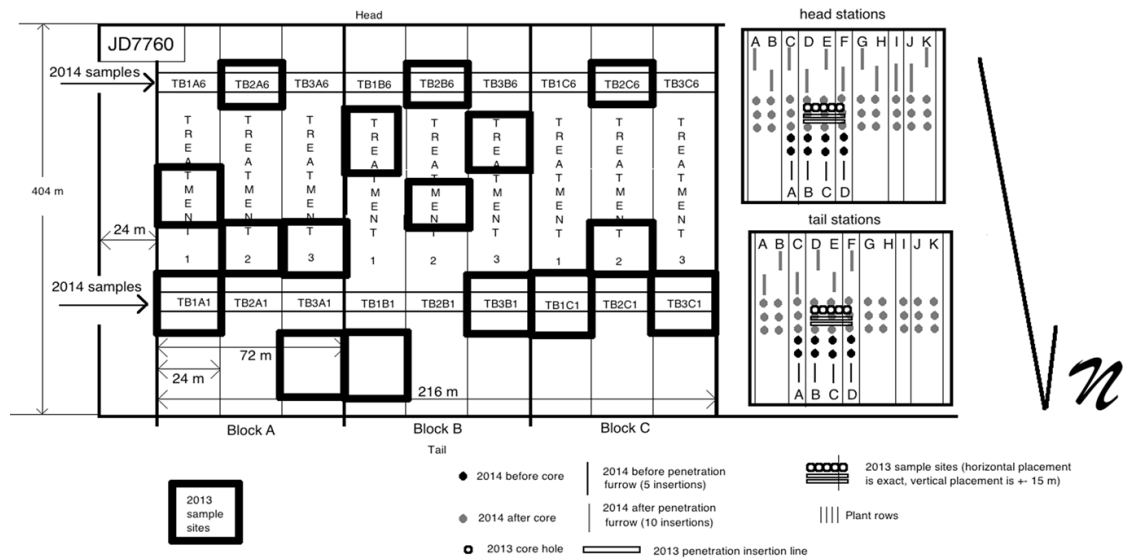
Figure 3 Soil sampling regime, K7, Norman Farming.

Figure 4 The JD tractor used in the trial

Figure 5 The tillage equipment used in the trial.

Measurements during the 2014 pick

The order of picking subplots was different to the order of tillage (as shown in Figure 7) due to the need to minimise the number of partly formed bales. By picking all three replicates, only one partly formed bale was produced per treatment. The picking sequence (shown in Figure 7) was as follows:

T1R1 → T1R2 → T1R3 → T2R1 → ... → T3R3

The reasons for this picking pattern is explained below in the yield measurement section. Once an entire treatment was picked, the machine was re-fuelled and the picker finished the bale either within the next subplot or outside the plot area.
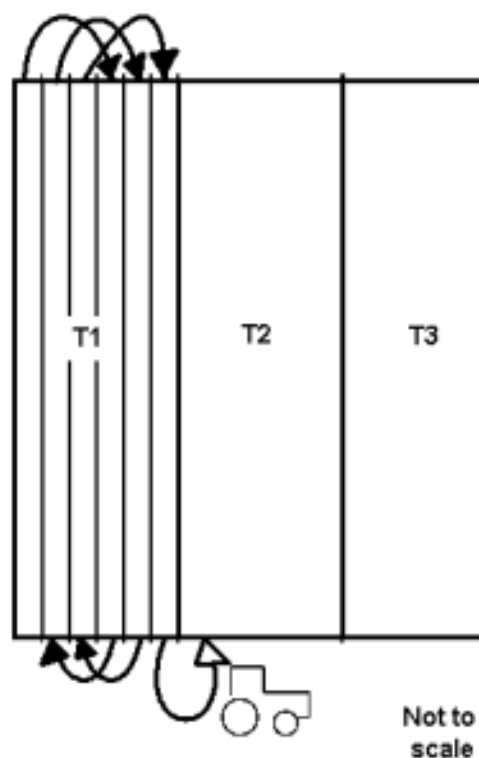
Figure 6 The tillage sequence for the trial
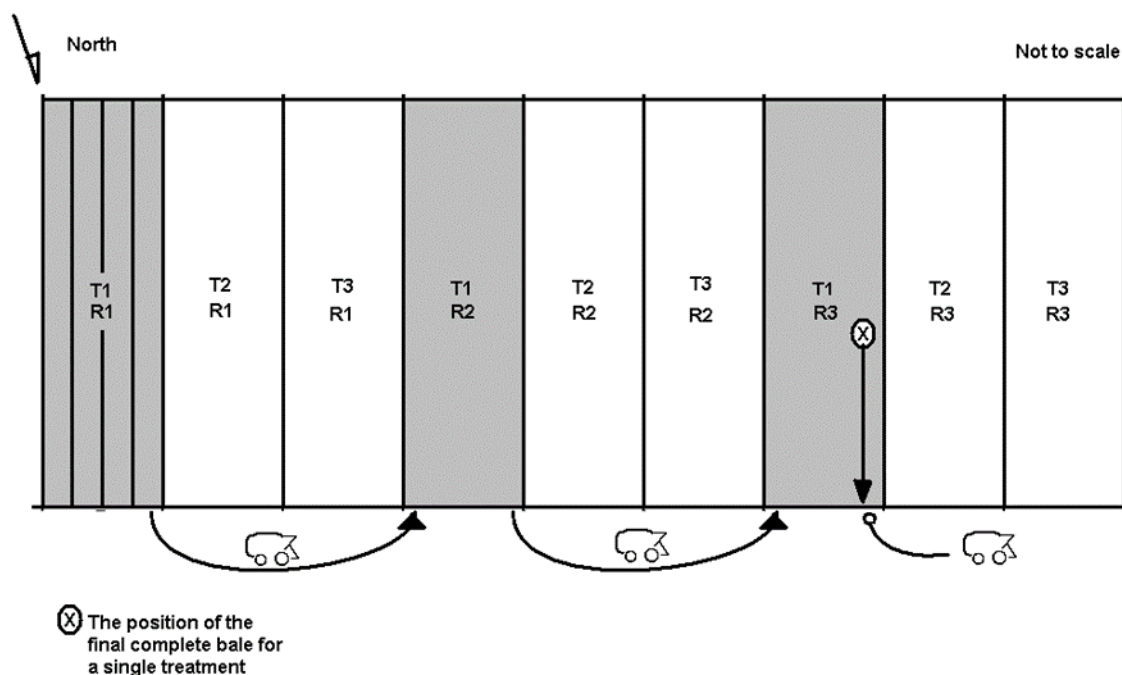
Figure 7. The picking sequence for harvesting the plots

Fuel use

To determine fuel used by the harvest equipment, GreenStar data was accessed for detailed fuel use, logged per second. A video recorder was used to monitor the GreenStar display to determine the average time taken and the average fuel used during turns, but not discussed here. It was found that the GreenStar system does not record fuel use whilst turning, due to the area accumulation being

turned off. Fuel use for each treatment was measured by filling the machinery at the start of the first subplot, and filling at the completion of each treatment (three of), then measuring the fuel as it is pumped out of mobile storage using a fuel flow meter.

Yield measurement

Yield was determined by picking the three replicates of a single treatment and carrying any cotton on-board to the next subplot (three subplots). GPS coordinates were recorded for each location of bale completion / commencement and bale unloading (as per the following section bale measurement). Knowing how much cotton has been grown in a subplot is not as simple as it sounds due to nature of the JD7760 and the size of the plots (0.96 ha). It is not possible to determine the volume of cotton of incomplete bales (at the end of a subplot), so the area used to form a complete an incomplete bale of a nearby field was used. The average yield of the nearby field was subtracted from the complete bale based on the area picked, which provided a fair comparison for all treatments without producing incomplete bales.

Area measurement

The GreenStar display was used to measure the area planted to cotton that was grown on each subplot, and compared to GPS coordinates taken after the traffic of the field as a double check.

Soil measurements

As detailed in Figure 3, a suite of soil measurements were taken at different locations and different times in the field. The measurements included soil penetration resistance using a Rimik CP20 cone penetrometer and soil cores used to calculate bulk density. Issues were encountered with the soil penetration equipment and readings were not complete, hence will not be discussed.

Two traverses were conducted in each of the treatments in all three replicates, before and after traffic. Cores were taken by inserting a 50 mm diameter core into the soil using either hand-held petrol powered soil corer or a tractor mounted soil coring rig. Samples were taken in each furrow across the width of the picker resulting in bulk densities being recorded for the following positions; directly under the centre of the picker (or diff row), under the tyre of the inner dual, under the tyre of the outer dual, and the guess row. The procedures for processing and analysis of the bulk density samples are detailed in previous chapters

Results and Discussion

Elevation

The elevation map (Figure 8) was generated from data collected during the tillage treatment. As the tractor was operating with RTK guidance, the elevation data is very accurate (several cm accuracy). The elevation difference across the entire field is only about 1.5 m and the field falls from the S to the N. There is evidence of the laser levelling in the 'bays' and the underlying soil colour patterns are clearly visible in Figure 1.

Tillage Measurements - 2013

Based on the trial layout initiated in 2012 where there were 3 replicates of 3 different tillage treatments (minimised treatment pupae bust (L), treatment comparable with standard for basket picker (M), and heavy tillage considered necessary due to weight of JD7760 (H)). Greenstar data was collected during the tillage trial in 2013. The summarised results are shown in Table 2 with the fuel consumption map being displayed in Figure 9. As would be expected, the lowest fuel consumption

was in the Treatment 1 (the low tillage practise) with progressively more fuel being used advancing to Treatment 3, the high tillage practice. As the implement was inserted deeper into the soil for the high tillage treatment, more draft force was required from the tractor resulting in increased wheel-slip and fuel consumption. The H tillage treatment has substantially more wheel-slip than the other treatments and use more than twice the amount of fuel/hectare than the low treatment.

Table 2. The 2013 tillage and efficiency measurements for each treatment.

Treatments	Wheel slip (%)	Average Engine speed (rpm)	Average Fuel use (l/ha)	Target tillage depth and speed
Treatment 1 (L)	2.6	1220	10.3	10 cm @ 5.5 kph
Treatment 2 (M)	12.8	1380	21.2	17 cm @ 4.2 kph
Treatment 3 (H)	31.8	1390	33.7	23 cm @ 3.2 kph

Pick Data – 2014

Once again, the productivity data for the trail was obtained from the Greenstar 2630 display in the picker. The summary of the data is shown in Table 3 with the corresponding maps for yield and fuel use being shown in Figure 10 and Figure 11.

On a treatment level, there was no difference in the speed and the fuel use across the treatments. There was however a considerable range of fuel consumption both within the field and also within short distances within the row as detailed in the smoothed fuel consumption map (Figure 11). This map has been kriged using Vesper. Kriging is a smoothing process which predicts the value of a point based on neighbouring points and has resulted in the markedly high and low values being removed. Looking at the raw data (which is displayed as Figure 12), the fuel consumption varies from around 40 to more than 90 l/hr within the space of 100 m (in the direction of travel) with this fluctuation driven by the power consumption of the baling process, which is intermittent.

The yield did however differ, although it was not statistically significant. Figure 10 shows that the highest yielding area is in the Southern end of the field and the lowest in the N. The L – M – H treatments are visibly and consistently different, however. The yield impacts of the tillage treatments are clearly demonstrated in the maps, and have been determined as treatment differences. The minimised treatment areas (L) (the right hand plot in each of the replicates) is visually different to the other 2 plots, highlighted by the predominance of red yield values (<3.7 t/Ha) in the 'L' plots. There is little noticeable difference between the 'M' and the 'H' plots. There is good agreement between the tillage imposed (Figure 9) and the yield (Figure 10).
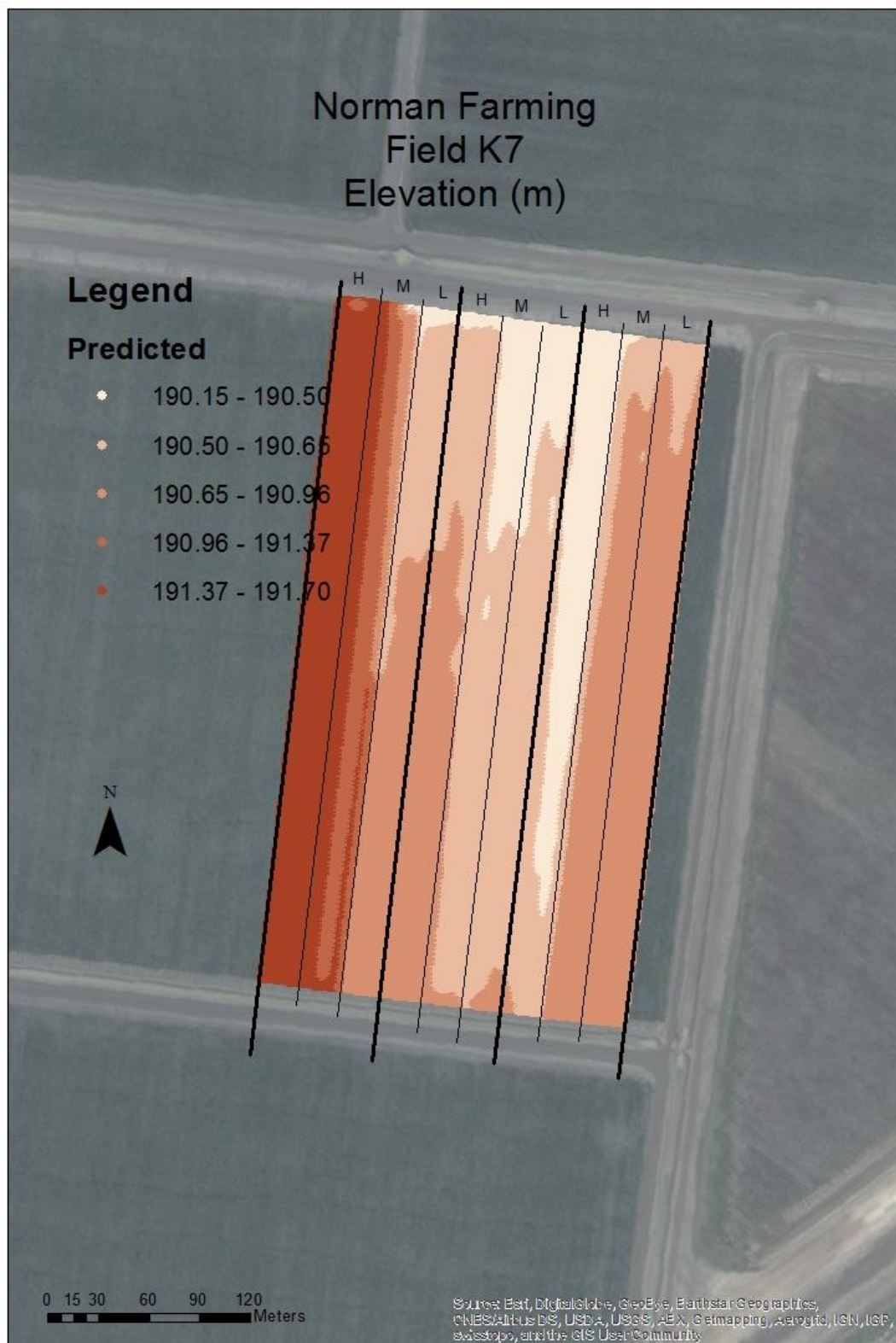
Figure 8 Elevation results for the trial site
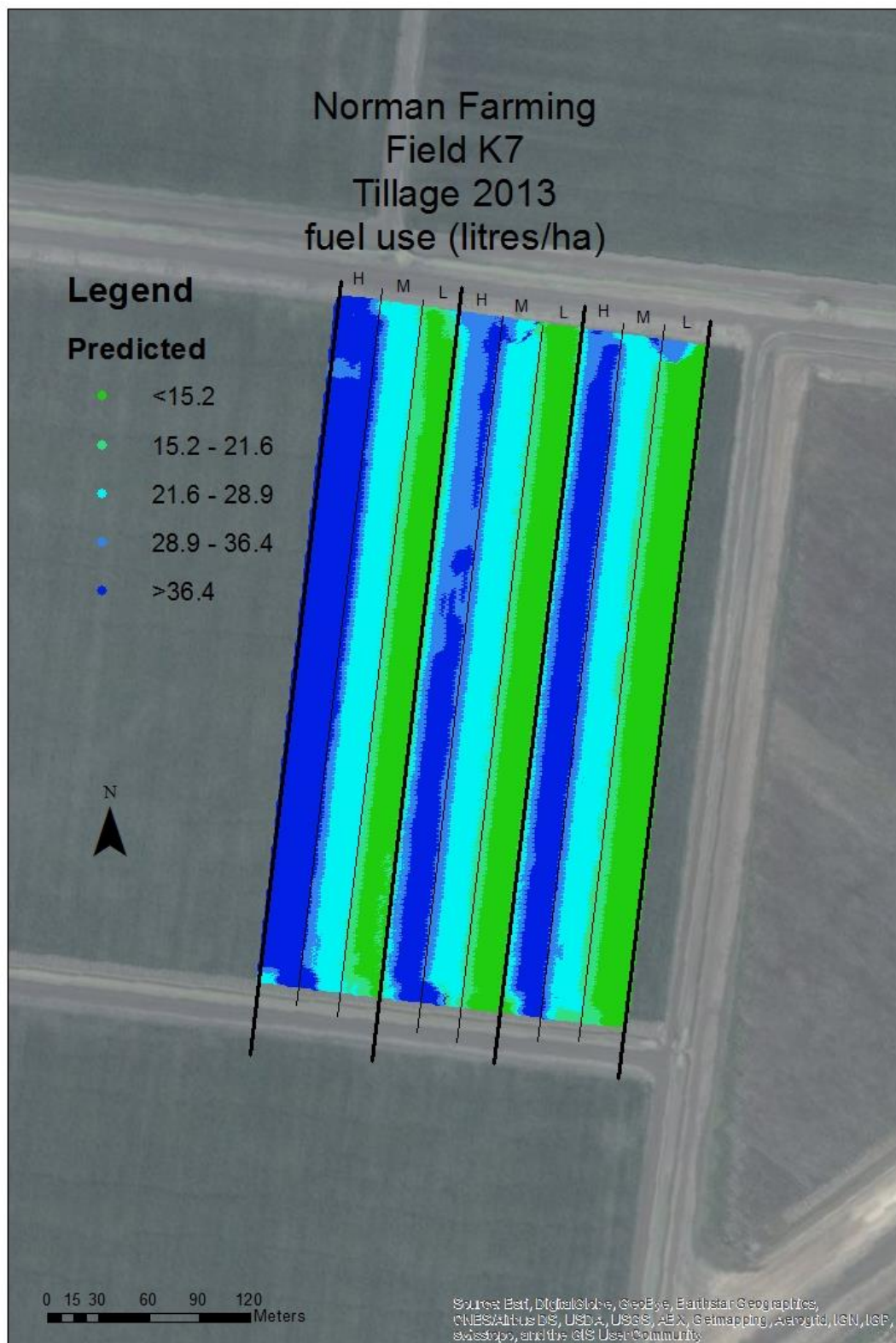
Figure 9 Fuel consumption figures from the initial working in 2013
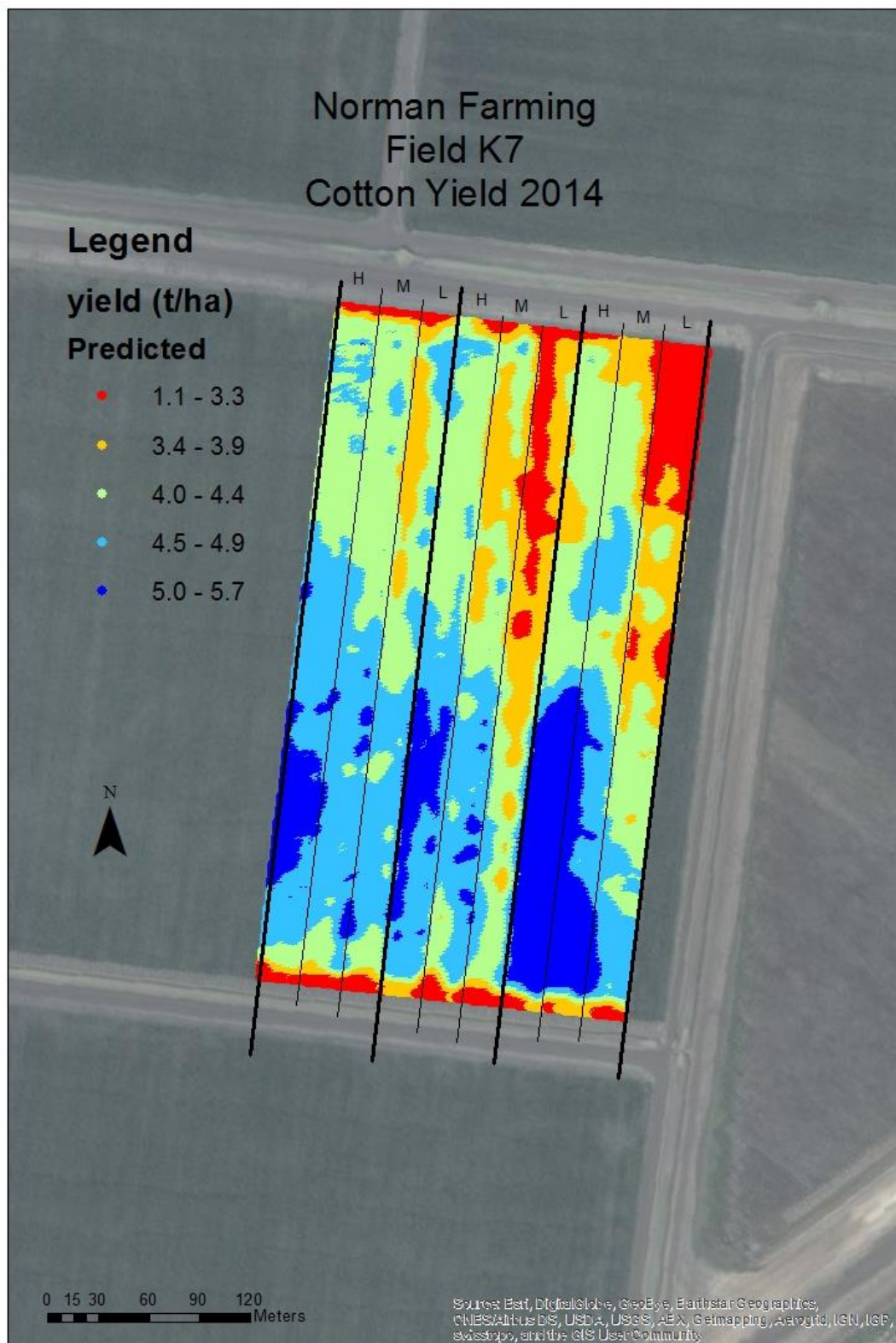
Figure 10 Cotton yield from 2014
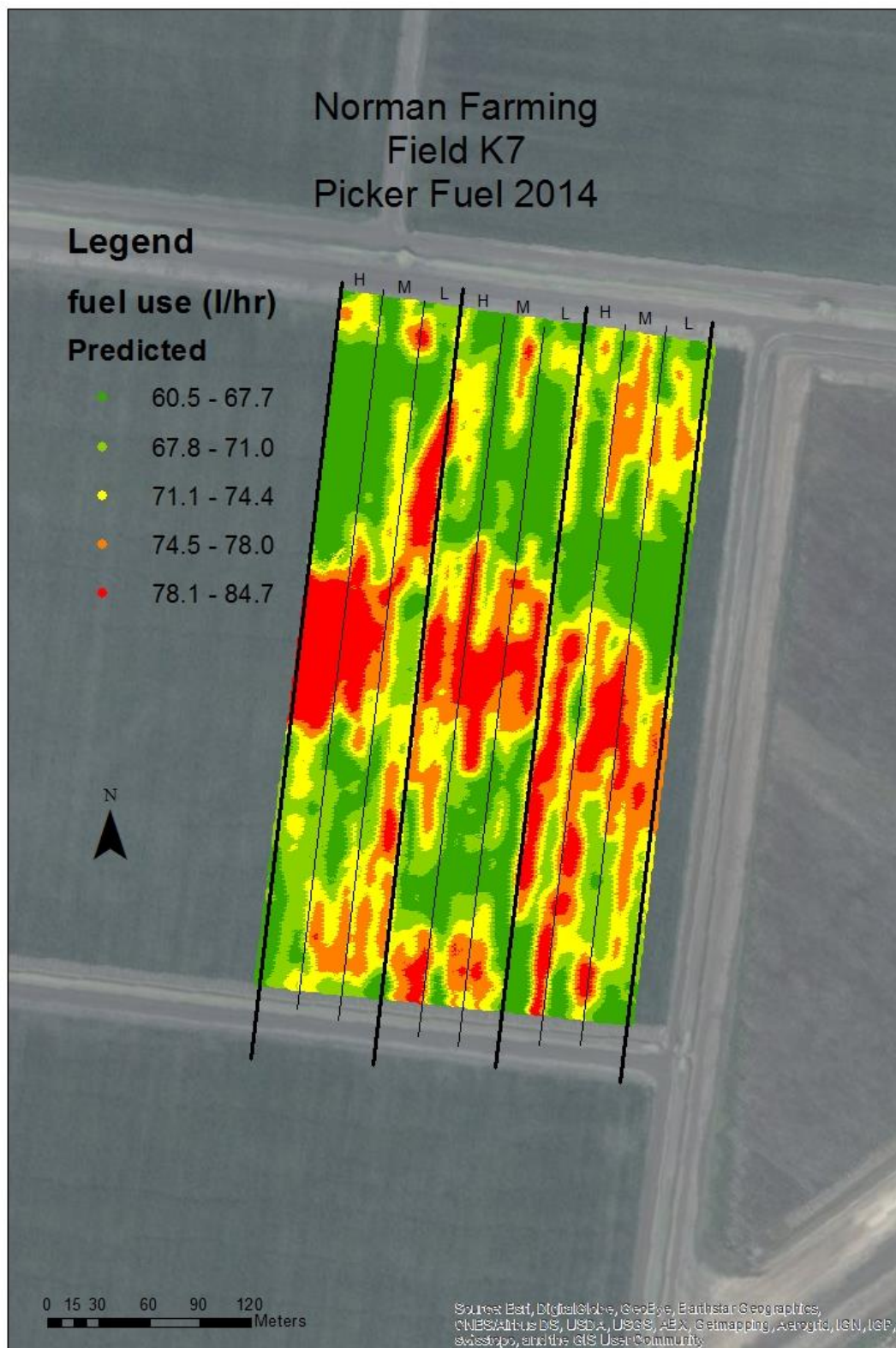
Figure 11 Picker fuel consumpiton from 2014
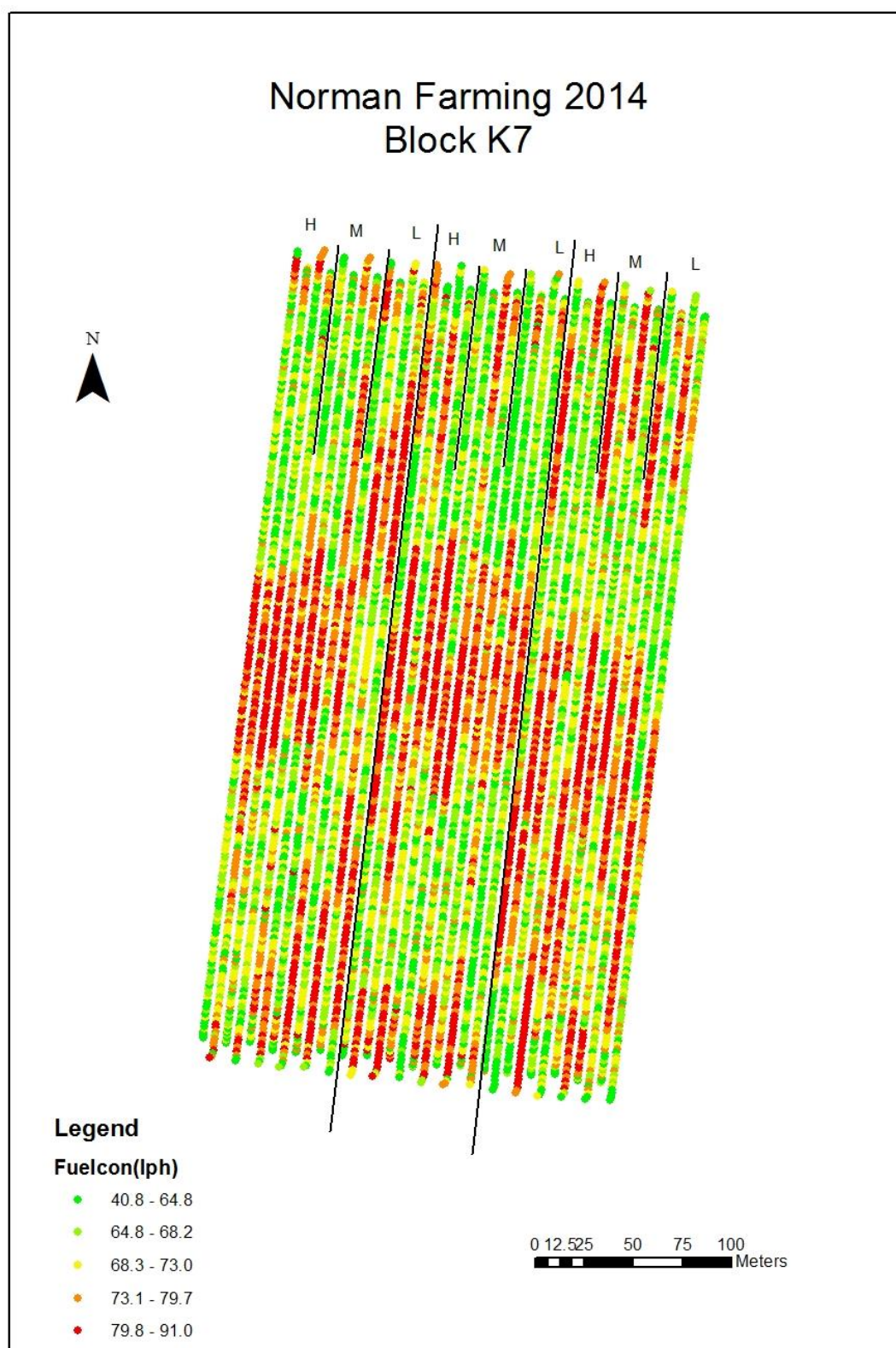
Figure 12 The dot trace of the fuel consumption for the 2014 pick

Table 3 Summary picking data for the 2014 harvest.

Treatment	Rep	Yield (t/ha)	Speed (kph)	Fuel (lph)
1 (L)	R1	4.18	6.68	72.57
1 (L)	R2	3.66	6.68	70.04
1 (L)	R3	3.72	6.62	71.42
	aver	3.85	6.66	71.34
2 (M)	R1	4.40	6.62	71.59
2 (M)	R2	4.15	6.65	71.35
2 (M)	R3	4.52	6.62	72.82
	aver	4.36	6.63	71.92
3 (H)	R1	4.54	6.61	71.23
3 (H)	R2	4.59	6.67	72.21
3 (H)	R3	4.61	6.53	71.58
	aver	4.58	6.61	71.68

Tillage Measurements - 2014

In order to achieve deeper cultivation, larger capacity tractors were utilised for tillage imposed in 2014. Rather than the JD8320R tractors used the previous year, the tractor utilised was a New Holland T8-390. This tractor, with 390 hp, had about 70 more horsepower than the previous John Deere. As the entire farming system was using GS2 Autosteer, the 2630 display was also used in the New Holland. Unfortunately, inconsistencies with CANBUS protocol meant that instantaneous fuel consumption was not recorded. The figures detailed in Table 4 detail the block totals recorded from the meter on the fuel storage. Note, wheel slip and engine speed were also not available. The two passes for treatment 3 in 2014 ensured that the fuel use far exceeded that used in 2013 (52.4 vs 33.7 l/ha) with nearly a 20 l/ha difference.

Table 4 The tillage treatment impose in July 2014

Averages for treatments	Wheel slip (%)	Average Engine speed (rpm)	Measured Average Fuel use (l/ha)	Target tillage depth and speed
Treatment 1 (L)	N/A	N/A	18.0	10 cm @ 6 kph
Treatment 2 (M)	N/A	N/A	25.3	23 cm @ 3 kph
Treatment 3 (H)	N/A	N/A	22.7 + 29.7	2 passes, 17 cm @ 3 kph then as deep as possible (≈35 cm)

Combined Production and Energy Data

In order to fully assess the impact of the tillage treatments on production, the data for the life of the trial has been amalgamated and is displayed in Table 5.

Table 5 Combined tillage information along with the yield data.

Treatment name	Nominal Treatment	2014 Total bale weight (kg)	Area (Ha)	2014 Seed in cotton (kg/ha)	2013 tillage fuel use (l/ha)	2014 picker fuel use (l/ha)	2014 tillage fuel use (l/ha)	Total fuel use (l/ha)	Productivity (kg cotton / litre fuel / ha)
Treatment 1 (L)	10 cm	9330	2.91	3208	10.3	17.9	18.0	46.2	69.5
Treatment 2 (M)	17 cm	10245	2.91	3522	21.2	18.1	25.3	64.5	54.5
Treatment 3 (H)	23 cm	10630	2.91	3654	33.7	18.1	52.4	104.2	35.1

As can be seen from the above data, there was a slight increase in yield as the tillage intensity increased from 'L' – 'H' (3200-3650 kg/ha), or about a 14 % yield increase. This yield increase however, was not commensurate with investment in fuel in the preceding tillage operations, with approximately 2 times more fuel being used to produce this additional yield (L – H) and 40% more fuel being used in the 'L' – 'M' comparison. If we look at a productivity measure (kg of cotton produced / litre of fuel burnt / hectare of land), it is evident that the light tillage treatment (L) is approximately 2 times more productive than the heavy (H) tillage treatment. A word of caution, this is only one year of yield data and the benefits of the intensive tillage may become evident over time and the impediments due to the minimal till may compound with time

As this is only data for one season, the long term implications of the intensive tillage treatment (H) have not been quantified. It is thought that the benefit may potentially accrue in subsequent years. Additionally, the impact of the 'L' pupae bust treatment will most likely compound in subsequent years with the yield potential decreasing over time.

The energy data raises an interesting discussion point. While yield increased with increasing cultivation intensity, and the fuel cost vastly increased, how this equates economically is a question of cotton, labour and fuel price. Working on reasonable 2015 prices for cotton, $500 /bale (227 kg/bale), and diesel, $1.2 /L (wholesale), the high intensity tillage treatment increased comparative profit by $862.35 /ha and $167.38 /ha as compared to the minimum and medium intensity tillage systems. Whilst labour costs have not been removed, the high intensity tillage system appears to be profitable over both minimum tillage and the tillage perceived required for the previous basket picking system (assumes other inputs for these management systems would be equal – in this case they were by design). Hence, there is merit in further investigating greater depth of cultivation, and any associated increase in yield, as well as the cost benefit analysis of this. It will be important to determine to what extent yield gains are due to hydraulic improvements, as compared to mineralisation of nitrogen via deep (>0.3 m tillage depth) tillage processes (Cowie et al. 2007).

Soil bulk density
There were no significant treatment differences in soil bulk density before or after traffic (see Figure 13). No difference post traffic was expected as all soil will have been freshly subject to the JD7760 and force is substantially greater than the soils ability to withstand compaction differentially due to

cultivation treatment. No significant differences prior to traffic suggests that the effects of cultivation on yield are attributable to peak water requirements earlier in the season. By the end of the season the cultivated soil within furrows had re-settled to its prior bulk density. This further suggests that cultivation does not ultimately decrease bulk density within furrows. As samples were not taken under rows, it is not possible to comment on whether density was less under beds for cultivated treatments.

Treatment effects were then analysed by depth with no significant differences found with depth once again.
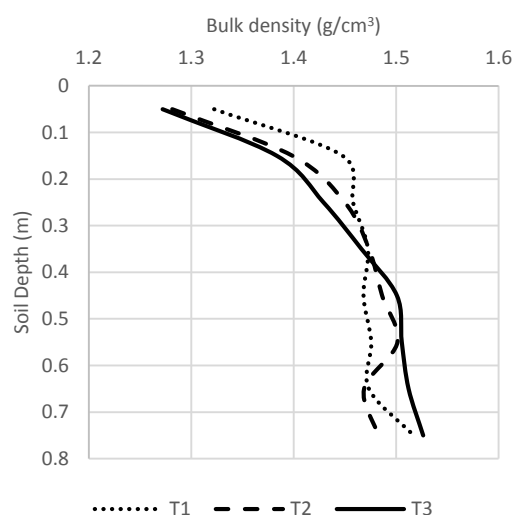
Figure 13 Bulk Density before traffic, by treatment
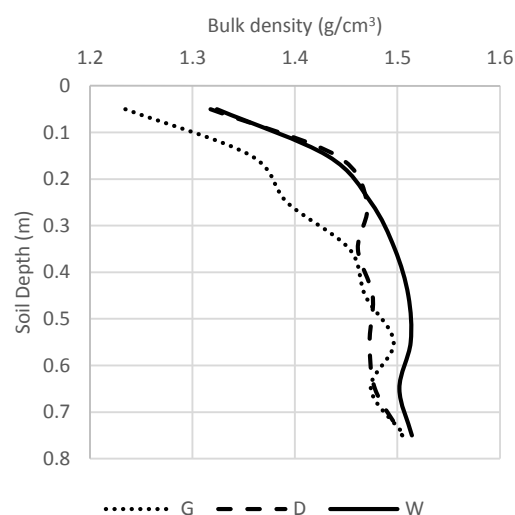
Figure 14 Bulk Density after traffic, by position
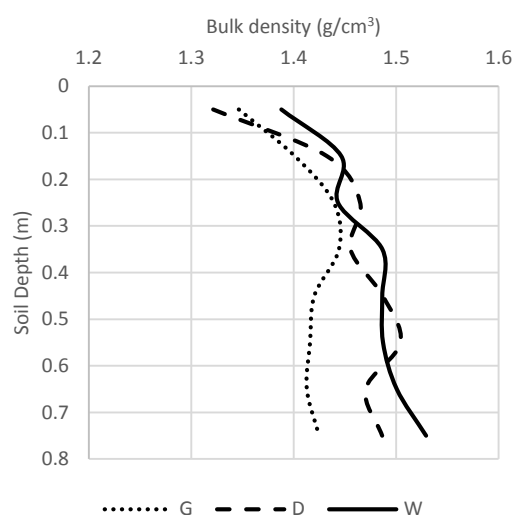
Figure 15 Bulk Density before traffic, by position

Given that there were no significant differences between treatments as a whole and by depth, the data were combined and analysed by furrow to investigate the effect of wheel traffic. Differences between wheel, guess and differential furrows prior to traffic (see Figure 15) were not significant in the surface soil, but were significant in the subsoil. In the surface, there was a tendency for the wheel traffic furrows to have a greater bulk density than the guess furrow, while in the 0.5 through 0.8 m

depth the guess furrows had a bulk density significantly ($p<0.01$) lower than the wheel traffic furrows and the differential furrows (significant pairs were tested using a Tukey honest significant difference tested at alpha=0.1).

Comparing traffic furrows after traffic (see Figure 14) resulted in a significant difference ($p<0.01$) whereby wheel traffic furrows had greater bulk density than guess furrows for depths 0–0.7 m. The differential furrow was significantly ($p<0.01$) greater in bulk density than the guess furrow for the 0 through 0.3 m depth.

These results suggest that cultivation effects do not last through to the end of the season. However, based on the consistent trend for yield increase with increased cultivation, it is probable that cultivation serves to increase infiltration during peak growth periods for the cotton plant. There would be merit in further investigating tillage treatments and their differences throughout the season and irrigation incidences. Importantly, all treatments exhibited significant increase in compaction to a depth of 0.70 m, which is well beyond the maximum tillage depth of 0.23 m. Hence, whilst tillage at the current depths was able to increase yield slightly it is likely that subsequent traffic may induce a compaction pan beneath the tillage depth that could limit yield in future seasons. Deep ripping may provide a method to alleviate some of this compaction, but the cost verse benefit of this needs to be further investigated. Anecdotal discussions within industry suggest that tillage to much greater depths than 0.23 m has resulted in substantial increased yield. However, this needs to be quantified, economically evaluated in future work, and the mechanism for yield increase determined; i.e. as per above, does nitrogen mineralisation play a role, as for cleared land (Cowie et al. 2007).

Future Work Considerations

- In any future work, Greenstar data is essential. Whilst data collection is relatively simple (take a USB and when paddock is done, plug into the side of 2630 display and follow prompts to download data) the majority of growers did not collect this data, using the monitor as in-field, on-the-go information instead.
- To ensure accurate results for total fuel use, it is important to compare actual fuel use (from a meter) to that measured by the monitor. In this work calibration was achieved by using actual fuel use obtained by ensuring the machine was full prior to entering the field, and then refilled after exiting the field where the fuel required equates to the fuel consumed. Flat ground is required for this and all subsequent measurements need to be take on the same flat piece of ground (useful to mark where wheels are with paint). It is important that the picker is not on a different angle. Fill the fuel tank to the same level each time (i.e. to top of the neck of the tank, or to breather hose, or to the filter screen in the tank etc.)
- Time in field is an important variable in calculating field efficiencies that is often not recorded in grower's records. Note time when picker entered field and when leaving field. If cleaned down before/after picking, also note this as this can have a dramatic effect on field efficiencies.
- Fuel use during turns is not logged by the GreenStar monitor. If this information is important (as it was for this work), sit in the cab and record instantaneous values from the screen for a number of turns (>10) and note if head ditch or rota-buck end. Also note if turning back tight or skipping 1/2/3 rows etc. If the time is noted, this can be found in the yield data set and used to approximate for the whole field. Even doing this for the current work, fuel use for the monitor was underestimated by approximately 20%. This error may have something to do with the harvester (engine) being data-chipped to extract more power.

- Find co-operators who are interested in the results as competing priorities/personnel changes can strongly influence data integrity, or compromise continuation of the project.

Conclusion

- During a uniform harvest (little field variability) fuel usage fluctuates from <80 l/hr to >90 l/hr depending on whether the cotton is going into the accumulator or a bale is being formed in the chamber
- Fuel usage is not recorded on the monitor when the picker is turning, however values > 65 l/hr have been recorded when the picker is turning and a bale is still being formed. If a bale is not being formed, this values drops to about half.
- Total fuel usage for a block using the monitor totals vs a calibrated bowser can be 20% different (the monitor underestimating) and this is particularly evident when the picker has been 'chipped' to extract more power from the engine
- The Low tillage treatment in this experiment provided the optimum return for the fuel input invested, although when calculated against the price of cotton, slight gains in yield under high tillage were economically justifiable. Time for the consequences of the Low tillage treatment to fully materialise was not possible in this trial.
- The compaction implications on yield may not become evident for several years due to seasonal influences
- Bulk densities under the guess row were significantly different to those under the wheels.
- A consistent trend for increased yield with increased tillage was evident that was profitable on average taking into account fuel and cotton bale prices. This suggests there is merit in further investigating tillage to greater depths and at multiple sites over multiple years to determine what this relationship looks like.

Reference

Cowie, B.A., Thornton, C.M., Radford, B.J. (2007) The Brigalow Catchment Study: I. Overview of a 40-year study of the effects of land clearing in the brigalow bioregion of Australia, *Australian Journal of Soil Research*, **45**, 479-495

Financial analysis of adopting the John Deere 7760

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Introduction

The introduction of the John Deere round bale picking system (JD7760) has led to significant uptake by industry due to a number of important financial and social drivers. This adoption has occurred in light of the high capital cost of the machines and the weight and dimensions of the machine. This research seeks to understand the financial drivers and implications of compaction from a quantitative perspective and the social drivers from qualitative perspective though a number of case studies. This research will focus on the financial analysis of on-farm practice change for new harvest methods, from a business perspective the reduction in labour has been a major driver of adoption.

The scope of the research is limited with 4 farming systems, these farming systems were:

- Case study 1 – produces up to 1,000 hectares of dryland cotton with a strict controlled traffic regime and significant modifications to the commercial JD7760;
- Case study 2 – produces up to 1,000 hectares of dryland cotton with controlled traffic used for all activities except cotton harvesting;
- Case study 3 – produces up to 2,500 hectares of cotton both dryland and irrigated cotton with controlled traffic used for all activities except cotton harvesting;
- Case study 4 – produces up to 4,000 hectares of cotton both dryland and irrigated cotton with controlled traffic used for all activities except cotton harvesting;

The case studies built a depth of knowledge in seeking to understand the financial consequences of adopting JD7760. In general terms no two farming systems are the same and so the research focused on change in practice. The major impediment to comparing farming systems from a financial perspective is complexity, prices associated with practices change from region to region, from farm to farm and from paddock to paddock. Hence, this research utilises standard costing to compare practices from one farm to another. This method will allow understanding the change in practice without the added variable of price.

Research questions

The research raises two questions on the financial viability of the new harvesting methods in the Australian cotton industry:

- What is the cultivation cost increase moving from the previous basket system to new methods of cotton harvesting in Australia; and
- What is the real cost of practice change in adopting new harvesting methods in the Australian cotton industry?

Methods

The aim of the research is to develop the business case for understanding the implications of practice change, in completing this analysis a number of methods were considered. These included the direct comparison of one farmer's financial records against another to determine the implications of

introduction of round bale picking systems. Difficulties arise with this methods, due to the inconsistencies with the categorisation and measurement of farm financial information, and due to no standardised chart of accounts (Jack 2015; Slaughter and Mulo 2012).

The introduction of the JD7760 has provided positive financial and social outcomes for cotton growers. The research will use standard costing of the extra on farm activities as an outcome of the introduction of the round bale harvester. These standard costs will be applied to the different activities undertaken by the growers to combat the compaction caused by the round bale systems. This allows a direct comparison to be made, answering the research questions.

Interviews

The case study interviewee recruitment was "purposeful" rather than "representative" as such an approach best fits the project focus. Interviews were semi-structured to facilitate a relaxed dialogue maximising respondents answering honestly and openly. Similar to the focus groups (Chapter 2), interviews followed a recursive method of questioning (Minichiello *et al.* 2013) designed to elucidate the processes undertaken by producers and to allow iterative questioning and probing on key points. In addition to written notes, interviews were recorded in audio form so that a full analysis of the interviews could be undertaken. The interviewees engaged were engaged by the researcher due to their participation in previous studies. The interviewees were required to have purchased or use contractors who use the round bale harvest systems and have a systems understanding of the biophysical and financial information on-farm to answer the research questions.

The maximum variation within sampling was considered in determining the variation between case studies. The maximum variation has been address by drawing case studies from different regions, business sizes and tillage practices. The business sizes selected included smaller farms where the harvest equipment is used on the interviewee's farm in combination with a sub-contracting business and large farms with a number of the machines. The two farming systems that were considered included conventional cotton production systems and those that utilised a true controlled traffic farming system.

Interview questions

The interview questions were used as a guide for each of the case studies. The research areas and questions were:

1. Changes in yield and quality
    - Have you noticed any change in yield since purchasing the round bale picking system?
    - Have you noticed any changes in payments for cotton quality?
2. Your Farming System
    - Please describe your farming system?
    - Dryland or Irrigated?
    - What is your row spacing?
    - Are you in Controlled Traffic?
    - If so was there an additional cost to change to that system?
3. Pre harvest operations
    - What did your prep look like before the round bale system implementation, what were the individual operations?
    - What do you do now what are the individual operations?

4. Harvesting
   - What are your maintenance/operating costs?
     - What did your maintenance look like before the round bale picking system implementation with harvester, boll buggies and module builders?
     - What do you do now – is there an increase (fuel, grease, wrap….)?
   - Harvesting before round bale picking system
     - Tell me about your harvesting – how many people were involved?
     - Tell me about your boll buggies and tractors?
     - Tell me about your module builders and tractors?
   - Harvesting after round bale harvesting system
     - What has been the outcome in machinery changes after the round bale harvesting system?
     - Is there a greater opportunity to sub contract – are you able to get the work?
     - Tell me about your current harvesting process?
     - Tell me how you recover the bales?
   - Cartage
     - What did your cartage look like before the round bale picking system, what were you able to get on a truck?
     - What do you do now, what are you able to get on a truck?
5. Ginning charges
   - Have you noticed changes to ginning costs?
6. Machinery changes
   - Were you able to sell the old machinery?
   - What new machinery did you purchase?
7. Personnel changes
   - How many staff before the round bale picking system?
   - How many staff after the round bale picking system?
   - How has this affected your management style?
8. Post-harvest operations
   - What were your operations before the round bale picking system?
   - What do you do now?
- Close interview

Standard Costs

A set of standard costs (Table 1) were developed for the research, these were largely derived from work undertaken by NSW Department of Primary Industries with background information provided by the Department of Agriculture Forestry and Fisheries Queensland (NSW Department of Primary Industries 2015). These costs were adjusted for CPI and a 3 year moving average developed for use in the financial modelling (ABS 2015).

The models were developed on a per-hectare and a per-farm basis focusing on the implications for the practice changes required for adoption of the round bale harvest system. Largely, quantification focused on ground preparation before planting and after the harvesting activities. No case study interviewee was able to attribute yield loss or changes in quality due to the use of the JD7760.

Table 1 Costs (AUD$) of cotton practices expressed as a three year moving average adjusted for CPI

Surface Irrigation Cotton (Bollgard II®) Calendar of Operations		
Farm Enterprise Budget Series - Northern Zone		
Operation	**Month**	**Year Moving Average Per Ha**
Stalk pull and mulch	May	85.47
Discing	Jul	11.81
Hill Up	Jul	13.14
Middle busting	Jul	15.13
Side busting	Jul	22.27
Fertiliser - anhydrous ammonia	Jul	125.09
Herbicide - glyphosate ground spray	Jul	7.90
Wetter - non-ionic surfactant	Jul	1.53
Fertiliser - MAP plus potassium blend	Jul	84.59
Herbicide - trifluralin ground spray	Aug	26.28
Plus Incorporation	Aug	10.04
Fertiliser - urea	Aug	161.87
Rubber tyre roller	Aug	11.44
Pre irrigate	Sep	68.88
Fertiliser - MAP plus potassium blend	Sep	109.41
Planting - precision planter	Oct	9.77
Planting- seed Roundup Ready® Bollgard II®	Oct	112.56
Herbicide - fluometuron+prometryn (440 & 400	Oct	40.08
Crop insurance	Nov	113.65
Roundup Ready® Roundup	Nov	13.67
Operation	**Month**	**Year Moving Average**

		Per Ha
Irrigate	Nov	49.20
Insecticide - fipronil (200g/L)	Nov	16.91
Fertiliser - urea	Nov	134.68
Insecticide - fipronil (200g/L)	Dec	33.25
Cultivation – inter row	Dec	12.24
Fertiliser - urea	Dec	191.87
Roundup Ready® Roundup	Dec	13.67
Irrigate	Dec	49.20
Insecticide - fipronil (200g/L)	Dec	16.91
Herbicide - diuron (900 g/kg)	Dec	12.99
Herbicide - prometryn (500 g/L)	Dec	20.61
Irrigate	Dec	62.30
Cultivation - chipping casual labour	Dec	5.17
Irrigate	Jan	59.04
Insecticide - Abamectin (18g/L), target: mites	Jan	15.63
Roundup Ready® (shielded sprayer)	Jan	12.26
Irrigate	Jan	62.30
Licence Fees - Bollgard and Roundup Ready	Jan	145.14
Insecticide - dimethoate (400g/L)	Jan	18.45
Insecticide - indoxacarb (150g/L)	Jan	68.47
Irrigate	Jan	59.04
Crop insurance	Jan	62.68
Insecticide - Diafenthiuron (500g/L), target: SLW, aphids	Feb	61.70
Irrigate	Feb	59.04
Operation	**Month**	**Year Moving Average**

		Per Ha
Irrigate	Feb	49.84
Licence Fees - Bollgard and Roundup Ready	Mar	276.53
Insecticide - dimethoate (400g/L)	Mar	27.28
Defoliant - thidiazuron + diuron (120 + 60 g/L)	Mar	52.45
Defoliant - crop oil	Mar	8.91
Defoliant - ethepon (720 g/L)	Mar	15.96
Defoliant - ethepon (720 g/L)	Mar	42.88
Contract picking and wrapping round bale picker	May	300.00
JD7760 Baler	Apr	69.47
JD7760 Fuel	Apr	29.99
JD7760 Wrap	Apr	106.97
Contract picking & module building basket picker	May	346.12
Contract Module lifting	May	39.40
Contract module cartage to gin	May	143.89
Ginning charges	May	602.72
Levies	May	47.81
Consultant	May	68.38
Consultant	Jun	67.16
Pupae Busting	Jun	17.97
Soil moisture monitoring	Jun	4.13
Desilting & grading channels	Jun	51.66
Mulcher with root cutter	Jun	15.39
Sterilising channels	Jun	19.72
Refuge crop - pigeon peas @ 5%		28.21

Source: (ABS 2015; NSW Department of Primary Industries 2015)

Limitations

A number of limitations exist with this research:

- The financial research began in September 2015 to take advantage of findings from the biophysical research with limited resources to conduct a detailed study of the industry or the individual farming systems;
- Given the constraints of the project funding the researcher (economic analyst time provided as in-kind), detailed analysis of the financial and social attributes of the farming system was limited; and,
- Growers' records were severely limited at the paddock scale, which precluded much of the detailed information required, had further resources been available anyway.

It is hoped that future research from a whole farm perspective, using what is now known from the current research and carried out over at least three years, will allow a more detailed analysis to occur. This data will be extremely valuable in helping to shape adoption of future innovations and in assessing viability of management methods in the long-term.

Results - case study outcomes

Case study 1

The farm is a cotton farming business in Southern Queensland growing up to 1,000 Ha of dryland cotton annually. The farm implements a controlled traffic system for all crops throughout all crop rotations including cotton picking.

The introduction of the JD7760 into the farming system was made as an early adopter (Diederen *et al.* 2003) in 2010 with the new machine purchased locally. Extensive modifications were undertaken to allow for 9 meter 6 row harvesting and addition of a 4 bale trailer. The Interviewee commented that associated management intensity had changed with the introduction of the JD7760 due to:

- The changes to the picker to fit into the current controlled traffic farming system; and
- An increased attention to detail for controlled traffic particularly has led to no increase in ground preparation before planting and after harvesting.

Table 2 Practice changes for case study 1

	Post JD7760 Purchase
Equipment Changes	• Sale of excess harvesters, boll buggies and modules builders • Purchase of near new JD7760 with changes to the picker to achieve 9 m, 6 row harvest and widening of the front and rear axles • Construction of a 4 bale trailer to avoid dumping bales in paddock and allow bales to be offloaded in roadways
Pre-Season Changes	• No changes
In-season Changes	• No changes
Harvest and post-season Changes	• Introduction of a round bale harvester
Cost of practice change	• Annual cotton harvest $1,000 Ha • Net capital cost $750,000 • Cost of Machinery modifications $140,000 and trailer cost $150,000 • Annual standard cost is $0 excluding saving from JD7760

Case study 2

The farm is a mixed grain and cotton farming business in Southern Queensland growing up to 1,000 ha of dryland cotton annually in rotation with wheat. The farm is on a controlled traffic system for all crops throughout all crop activities excluding cotton harvesting. The JD7760 cotton harvester is further utilized on a contracting basis with a target of 1,400 to 2,000 ha per year.

Incorporation of the JD7760 into the farming system was made as an early adopter (Diederen *et al.* 2003) in 2012 with the new machine purchased internationally. The Interviewee commented that associated management intensity had changed with the introduction of the JD7760 due to:

- The issues in ensuring cotton module consistency has been alleviated with the round bale harvester providing a consistent 4 standard bales per round bale;
- Current farming practices are aimed at the drying of the soil profile through wheat plantings to combat compaction;
- A decrease in labour from 10 to 4 staff during the harvest has led to a significant decrease in labour oversight; and
- The decrease in machinery for contracting has led to a reduction in associated transport costs of the basket picker, boll buggies and module builders, as these have been replaced by the single shift of one JD7760.

Table 3 Practice changes for case study 2

	Post JD7760 Purchase
Equipment Changes	• Sale of excess harvesters, boll buggies and modules builders • Purchase of JD7760 harvester with minor modifications
Pre-Season Changes	• Use of chisel plough
In-season Changes	• Decreased machinery maintenance • Decreased labour
Harvest and Post-Season Changes	• Introduction of a round bale harvester
Cost of practice change	• Annual cotton harvest $1,000 Ha • Net capital cost $530,000 • Annual standard cost is $11,810, or $11.81 per ha, excluding saving from JD7760

Case study 3

The farm is a mixed farming business in Southern Queensland growing up to 2,500 Ha of cotton annually with a mixture of irrigated and dryland cotton. The rotations of cotton and grain are determined in consultation with the family considering the key drivers of price, soil moisture levels and on-farm stored water. The farm implements are controlled traffic for all crops except cotton, due to the issues associated with harvesting.

The introduction of the JD 7760 into the farming system was made as an early adopter (Diederen *et al.* 2003) in 2012 with the business directly importing a near new machine while the Australian dollar was strong. A number of modifications were made to the imported machine and the associated rationalisation of equipment at this point. The Interviewee commented that associated management intensity had decreased with the introduction of the JD 7760 due to:

- A decrease in repairs and maintenance particularly for hydraulics and the associated machinery down time during harvest;
- Original system had a labour requirement of 10 for harvesting, boll buggies, module building and transport requirements, this has reduced to 2 for harvesting and round bale transport; and
- Transport management intensity had decrease due to transport efficiencies.

Table 4 Practice changes for case study 3

Post JD7760 Purchase	
Equipment Changes	• Sale of excess harvesters, boll buggies, modules builders and mulchers. • Purchase of near new JD7760 picker, trucks and trailers and mulchers
Planning Changes	• Use of sidebuster replacing the use of a middlebuster • Use of chisel plough
In-season Changes	• Decreased maintenance
Harvest and post-harvest Changes	• Decreased repairs and labour • 1 round bale harvest replacing 3 pickers, 2 boll buggies and 2 module builders • 1 truck replacing 2 flatbed trailers
Cost of practice change	• Annual cotton harvest $2,500 ha • Net capital cost $385,000 • Annual standard cost is $50,700, or $20.28 per ha, excluding saving from JD7760

Case study 4

The farm is a mixed farming business in Southern Queensland and New South Wales growing up to 4,500 ha of cotton annually with a mixture of irrigated and dryland cotton. The business purchased three JD7760 pickers to supplement existing boll-basket pickers that will be depreciated from the farming system over time. The JD7760 pickers are utilised for 70% of the picking operations annually, with the existing 4 boll-basket pickers utilised for the remaining 30%. A further 2 boll-basket pickers are utilised for additional dry land plantings.

The past two seasons had seen a number of rain events at harvest that led to significant issues with compaction. Rain events of 80 mm and 120 mm where recorded at picking. It was observed that the basket pickers left wheel tracks of 150 mm to 200 mm, while the much heavier JD7760 system created wheel tracks of 800 mm. Two primary tillage passes were required with a sidebuster and a centerbuster to repair paddock damage while the soil moisture levels were higher. As this event is due to unforeseen rain it is difficult to attribute a permanent practice change due to the utilisation of the JD7760.

Table 5 Practice changes for case study 4

Post JD7760 Purchase	
Equipment Changes	• Purchase 3 new JD 7760, service trailers and 2 flat top trailers
Planning Changes	• Use of side buster
In-season Changes	• Decreased maintenance
Harvest and post-harvest Changes	• Replace 6 basket harvesters, boll buggies and module builders with 3 JD7760 pickers • Decreased labour
NPV of practice change	• Annual cotton harvest $4,500 Ha • Net capital cost $2,350,000 • Annual standard cost is $91,260, or $20.28 per ha, excluding saving from JD7760

Discussion

The uptake of the JD7760 system has been significant with greater than 80% adoption across the industry between 2008 until 2013 (Chapter 2). All participants in the case studies were existing owners of a round bale picking system, had modified the pickers to maximise efficiencies for their individual farming system and displayed strong feelings of ownership in their purchasing of the machine, displaying in many cases the "Ikea Effect" (Norton *et al.* 2011). The implication of the "Ikea Effect" is that managers devote resources to failing projects or do not look for potential flaws in a project; in this case we refer to the latter.

The benefits in relation to JD7760 systems have been identified within the case studies, these include:

- Reduction in labour cost from 5 full-time-equivalent employees (FTE) to 1.3 FTE;
- Modest increases in tillage costs of between $0 for a controlled traffic system to between $11.18 and $20.28 per ha for remedial tillage perceived to address compaction problems (Table 6);
- Retainment of higher skilled permanent labour, and its effect on the long term profitability of the farming system (Slaughter *et al.* 2015);
- Reduction in risk by not employing unskilled or backpacker labour, and/or reduction of timing issues in not having skilled staff (Slaughter *et al.* 2015); and
- Reduction in contract picking cost between a basket picker ($346.12, Table 1) to between $290 and $300 per hectare for a JD7760.

Table 6 Grower capital and remediation costs

	Case Study 1	Case Study 2	Case Study 3	Case Study 4
Year commenced	2010	2012	2010	2013
Average yearly planting	1,000	1,000	2,500	4,500
Net capital costs	$750,000	$530,000	$385,000	$2,350,000
Soil remediation costs	$0	$11,810	$50,700	$91,260
Remediation costs per ha	$0	$11.81	$20.28	$20.28

The net capital costs (Table 6) within this study were derived by determining the capital sales and purchases for the individual case studies. Early adopters received significant benefits, and these varied with each case study, due to a number of factors:

- Favourable Australian dollar in 2010 compared to 2013;
- Higher prices 2010 for existing plant and equipment, the market for existing plant and equipment has now created a favourable market for second hand equipment (Pers. Comm. Vanderfield's Toowoomba, 2015).

The adoption of an innovation such as the JD7760 is not linear; the passage from research to development to extension to adoption is not a straight line. The Farmer Adoption Model (Figure 1) is

circular to mimic the nonlinear nature of adoption leading to the farmers' conversation with innovation and ultimate adoption (Cooksey 2011; Smith *et al.* 2007).

Figure 1 Farmer Adoption Model

Farmers are generally poor at the collection of information and the application of the information to innovation within their individual farming systems, mainly because automated collection has been hampered due to connectivity issues. Additionally, the Australian market price of data interrogation is comparatively exorbitant to other countries where data is highly valued. However, both of these hindrances will improve with the agricultural digital revolution (Bennett 2015). Many farmers move from planning to implementation without a rigorous understanding of innovation options for their individual farming systems. This skip in process is often due to a lack of planning systems on farm (Slaughter *et al.* 2015), as well as a perception that innovation/professional-development is an extracurricular activity, rather than work (Bennett and Rose 2014).

What is unknown is the long term effect of heavy machinery on soils, particularly where soils are not allowed to dry sufficiently prior to harvest. While it would appear from the case studies that the additional tillage required to overcome the compaction caused by the heavier JD7760 (compared to previous basket pickers) is cost effective, it is clearly demonstrated as unnecessary when compared to the CTF system. The financial and non-financial savings attributed to the JD7760 are clearly demonstrated in the contractor rates; savings brought about by increased speed of harvest, as well as reduction of infield infrastructure and manpower. In favourable seasons, and after only recent incorporation of a JD7760 into the farming system, this may well be the case; however, longer term impacts on production costs are unknown.

The economics used for the case studies involved the use of centre and side busting as the remediation method which equates to an increase of $7.14/ha. This form of tillage can only address compaction in

the top 20 or so centimetres of soil. No consideration has been made for the compaction compounding over time, which will be highly likely.

In other sections of this report, it is detailed that compaction caused by the JD7760 is evident at 80 cm. Details of what one farmer's tillage practice was in endeavouring to maintain plant available soil moisture is presented in the energy chapter of this report. Here, the farmer was investing 52.4 L/ha per season to mitigate compaction. Additionally, anecdotal evidence talks of a grower in Moree using a Caterpillar D12 pulling deep rippers to break up compaction at 80cm. This treatment is expensive, but considered appropriate, only in terms of alleviating compaction, to maintain the soil resource hydraulic function; the effects of such tillage are unlikely to be conducive to optimal overall soil function.

Summary and recommendations

If wheel tracks can be constrained to a smaller proportion of the paddock and these become permanent features in the landscape (as in one of the case studies and also that used by Auscott in Warren (Chapter 5)) where the increased GM from this farming system is ≈$192/ha (based only on Auscott data). Incorporating controlled traffic farming into the cotton system must be considered for heavy equipment. If the equipment is confined to the harder permanent track, cotton growers do not need to be concerned about remediation of the compaction as it is constrained to the same part of the field every year; in fact controlled wheel-track compaction actually improves rolling resistance in-field and allows a larger window for soil traffic to occur without significant detriment.

The adoption of the JD7760 has be astonishing, from a grower perspective they have met the challenge with respect to the analysis conducted for the business case to introduce the machine into their individual farming system. The research has identified that in a normal season producers are maintaining soil hydraulic function at 20–40 cm (via cultivation), although the research questions the ability for the grower to meet the long term implications of soil remediation at 80 cm.

Investment decision making surrounding picking is arguably one of the greatest challenges a farmer can make. Farmers must identify, evaluate, select, fund and implement a picking system for their current farming system. In understanding this decision correctly, the farmer should evaluate and select picking systems in the most cost-effective manner. A farming enterprise invests in innovation depending upon a number of financial factors, and every farm action has a financial consequence (Damodaran 2010).

With a need for farming enterprises to maximise profitability, the adoption of an innovation framework, based on the conceptualisation of Figure 1, will allow cotton businesses to identify weaknesses within the enterprise and adopt the innovation required. Further financial systems research is required to understand the long term effects of heavy machinery on our soils.

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4. Innovation impact assessment framework for adoption decisions in the Australian cotton industry

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Introduction

The John Deere 7760 (JD7760) is perhaps the most rapidly adopted significant innovation in the history of the Australian cotton industry. Inception occurred in 2008 and 82% adoption of the machine had occurred by 2013, with the capacity to pick the entire Australian cotton crop roughly one and a half times. Such rapid adoption meant that time compression of the innovation adoption lifecycle (Figure 1) occurred with the time from early adopters through to late majority conservatives being 24-36 months; substantially fast for a machine with market price AUD$750K at the time. The Chasm that exists in the adoption lifecycle, where an innovation fails or succeeds, was effectively non-existent, which can be explained by the "Ikea Effect" (Norton, Mochon & Ariely 2011) whereby managers will devote resources without looking for potential flaws in a project. The ramification for the broader industry is that decisions are made rapidly and the time to learn from pitfalls identified by innovators/early adopters is severely diminished, or non-existent, leading to greater chance of unforeseen impacts on the production system. Impact compounds as the extent of effect is now occurring to the vast majority of the industry, as opposed to being identified and contained to a small portion of the industry. This identifies a need for growers to be provided with a tool to help make informed decisions and to prompt consideration of potential pitfalls prior to purchase.
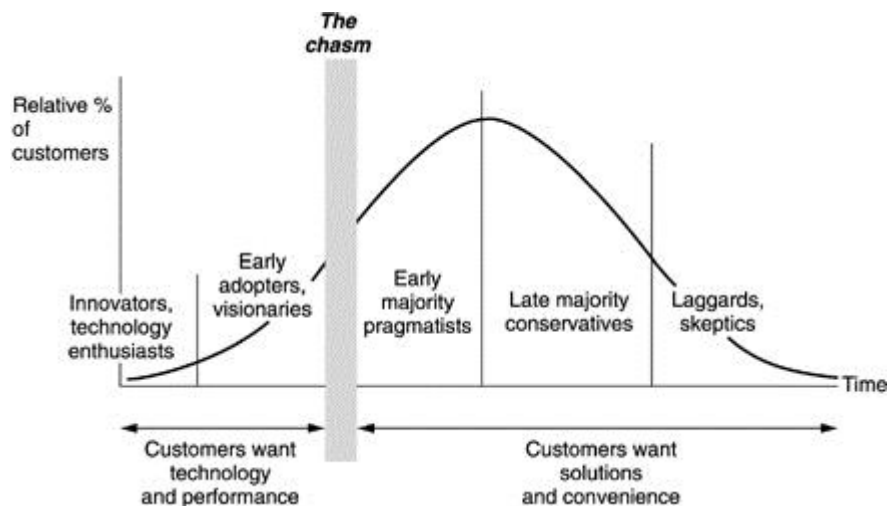
Figure 1. The innovation adoption lifecycle (After Norman 1998)

No two farming systems are identical, and growers have a firm belief that their system is vastly different to others, irrespective of proximity (Bennett & Cattle 2013, 2014). This highlights the importance of ensuring that any adoption decision framework allows real system differences, and perceived system (perceived individual importance of system components) differences to be incorporated. For tools to be useful, they need to either allow tailoring to the specific farming needs (Startasts 2005), or facilitate individual nuances. Therefore, this section develops a basic innovation impact decision making framework to aid in informed adoption, based on the JD7760 impact

assessment (Chapter 3) and Australian perspective on integrating the JD7760 in the cotton system (Chapter 2).

Development

In undertaking the discussion forum, survey and impact assessment design and the research team were required to undertake an *ad hoc* risk assessment process to help design how aspects would be approached. In this case, the JD7760 was the focus, so developing questions and identifying constraints was facilitated by rapid focus, due to a discrete context. However, if the framework is to be useful for other innovations, where the context boundaries are undefined, then the framework needs to facilitate consideration of the full farming system, whereby impacts can be weighed up against key constraints to the individual production system and irrelevant constraints rapidly removed from the assessment. It was identified that the framework needed to be:

1. Inclusive of all farming system components;
2. Allow addition of further important system components as they arise;
3. Provide the ability to identify if the impact is positive, negative, or nil;
4. Determine the likelihood of the impact occurring (defines magnitude of frequency and severity);
5. Allow individual importance for farming system components to be incorporated;
6. Curb the influence of individual importance where potential for irreparable impact is high;
7. Provide appropriate independence from purely emotional decision (reduce the Ikea Effect);
8. Identify system components that may require further in depth consideration;
9. Operate with low data input
10. Provide a comparison of positive and negative impacts;
11. Promote reflective thought processes (Boud 1999); and,
12. Be simple to use.

Points 3–5, 8, 9 and 10 are processes the majority of people will automatically go through in making a decision on an everyday basis. However, emotional influence (equivalent to "gut feeling") on decisions can have a vast influence, as previously discussed, and the more emotional a decision becomes the less reflective (Point 11) on past experience the thought process becomes. Reflection on past experience is perhaps one of the most important aspects in developing a framework that is capable of identifying potential impacts of an innovation. Reflecting should be done as an individual and in a collective nature, which will allow reflection on a particular farming system practice/constraint to be evaluated within the farm-context, innovation-context and broader-context. Collective reflection also helps to supply some independence in terms of emotive decision making and help to redefine the individual importance we may place on a specific practice/constraint. For the purpose of this framework, we proposed approaching reflection through a traffic light system where if an impact is potentially:

- Highly negative (red) the user should stop and consider this component after the initial analysis and consider if the constraint is able to be managed to reduce risk, or if it outweighs purchase. Furthermore, whether this constraint has impact on any other of the components that has not been yet identified;
- Moderately negative (yellow) the user should hesitate during the analysis and consider how this impact might affect other components;

- Positive (green) where the component has no adverse impact and requires no further thought until red constraints are reconsidered for their effect on other components.

This does not directly facilitate collective reflection, but should help to raise a set of questions concerning overly negative impacted components. The fact that this list of potential queries is systematically defined and then collated makes the process of discussion simpler, thus increasing the probability of it occurring.

A decision framework such as this would be well suited to computational, automated, and/or probabilistic modelling of risk, but there is a tension between Point 1 and 9 when automating such a process. Identifying all relevant farming-system components is not an impossible task, and various farming systems ontologies exist (e.g. van Ittersum et al. 2008), but by virtue of the complexity of farming systems, this would require a large amount of data to populate the model. Troldborg et al. (2013) used Bayesian belief networks (BBN) to overcome data availability whereby expert opinion can be used to supply probability states for system components where actual data is not available. However, such an approach is beyond the scope of the current work, and requires significant intellectual resource (time cost) to populate nodes where data does not exist, but could be considered in future iterations. Hence, we have opted for a simple tool that can operate in Microsoft Excel. This allows the individual user to easily edit-in further system components (Point 2) in the non-exclusive list of system components.

The downside to this approach is that data input is based purely on user self-assessment, but this can be overcome by conducting the assessment with the farm agronomist, or in a collective environment. In order to have individual autonomy of process, the framework would need to be complex and operate based on a large dataset to inform risk probabilities and describe system component interactions. Generally, growers have significant experiential familiarity with their properties, so can help describe interrelationships and how these change for many system components. But, where grower experience with certain interactions does not exist, the process will fail to identify unexpected impacts. Thus, in compromising for low data input, to maintain independence and rigour in identifying latent impacts there is a requirement that the assessment be done with at least one other experienced person. We suggest the property agronomist, or a community of farmers all seeking to undertake the assessment facilitated by an industry extentionist, would be suitable.

Framework

The framework is depicted in Figure 2 as a screen shot of the assessment list, inputs and outputs. The farming system is split into **modules**: Soil resource; Water resource; Plant resource; Machinery; Labour; Marketing; Management; Ginning; Transport; Climate; and, Technologies. These modules were selected to allow adequate representation of the various operating subsystems of the farming system. The components within each module are not intended as an exhaustive list, having been drawn from focus groups, project outcomes, and literature. Each module allows additional components to be added as required, but removal of components is not advised as they may not be applicable to a current innovation of consideration, but could be for future ones.

To combat this the **impact** column provides a not applicable option (N/A) in the drop down rating scale list for each cell within the column. The impact rating scale is provided numeric value from -5 (highly negative impact) to 5 (highly positive impact). There is no neutral option of a zero value; if

Input Sheet

Farming System Consideration	Impact (-5 to 5)	Likelihood (1-5)	Importance (1-5)	Traffic light
soil resource			3	N/A
organic carbon	N/A		3	N/A
plant root depth	-1	4	3	-12
drainage	N/A	5	3	N/A
waterlogging			3	N/A
compaction potential	-2	4	3	-24
bulk density	-2	3	3	-18
tillage depth	-3	2	3	-18
moisture transfer in/out of soil	-2	2	3	-12
trafficability/timeliness	2	3	3	18
health/microbes	N/A		3	N/A
mirco-relief	-1	2	3	-6
water resource			3	N/A
runoff/tailwater	N/A		3	N/A
waterlogging	N/A		3	N/A
groundwater contamination			3	N/A
loss of nutrients	N/A		3	N/A
water use efficiency	-2	2	3	-12
irrigatrion uniformity	-3	2	3	-18
plant resource			3	N/A
pests	N/A		3	N/A
diseases	N/A		3	N/A
weeds	N/A		3	N/A
row spacing	-2	5	3	-30
planting density	N/A		3	N/A
establishment costs	-1	2	3	-6
fertilisation	N/A		3	N/A
performance of chemical application	N/A		3	N/A
fallow efficiency	N/A		3	N/A
machinery			3	N/A
consumables cost	-2	3	3	-18
efficiency field operations	3	3	3	27
availability of consumables	-1	2	3	-6
min till/CTF compatability	-2	2	3	-12
WH&S implications	1	3	3	9
upgrade costs	-3	3	3	-27
other capital equipment needs	-1	2	3	-6
mobility/portablity of equipment	1	2	3	6
harvesting losses	N/A		3	N/A
harvesting costs	-2	3	3	-18
harvesting window	3	3	3	27
sale previous equipment	-1	3	3	-9
purchase costs	-3	3	3	-27
work rates	3	4	3	36
labour			3	N/A
availablity	1	3	3	9
retention	1	3	3	9
ability to contract pick to cover costs	-2	3	3	-18
WH&S impacts	2	2	3	12
marketing			3	N/A
forward selling	N/A		3	N/A
overseas factors	N/A		3	N/A
management			3	N/A
agronomist assistance	N/A		3	N/A
Manager's knowledge	N/A		3	N/A
decision support tool	N/A		3	N/A
BMP	N/A		3	N/A
ginning			3	N/A
moisture costs	-3	2	3	-18
quality issues / neps......	1	2	3	6
transport			3	N/A
costs	-1	3	3	-9
special permissions to travel on roads	-1	2	3	-6
climatic			3	N/A
susceptibility to climatic extremes	N/A		3	N/A
technologies			3	N/A
personnel to run	-1	2	3	-6
compatability with PA	1	2	3	6
backup/repairs	-3	3	4	-36

Farming System Evaluation Framework - Australian Cotton

innovation - purchase JD CP690

Summary Sheets

score	important issues- negative
-24	compaction potential
-18	bulk density
-18	tillage depth
-18	irrigatrion uniformity
-30	row spacing
-18	consumables cost
-27	upgrade costs
-18	harvesting costs
-27	purchase costs
-18	ability to contract pick to cover costs
-18	mositure costs
-36	backup/repairs
-270	

score	important issues- positive
18	trafficability/timeliness
27	efficiency field operations
9	WH&S implications
6	mobility/portablity of equipment
27	harvesting window
36	work rates
9	availablity
9	retention
12	WH&S impacts
6	quality issues / neps......
6	compatability with PA
165	

Return Ratio = -0.61

Figure 2. Farming system evaluation framework for informing decision making processes in innovation adoption assessment. The example innovation used is purchase of a John Deere CP690.

the impact is neutral, then the component is N/A. This ensures risk ratings can be calculated properly, avoiding zero values and not unduly triggering traffic lights.

The **Likelihood** column uses a drop down scale for each cell with a rating from 1 (unlikely) to 5 (highly likely). This cell is multiplied with the impact rating to provide an **intensity** of impact, which can be thought of as severity of impact on the production system for a negative impact, and scale contribution to the production system for a positive impact.

Importance refers to the individual's personal opinion on how important a consideration is to their production system. This is ranked on a scale of 1 (not overly important) to 5 (overly important) and is multiplied by the **intensity** factor as a weighting; N.B. intensity is not displayed to the user. While the impact and likelihood cells are unpopulated to prompt the user to provide a ranking, the importance cell is default 3 on the 1 to 5 scale. The intention here is that the cell is already populated, not necessarily requiring user input, and by weighting with the median value we create a central datum of output on which to establish "the norm". The logic here, is that a user must feel rather strongly either way to decrease/increase the importance of a component.

Once the importance and intensity have been multiplied, this triggers a **Traffic light**. Red, yellow and green have been defined above, but are basically designed as "Stop and consider in-depth", "Hesitate and potentially consider further", and "Go on". The logic being that if an impact is positive, this is not going to be detrimental to the system, so further in-depth consideration is not necessarily required. However, failing to underestimate positive impacts decreases the overall positive impact, and *vice versa*. The green range of response is any positive value. The yellow range is defined as -1 to -15, which is based on ensuring the likelihood column has realistic function in adjusting traffic light response when weighted with an importance variable (Figure 3). The red range is ≥-15 bounded at -125; the maximum response representing an impact that is highly negative (-5), has highly likely occurrence (5), and is overly important to the individual (5). The response values in the traffic light cell have no physical meaning, but are summed to help compare positive impacts against negative ones (a pros and cons base assessment).

The **summary sheets** simply remove the N/A components and Yellow lights, compiling the positive and negative impacts in their own respective tables. This allows the user to assess each impact against the others identifying the most defining impacts of the innovation on the production system. The total weight of positive and negative impacts is the summation of the individual respective weighted components in the **score** column (the negative score also includes the yellow weights in the summation). These are then calculated as a **return ratio** whereby the larger number becomes the denominator and provides the +/- sign to the ratio. This allows a ratio between 1 and -1 where 0 is a neutral innovation impact and any deviation from this defines a percent impact in the +/- direction.

The **score** and **return ratio** are not intended to be used solely to make a decision, but to cause the user to reflect on the assessment process, particularly if the return ratio is negative. The intended process here is that the negative summary can quickly be revisited and the weightings can be investigated further; i.e. is there a management practice that could be used to help decrease the negative impact? This will lead to informed and managed risk mitigation prior to adoption. That particular impact rating can then be adjusted accordingly and the next highest impact focussed on, etc.

Negative impacts in the red should also be analysed to see if they affect any of the currently rated positive impacts. Sometimes it is easy to forget how some components interact. The summary sheets help facilitate easy comparison of these.

When the return ratio is highly positive, then this is also a cause for reflection: Have any impacts been exaggerated in the effect? Has individual importance of the particular component caused the positive impacts to be skewed; i.e. a positive value of 125 – highly positive impact, highly frequent occurrence and overly important to the individual? The intention is that highly positive return ratios be used to prompt further collective reflection on the assessment.

Importance 3

3	1	2	3	4	5
-5	-15	-30	-45	-60	-75
-4	-12	-24	-36	-48	-60
-3	-9	-18	-27	-36	-45
-2	-6	-12	-18	-24	-30
-1	-3	-6	-9	-12	-15
1	3	6	9	12	15
2	6	12	18	24	30
3	9	18	27	36	45
4	12	24	36	48	60
5	15	30	45	60	75

1	1	2	3	4	5
-5	-5	-10	-15	-20	-25
-4	-4	-8	-12	-16	-20
-3	-3	-6	-9	-12	-15
-2	-2	-4	-6	-8	-10
-1	-1	-2	-3	-4	-5
1	1	2	3	4	5
2	2	4	6	8	10
3	3	6	9	12	15
4	4	8	12	16	20
5	5	10	15	20	25

2	1	2	3	4	5
-5	-10	-20	-30	-40	-50
-4	-8	-16	-24	-32	-40
-3	-6	-12	-18	-24	-30
-2	-4	-8	-12	-16	-20
-1	-2	-4	-6	-8	-10
1	2	4	6	8	10
2	4	8	12	16	20
3	6	12	18	24	30
4	8	16	24	32	40
5	10	20	30	40	50

4	1	2	3	4	5
-5	-20	-40	-60	-80	-100
-4	-16	-32	-48	-64	-80
-3	-12	-24	-36	-48	-60
-2	-8	-16	-24	-32	-40
-1	-4	-8	-12	-16	-20
1	4	8	12	16	20
2	8	16	24	32	40
3	12	24	36	48	60
4	16	32	48	64	80
5	20	40	60	80	100

5	1	2	3	4	5
-5	-25	-50	-75	-100	-125
-4	-20	-40	-60	-80	-100
-3	-15	-30	-45	-60	-75
-2	-10	-20	-30	-40	-50
-1	-5	-10	-15	-20	-25
1	5	10	15	20	25
2	10	20	30	40	50
3	15	30	45	60	75
4	20	40	60	80	100
5	25	50	75	100	125

Figure 3. Tables of possible impact weights based on multiplication of Impact (y-axis), Likelihood (x-axis) and Importance (value in upper left), and categorised by red, yellow and green categories of impact. An importance of 3 is the comparative datum for the impact assessment.

The individual importance weighting tables are displayed in Figure 3 and show that the highest tolerable negative impact that could fall into the yellow category (hesitate on consideration only) is -12. Increasing importance is the same as taking a more conservative approach to negative impact assessment. However, when decreasing importance below 3 it is observed that highly impacting impacts occurring from time-to-time are considered acceptable and, probably of greater importance, moderate to high impacts that have high likelihood of occurrence become tolerable. This highlights that lowering the perceived individual importance of an impact needs to be done with due consideration. Hence, the advice that someone independent to the adoption process is involved to help provide reality checks to perceived importance of farming system components.

Case study

The case study used for Figure 3 demonstrates an assessment for the new John Deere CP690 cotton picker, which is a slight improvement on the JD7760, but has greater weight. In this case, the grower considering an upgrade from the JD7760. This example has been filled out not entirely accurately to demonstrate some limitations and important consideration in using the tool. The user has filled out the impact column selecting their subjective impact ratings for each component, and indicating those that aren't applicable. However, "waterlogging" has been left blank, and we presume this is because it was skipped by accident, or on purpose and not returned to. If this tool is to be developed further, then an alert for unfilled components would be a good feature.

The user has indicated that soil compaction has a greater than slight impact and that the likelihood of occurrence is quite likely, leaving the default importance. This highlights two issues. Firstly, run-off/tail-water have been selected as N/A, but increased compaction will increase this without management,

which means that some negative impact should have been indicated. The tool is not capable of identifying the links between factors, without requiring more data and a more complex design. Hence, the requirement for collective reflection on the assessment. Secondly, the CP690 is a machine that has greater weight and horsepower than the previous JD7760, which means that the compaction impact should be indicated as highly impacting (-5; assuming the grower irrigates right up to defoliation). The tool is subjective and relies on experience/understanding of each particular component. Hence, there is a risk that components not well understood will be selected as N/A (Bennett and Cattle 2013), or under estimated, and that the interrelationships between components missed. To overcome this, the tool is design for collective reflection with an independent party, but to truly overcome these issues movement to an automated system based on multiple data inputs is required.

The case study has a 61% negative return ratio, suggesting that purchase of this machine is going to have an overall negative effect on the production system. This does not advise against the purchase, but prompts the user to return to the negative impact summary and look at the weightings. The highest one in this case is back-up/repairs, which is referring to the availability of parts/repairs and the back-up time any delay might cause. Assuming that the CP690 is at inception to the Australian system, the current importance of this might be high as parts and services in Australia for this machine are only just commencing, while over time this may not be a problem. This would be a mitigative factor that could be used to decrease the negative impact.

The next highest factors are either fixed cost related, 'row-spacing' or 'soil compaction'. Not much is able to be done about the costs, but this should be used to prompt an investigation to what the other impacts may cost per hectare and whether or not the machine can be recovered in the short-term. Row-spacing and compaction are linked in this case. The machine works in the 1.0 m rows, but causes compaction of the hill shoulders. Soil compaction also occurs directly beneath the machine. This then affects irrigation uniformity and tillage depth. Looking at the negative summary should then prompt the user to question what management techniques are available for mitigating soil compaction. If controlled traffic conversion were to be undertaken for example, then these impacts could all be reduced moving the machine into a positive return ratio.

Summary

An innovation impact assessment framework for informing adoption decision making processes has been presented. The tool is simple to use and designed to aid in prompting users to stop and think about the potential impacts through both an individual (self) and collective reflective process. Steps have been taken to ensure it is a flexible framework, but that it allows individual importance to be valued, whilst still providing a rigorous and comprehensive process of consideration. For the most reliable results, this tool should be used with someone who is independent to the innovation decision, and who has good experience with farming system component interactions; agronomists and extension officers could adequately meet this requirement. The tool provides a numerical output to aid in weighing up the decision making process, but is not intended to be the defining value on which financial decisions are made. The tool provides prompting to aid an informed decision process and facilitate reduction in the effect of unforeseen impacts; a financial analysis should still be undertaken, and this tool may aid in informing that, but does not replace it.

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5. Soil traffic management strategies

This section provides evaluation of management options for minimising soil compaction caused by use of the John Deere 7760 (JD7760) in the Australian cotton industry. Based on the results obtained when investigating impacts of the JD7760 on the soil resource, focus was placed on comparing controlled traffic farming to conventional practices. Further management practices aimed at limiting soil moisture during unforeseen wet harvest are also presented, along with a base evaluation of the merit of manipulating tyre inflation for heavy machinery.

The aim of this section is to provide the Australian cotton industry with information on which to help make farming system management decisions. In doing this, the number of sites that could feasibly be investigated had to be limited. However, it should be noted that the majority of the industry grows cotton on Vertosol soils with high clay content. Furthermore, the weight of the JD7760 and the contact stress and wheel load this impacts on the soil resource are significantly greater than the cohesive forces that dominate Vertosol soil strength beyond the plastic limit. Hence, whilst the absolute effect of the management options may vary across regions, the results would be expected to be emulated within all regions with Vertosol soils.

Irrespective of region or soil type, with axle loads in excess of 20 Mg and wheel loads in excess of 5 Mg, the most effective management strategy for soil compaction is avoidance of traffic during conditions where soil moisture exceeds the plastic limit (point where the soil stops behaving like a solid and begins behaving like plasticine). Ultimately, soil moisture at traffic is more important than the stress imparted by the trafficking machine for high clay content soils such as Vertosols.

Efficacy of controlled traffic for management of heavy machinery traffic in cotton

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Introduction

The John Deere 7760 (JD7760) has a six-row frontage designed to pick six rows at a row-spacing of 1.0 m, which is compatible with a 12 m planting system common in current industry systems. Because the machine is fitted with dual tires on the front axle, the area traversed is larger compared to four-row frontage basket pickers. Additionally, to incorporate the module builder onto the picking system of the JD7760 required a significant increase in weight, whereby the machine is approximately double the weight of previous basket picking systems and approaches 40 Mg as a second module is formed.

Developments in grain harvesting technology have also resulted in increased machinery size, which has enabled increasing the frontage harvested (increased effective capacity). Such machines weigh up to 30 Mg fully loaded carrying approximately 70% and 30% on the front and rear axles, respectively (Ansorge & Godwin 2007). Table 1 compiles information available in the literature showing crop yield reduction caused by traffic-induced soil compaction. These data confirm that crop yield is significantly affected by soil compaction and that yield penalties are expected to be greater in situations where heavier axle loads are used, as well as soils with higher clay content. For cotton, Hadas et al. (1985) observed that residual compaction caused yield reduction through reduced plant population (poor establishment) and increased stand variability, particularly when soil bulk density (sandy loam) was higher than approximately 1.25 g cm^{-3}. McGarry (1990) observed a 73% cotton lint yield reduction in a compacted Vertisol (depth range: 200-400 mm), which impeded root growth and water permeability at the first irrigation causing waterlogging and lodging.

Table 1. Yield loss and calculated gross income penalty observed in arable crops affected by compaction during harvest of the previous crops

Crop	Yield loss (Mg ha^{-1})	Yield reduction (%)	Value (AUD ha^{-1})	Source
Sorghum (grain)	0.9	50[z]	221	Jensen et al. (2000)
Wheat	0.75	30[z]	236	Jensen et al. (2000)
Wheat	0.7	21	221	Radford et al. (2001)
Wheat	0.9	15	284	Neale (2011)
Maize	0.41	30[z]	72	Jensen et al. (2000)
Maize	2.18	43	382	Radford et al. (2001)
Soybean	0.79	30	379	Botta et al. (2007)
Canola	2.1	66[z]	1050	Chan et al. (2006)
Cotton (seed)	0.11	7	30	Ishaq et al. (2003)
Cotton (seed)	0.95	22	257	Kulkarni et al. (2010)

Sorghum (*Sorghum bicolor* L.), wheat (*Triticum aestivum* L.), maize (*Zea Mays* L.), soybean (*Glycine max* L.), canola (*Brassica napus* L.), cotton (*Gossypium hirsutum* L.).

[z] Reduction of yield in traffic-affected rows only as compared to non-traffic affected rows.

Value is yield loss (Mg ha^{-1}) × price of crop (AUD Mg^{-1}) based on the average grain price for the period 2009-2013 (Flores-Piran, 2014).

Given that the JD7760 is a heavier machine than the grain harvesters used in Table 1, it is likely that a significant yield decrease could be observed in cotton systems. Chapter 3 confirms that the JD7760 causes a significant increase in soil compaction within the major rooting depth. Cotton industry soil management literature (SOILpak; McKenzie 1998) and Australian perspective scientific literature (e.g. Tullberg, Yule & McGarry 2007) suggest that controlled traffic farming (CTF), where all wheel track

widths are matched and permanent, is the most effective way to limit compaction effects of the cotton production system. Despite this and effort spent on education and extension, the rate of adoption of CTF in Australia has been relatively slow, mainly due to incompatibility of imported equipment, associated costs of conversion and warranties (Chamen, 2014; Tullberg et al., 2007).

Therefore, this investigation was designed to compare a standard JD7760 side-by-side to a CTF converted JD7760 in terms of soil compaction and subsequent effect on farming system yield and gross margin.

Methodology

The experimental site (Figure 1) was located at Auscott Warren, 31°47'24.4"S 147°44'01.4"E, 195 m above sea level, situated 11 km south-west of Warren, NSW, Australia. The soil was classified as a Grey Vertosol, typical of the cotton industry. Whilst the soil had more sand content than Vertosols surrounding the Narrabri/Moree regions, the Warren Grey Vertosol was observed to crack to the surface under drying cycles.

Experimental design

The western end of the field was used to establish experimental treatment strips which consisted of either 1.0 or 1.5 m row spacing at a treatment width of 12 m (Figure 1). The 1.0 m system represents the current convention suited to picking using a 2.0 m internal track machine such as the JD7760 in dual wheel configuration (Figure 2A). This machine was used for these treatments. The 1.5 m system increases the row spacing allowing a larger catchment per cotton row per area, comparatively, suiting a 3.0 m internal track JD7760 in controlled traffic farming (CTF) configuration, as was used in this instance. To accommodate a 12 m treatment frontage, which avoided the necessity to purchase further planting and cultivation implements, the CTF JD7760 was configured further to pick a 6 m frontage, or 4 rows (Figure 2B).
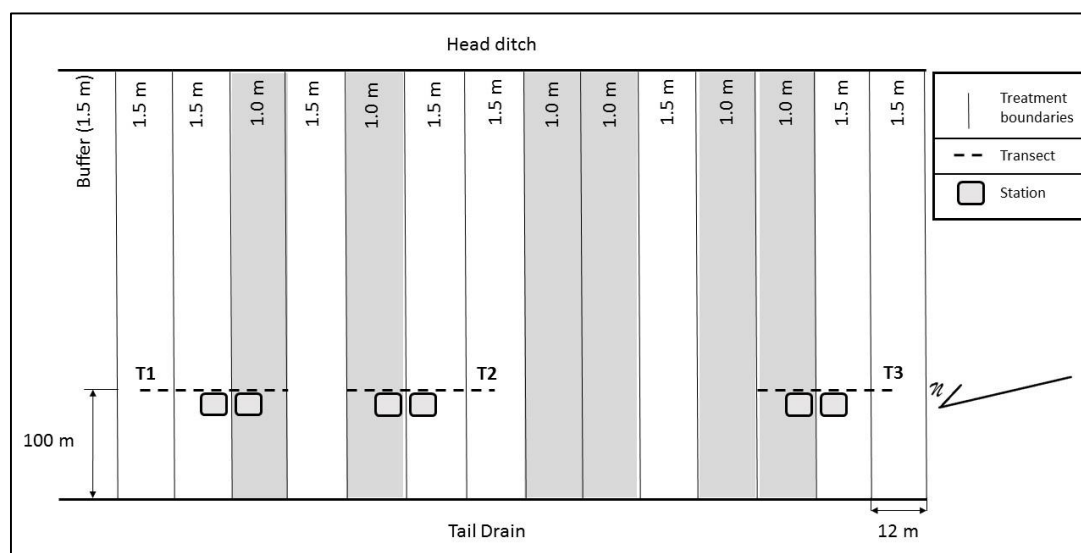

Figure 1. Experimental layout for the Auscott site whereby 1.5 m row spacing refers to the controlled traffic configured JD7760 picking 8 rows per treatment (12 m), and 1.0 m row spacing refers to the standard JD7760 picking 12 rows per treatment (12 m). T1, T2, and T3 represent transects for measurement, whilst stations represent monitoring locations for replicated soil cores taken before and after traffic.

Treatments were replicated 6 times, running the full length of the field, and a buffer of 1.5 m row spacing cotton was established at each end of the experiment (12 m of cotton). Treatment replicates for each treatment were then randomly allocated within the experimental area.
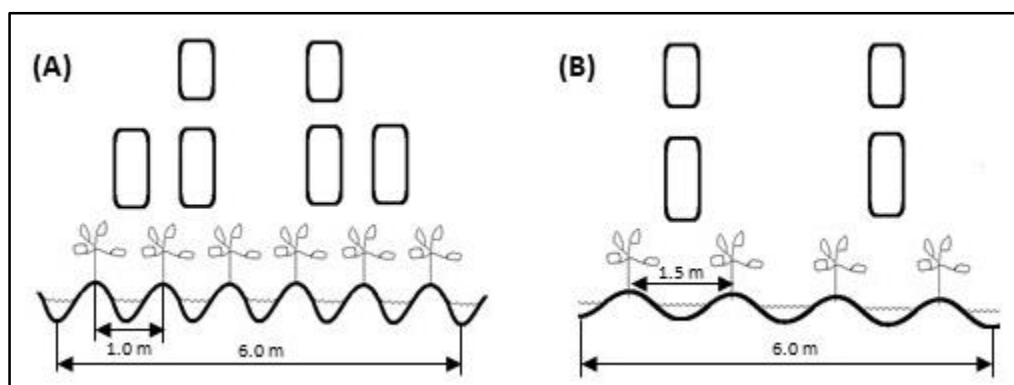

Figure 2. John Deere 7760 configuration for (A) 1.0 m row spacing system, and (B) 1.5 m row spacing system

Field history

The experimental site has been used for cotton production since 1968 with 24 cotton crops grown between inception and 2009, and the remaining 18 years fallowed. During this period, the peak performance of this field was in 2002 with 9.12 bales/ha. In 2010 the field was flooded naturally requiring it to be reformed. A wheat crop was grown post flood in 2010 and in 2013 the experimental area of the field was listered into the current replicated trial (Figure 1) to suit a 36 m spray-rig and match a 12 m system. Within the experimental period 2013 through 2015, Sicot 74BRF cotton was grown in the 2013/14 and 2014/15 summer season. Spitfire wheat was grown directly following 2015 cotton harvest and field preparation, planted in late July and harvested in the first week of December 2015.

Field preparation prior to the first cotton crop post flood (2010) included listering, fertiliser spreading, and a Lilliston cultivator pass, all on 12 m frontage. The 1.5 m system was also subject to a Go Devil pass on a 12 m pass, and the 1.0 m system had a 6 m frontage lister pass prior to all other field preparation activities. Field preparation between cotton crops mulching, root-cutting, listing, fertiliser spreading and Lilliston cultivation. Mulching occurred on a 6 m frontage for both systems, whilst root cutting occurred on a 6 m frontage for the 1.0 m system and 12 m frontage for the 1.5 m system. The 1.0 m system again had a second pass of the lister, this time at 12 m frontage, while the 1.5 m system was again go-devilled at a 12 m frontage to help reform hills. These land preparation activities were considered by be reasonably comparable with any cultivation bias towards the non-CTF 1.0 m system in terms of greater cultivation in that system (minimal to insignificant bias).

The dryland wheat crop was sown in mid-late July as a limitation of rainfall at cotton harvest and subsequent delayed operations, and is part of a broader holistic CTF approach to cotton production (McKenzie 1998), but was uniformly applied to the experimental site to protect its integrity. Planting density and row spacing over the 1.0 and 1.5 cotton row spacing systems was equal; i.e. green and brown hectares were equal for both systems in contrast to the cotton crops.

Rainfall and irrigation

The 2013/14 and 2014/15 cotton seasons were locally and regionally classified as very dry with wet finishes when considering the average monthly rainfall for Auscott and Warren, NSW (Figure 3). There

is general agreement between the long-term averages for Auscott (17 years) and Warren (81 years) weather stations. Accordingly, the 2014/15 season is noted as a better season in terms of managing moisture deficit, which is further supported by later and less irrigation requirement, as compared to the 2013/14 season (Table 1). In the 2013/14 season irrigation was comparable for the 1.0 and 1.5 m systems, while in 2014/15 79 mm less irrigation was applied to the 1.5 m system.
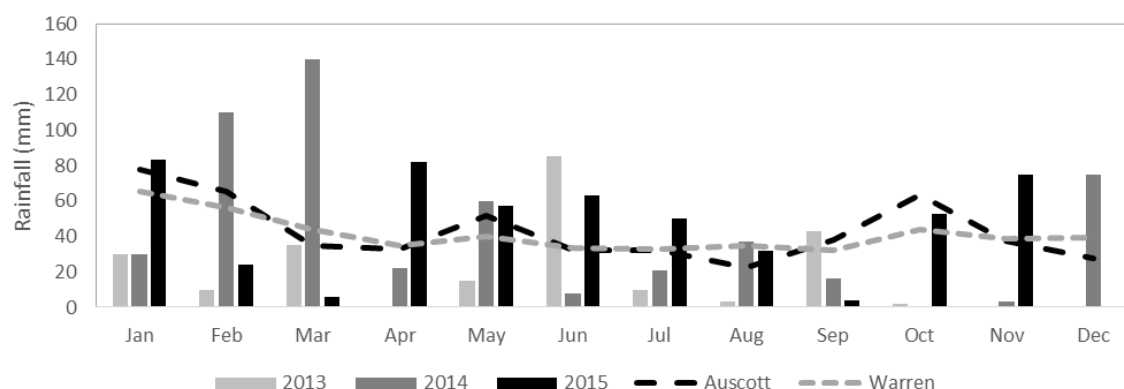

Figure 3. Total monthly rainfall for the experimental field throughout the cropping period. Hashed lines represent regional long-term averages, where Auscott refers to local weather-station data between 1969 and 1982, and Warren refers to regional weather-station (approx.. 15 km away) data between 1935 and 2014.

Table 2. Total monthly irrigation for the experimental period during the 2013/14 and 2014/15 cotton season. 1.0 and 1.5 m systems refer to the treatment row spacing systems used in this experiment. Missing data infers no irrigation during those months for that particular season.

| Season | Irrigation (mm) | | | | | | | | | | | |
| | Nov | Dec | Jan | Feb | Mar | Total | Nov | Dec | Jan | Feb | Mar | Total |
	1.0 m System						1.5 m System					
2013/14	150	270	420	–	–	840	150	270	420	–	–	840
2014/15	–	80	315	284	95	774	–	60	210	305	120	695

Soil sampling

Soil sampling occurred at stations (Figure 1), before and after JD7760 traffic, and as transects (Figure 1) after traffic. Sampling transects were constructed to investigate 12 rows of cotton per row spacing treatment along a single transect, meaning that 18 m and 12 m of the 1.5 and 1.0 m systems, respectively, were sampled per transect. In order to achieve this buffers at both ends were required to be utilised for one machine frontage, leaving a 6.0 m buffer at each end of the field. Stations were positioned within the confines of the experimental design and were positioned such that the lateral distance between picking systems was minimised (Figure 1).

All sampling occurred within 100 m of the tail drain to accommodate manual sampling using a Christie's Engineering CHPD78 Post Driver. The post driver uses a slight, but highly repetitive, hammering action to push sampling tubes to depth. Manual sampling was required due to standing cotton. As the sampling method used a hammering action, soil core length was measured and the depth of the hole

confirmed to ensure compaction had not occurred during sampling; this method did not cause compaction of samples.

Station soil samples were taken across the machine frontage from the furrow for both systems, before and after traffic. Two replicates of each furrow were obtained. This provided a total of 72 cores per sampling incidence. Transect cores were taken along the entire length of the transect from the furrow after traffic. A total of 75 cores were taken per sampling incidence. All cores were taken to a depth of 0.8 m to coincide with the maximum depth of cone penetration resistance. As such, cores were separated into 10 cm subsamples, providing a total of 576 and 600 samples per incidence of station and transect sampling, respectively. Subsamples were stored in sealed foil lined bags and placed in the shade prior to further measurement.

Moisture content and soil bulk density
Soil samples were weighed as soon as possible after sampling to determine the field wet weight of each sample. Samples were then placed in an oven for at least 72 hours at 105°C and weighed to determine the oven dry weight of the samples. By difference of the wet and oven dry weights, the sample moisture content was determined and reported gravimetrically (mass per mass) and volumetrically (mass per volume).

Soil bulk density was used to determine changes in compaction and inform volumetric moisture content. As the soil samples had very carefully been split into 10 cm lengths, this was used as the height dimension, along with the cross-sectional area of the soil core cutting tip to determine the volume of a 10 cm sample. The oven dry weight was used the bulk density of each sample and reported as mass per volume (g/cm^3).

Optimum moisture content
The optimum moisture content of the soil for compaction was determined in the laboratory consistent with the standard Proctor test consistent with Australian Standard method AS1289.5.1.1. Whilst this test is designed to determine suitability of construction foundations, the static to dynamic load equivalent of the test was comparable with the calculated wheel load of the JD7760 at the surface, as reported by Bennett et al. (2015). Hence, for the purpose of identifying the optimum moisture content, this method was considered adequate.

Penetration resistance
As machine traffic causes consolidation of soil solid particles, resulting in compaction, penetration resistance of an ASABE penetration cone was used to determine changes in soil strength as a result of traffic. Penetration resistance is highly influenced by penetration velocity, soil moisture and soil bulk density. Velocity was controlled for using a constant drive device. To understand the effects of moisture and bulk density these were measured directly in soil cores proximal to insertion points in furrows.

Penetration resistance was measured using a Rimik CP40ii Cone Penetrometer with a 100 kg load cell. The cone penetrometer was mounted to the constant drive device and penetration resistance measured every 0.2 m along each transect after traffic. This allowed direct comparison of 1.5 and 1.0 m system relative differences at the time of traffic. Penetration resistance was measured every 0.01 m with depth to an extent of 0.75 m, resulting in 10,950 measurements per transect.

Yield

Cotton yield for the 2013/14 and 2014/15 seasons were measured using the John Deere yield monitoring equipment. Equipment was calibrated prior to picking and then the machine individual yield normalised using ginned yield of the cotton. Treatment replicates were picked individually and the normalised yield maps used to provide data for statistical interpretation of yield differences.

For the subsequent dryland wheat crop grown July though to November 2015, harvester and logistical limitations required that only the total yield of each treatment be reported. Whilst this does not allow statistical inference, the data can be coupled with replicated soil data to infer the practical significance of any differences.

Results

The impact of the JD7760, irrespective of CTF or otherwise, was to increase soil strength and bulk density under the wheel, with differences noticeable to the extent of investigation at 0.8 m. The major apparent differences between the two systems was due to the smaller traffic footprint and wider internal machine track of the CTF JD7760, whereby less soil was impacted under the machine.

Soil moisture

Soil moisture results have been presented gravimetrically (GMC) to allow comparison back to the Standard Proctor test compaction curve, which is defined using gravimetric moisture content (Figure 4). For the grey Verstosol it was found that the optimum moisture content was on average 21.37%, resulting in a maximum dry density (MDD) of 1.57 g/cm^3. Prior to traffic by either the CTF or standard JD7760, the top 0.3 m of the soil profile was proximal to the OMC for compaction for both the 2013/14 and 2014/15 cotton season (Figure 4, A and B). Post-harvest in the 2013/14 season, GMC was similar between 1.0 and 1.5 m systems in the 0–0.5 m profile depth. However, the 0.5–0.8 m GMC was significantly different between the traffic systems, but not within the traffic systems, which could be expected given the moisture content at harvest was independent of traffic at harvest; i.e. 2013/14 traffic impacts would be expected to affect 2014/15 GMC, rather than 2013/14 GMC. In comparison, There was no significant different between GMC at any depth, within, or between traffic systems for the 2014/15 season, although the CTF system was slightly and consistently lower in GMC between 0.5–0.8 m soil depth. For both the 2013/14 and 2014/15 seasons the surface soil was subject to high rainfall proximal to harvest (May) resulting in a wetter than expected surface profile.

A wheat crop was planted post-harvest of the 2014/15 cotton crop as a compaction bioremediation crop in the subsequent winter season. Importantly, this crop was treated as a dryland crop, relying on soil moisture and rainfall only. Hence, with no irrigation between Figure 4B and C and the same planting density/row-spacing for wheat, the differential GMC results in Figure 4C can be attributed to traffic system impacts. When considering the non-traffic furrows between systems there is a significant reduction in GMC from ≈17.5% in the 1.0 m standard JD7760 system to 13.6% in the 1.5 m CTF system throughout the 0.4–0.8 m depth. When considering all furrows within a system, the difference between systems within this same depth is still significant, but the reduction is less. Notably, the moisture content in the 0.4–0.8 m depth for Dual-G and Dual-Ave in Figure 4C are consistent with moisture contents at this same depth in Figure 4B. Similarly, CTF-Ave only deviates slightly from Figure 4B in Figure 4C.
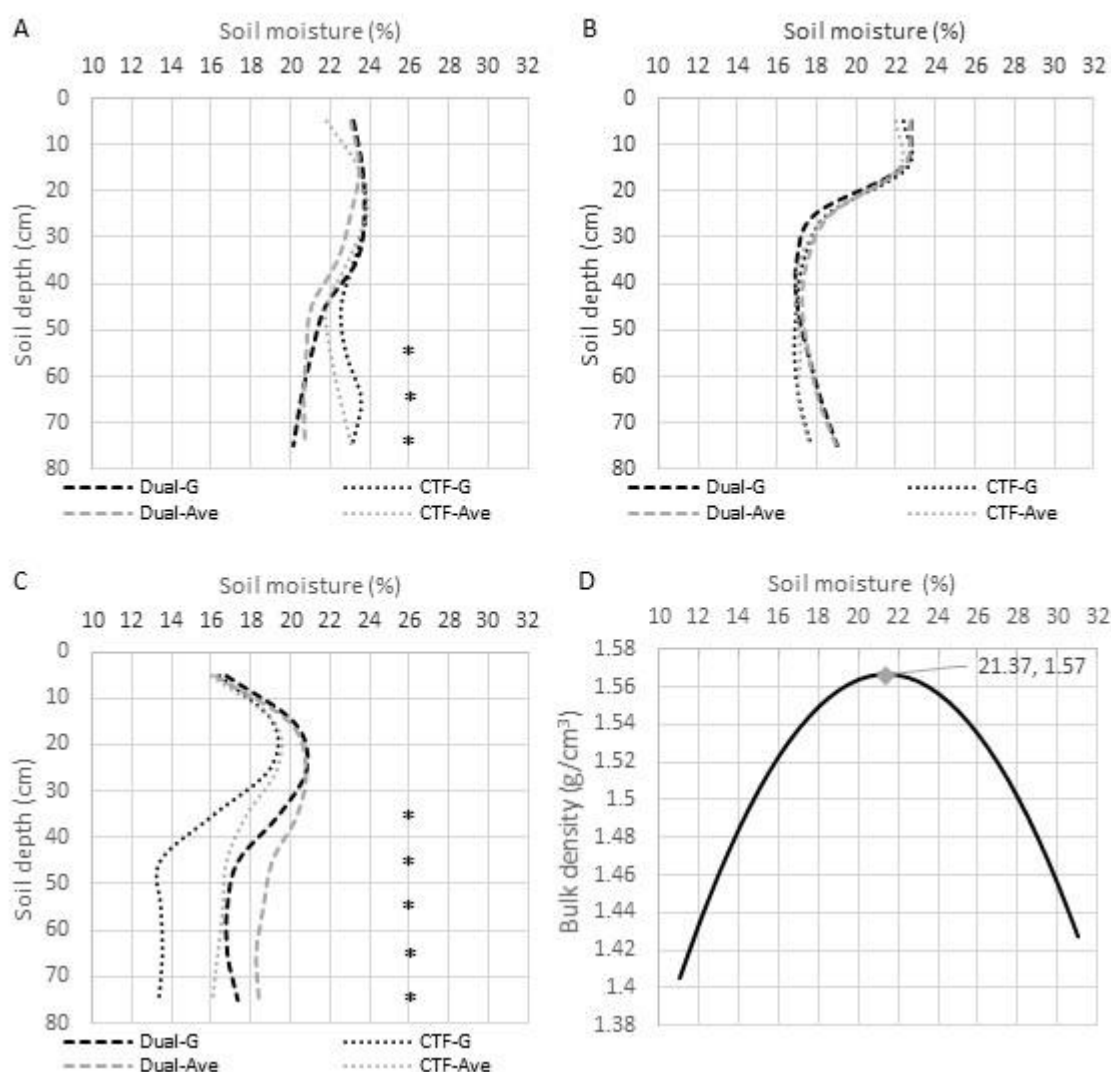
*Figure 4. Gravimetric water content post-harvest traffic with a John Deere 7760 (JD7760) in the (A) 2013/14 and (B) 2014/15 cotton season, as well (C) prior to grain harvest in November 2015. The optimum moisture content (OMC) as determined by a Standard Proctor test is depicted in (D) with OMC 21.37% and maximum dry density of 1.57 g/cm³. Dual refers to the standard dual-wheel configuration of the JD7760, CTF refers to the controlled traffic farming configuration of the JD7760, G refers to non-traffic furrows within the respective system, and Ave refers to average of all furrows within the respective system; * depicts significant difference between systems at a confidence interval of 90%.*

Soil bulk density

Soil bulk density was observed to increase where wheel traffic occurred, irrespective of row-spacing or traffic system, with the greatest increase in bulk density at the surface (Figure 5). For the dual-wheel standard JD7760 the impact on soil bulk density throughout the profile was statistically similar for both the inner and outer dual wheel. As such, the bulk density data for these furrows were combined as a single dataset. For the 2013/14 and 2014/15 cotton seasons and the 2015 wheat season there were no significant differences between the standard and CTF JD7760 traffic systems at any depth. The major difference between the systems is then attributed to the machine footprint on the ground where 66% of furrows are subject to traffic under the standard JD7760, as compared to 50% of furrows under the CTF JD7760.

Significant differences within traffic systems with profile depth were generally similar for the standard and CTF JD7760 systems. For the 2013/14 cotton harvest, significant increases in bulk

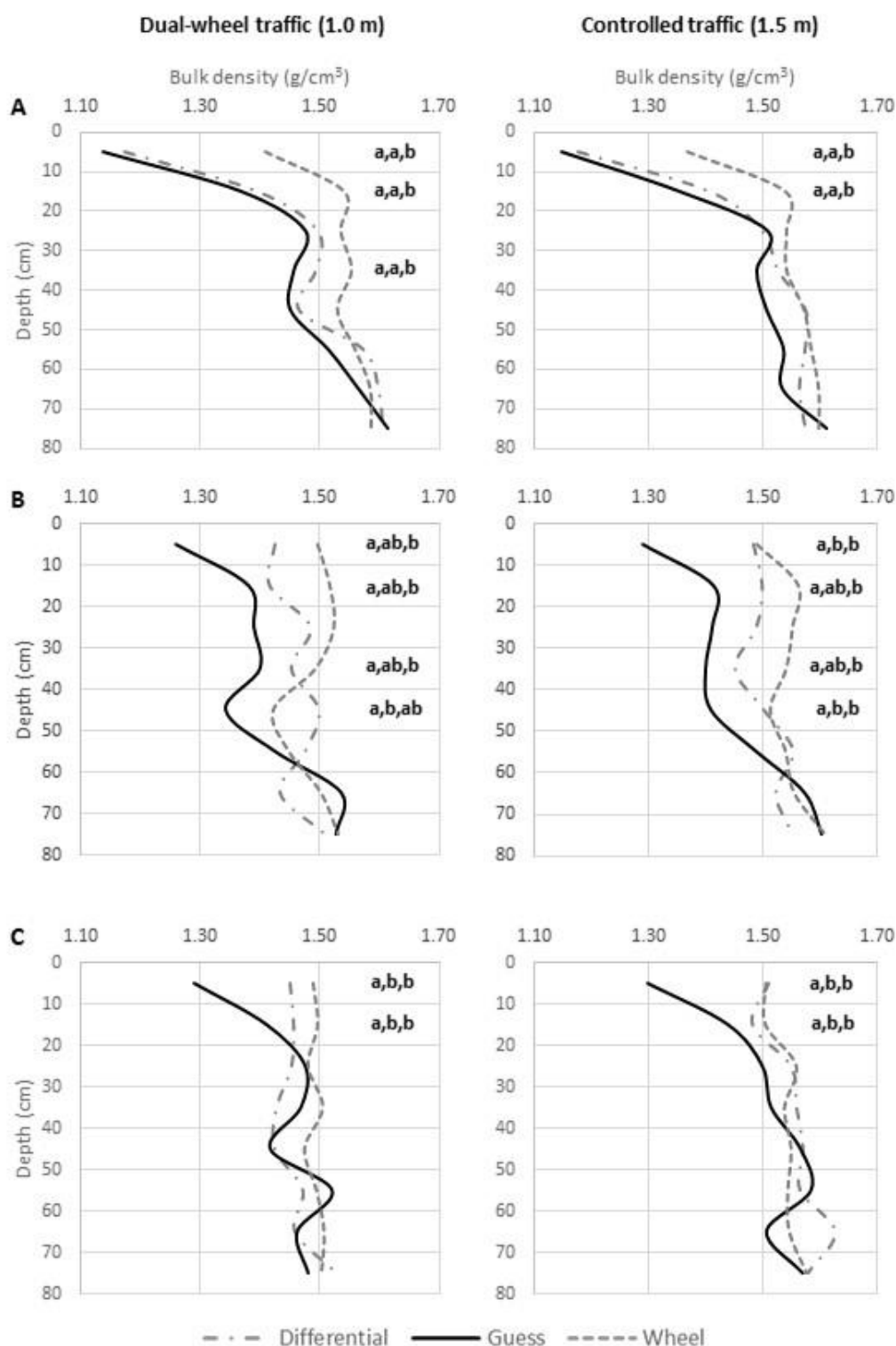Dual-wheel traffic (1.0 m)   Controlled traffic (1.5 m)

Figure 5. Bulk density after traffic by the respective system at (A) 2013/14 and (B) 2014/15 cotton harvest, as well as (C) bulk density immediately prior to wheat in November 2015. Differential refers to the furrow under the machine centreline, Guess refers to non-traffic furrows not under the machine centreline, and Wheel refers to traffic furrows. Dual wheel configuration John Deere 7760 was shown to have no significant difference between inner and outer wheel, so all wheels are represented as one treatment (Wheel). Lowercase pronumerals represent significant difference between treatment furrows within the corresponding depth range and respective system at p<0.1 with order of pronumerals corresponding to Differential, Guess and Wheel, respectively.

density were observed at 0–0.2 m for both traffic systems, and at 0.3–0.4 m in the standard JD7760 system. The furrow directly under the differential in this season was observed to have bulk density very similar to the guess furrows, which served as the control furrows for system comparison. After harvest in the 2014/15 cotton season significant increase in density, as compared to the guess furrow, was observed under the wheel to a depth of 0.3 m for both traffic systems. For the CTF system, significant bulk density increase in both the differential and wheel furrows was observed at 0.4–0.5 m soil depth, while similar results for the standard JD7760 system were obtained, only the differential furrow was significantly different to the guess furrow. For both systems there was a clear trend for increased density due to traffic at 0.2–0.3 m, but due to a high level of cracking (inclusion of voids in sampling) the variability of this depth did not allow for significant differences.

Figure 5C shows the Standard and CTF JD7760 systems after a season of wheat grown subsequent to the 2014/15 cotton season. The surface depth (0–0.3 m) was subject to unseasonably high rainfall at wheat harvest time. The result of this in terms of soil bulk density was to cause the surface depth to re-swell, meaning that surface cracks from moisture draw down were severely limited post-rainfall. Hence, soil sampled from this depth was at a moisture content similar to the previous cotton seasons and compaction results were observed to remain significant in the 0–0.2 m depth for both traffic systems. No further significance was detected with depth due to increased variability of the guess furrow (control) due to removal of moisture from this area, but to a lesser extent under the traffic furrows.

From Figure 5 it is apparent that significant changes in soil bulk density were generally limited to <0.5 m, and most often detected in the 0–0.2 m soil depth. However, the nature of Vertosols is to be highly heterogeneous as a result of high frequency shrink-swell behaviour. Hence, changes in bulk density heterogeneity provides another measure on which to base discussion of machine impact. Therefore, to assess any potential impact of machine traffic at depth, equality of variance was assessed at the 0.7–0.8 m depth (extent of measurements) whereby reduction in variance indicates a more homogeneous system. On the basis of the two traffic systems having no significant differences observed between them, they were combined and treated as a single dataset. For furrows where traffic had occurred, the variance was significantly ($p<0.1$) less than that of both guess and differential furrows (Figure 6). Decreased variance (i.e. increased homogeneity) was observed after traffic for both the 2013/14 and 2014/15 cotton seasons, and was observed to persist after a wheat rotation.

Penetration resistance

Cone penetration resistance is depicted in Figure 7 for the duration of the experiment and clearly shows a significant ($p<0.001$) trend for increased penetration resistance beneath traffic furrows for both systems and at all sampling periods. In interpreting these results it is important to note that hills would have been present every 1.5 or 1.0 m depending on the system. These hills ranged from 0.4 to 0.6 m in height and thus would have acted as evaporation buffers, safeguarding moisture at the 0.1 m datum used. This also partially explains the trend for increased penetration resistance in non-traffic furrows as compared to hill regions whereby reduction in resistance will be highly affected by soil moisture content.
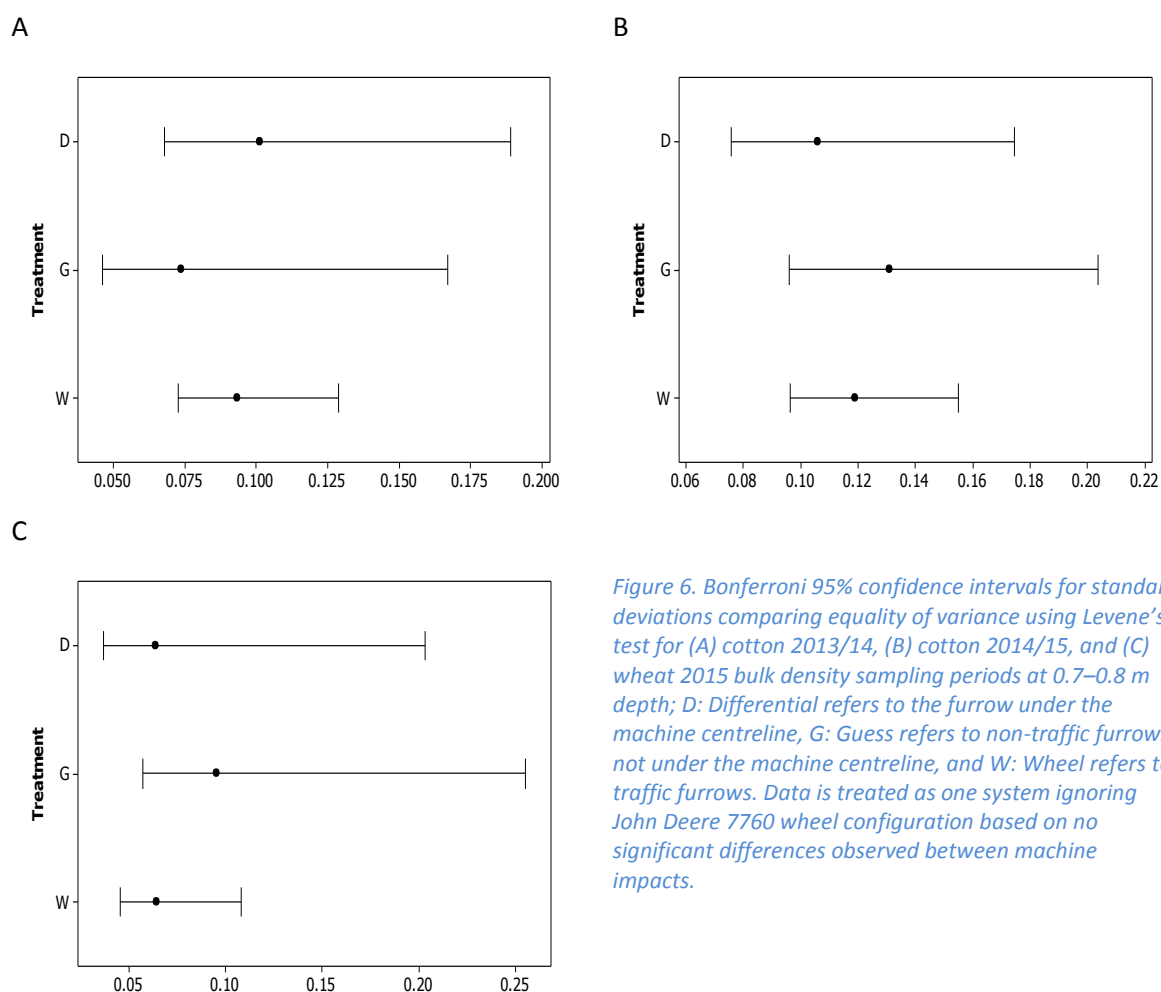
A

B

C

Figure 6. Bonferroni 95% confidence intervals for standard deviations comparing equality of variance using Levene's test for (A) cotton 2013/14, (B) cotton 2014/15, and (C) wheat 2015 bulk density sampling periods at 0.7–0.8 m depth; D: Differential refers to the furrow under the machine centreline, G: Guess refers to non-traffic furrows not under the machine centreline, and W: Wheel refers to traffic furrows. Data is treated as one system ignoring John Deere 7760 wheel configuration based on no significant differences observed between machine impacts.

Figure 7 A1 and B1 show impact effects extending from the surface to the extent of measurement, although there is a large amount of variability within the scale of measurement between rows. The soil profile had an approximate constant GMC of 22% with depth at the time of harvest traffic in the 2013/14 season. In 2014/15 the moisture within the top 0.3 m is comparable to the 2013/14 moisture, but the remaining profile depth was significantly drier, which accounts for some of the increase in penetration resistance within that profile depth, but does not account for significant differences between rows and furrows at depth. After the 2014/15 season harvest traffic (Figure 7 A2 and B2) there is very clear delineation between traffic and non-traffic furrows, with significant differences where resistance is higher under traffic for the 0–0.5 m and 0–0.3 m depth for the 1.5 m row spacing CTF JD7760 and 1.0 m row spacing standard JD7760 systems, respectively. This does not suggest that the standard JD7760 has less impact, in fact as demonstrated in Figure 7 A2 and B2 the lack of significance is due to a somewhat uniform high penetration resistance pan at ≈0.35 m under the standard JD7760. This same semi-uniformity of penetration resistance under the CTF JD7760 was not observed, and subsequently there is no apparent high resistance pan.
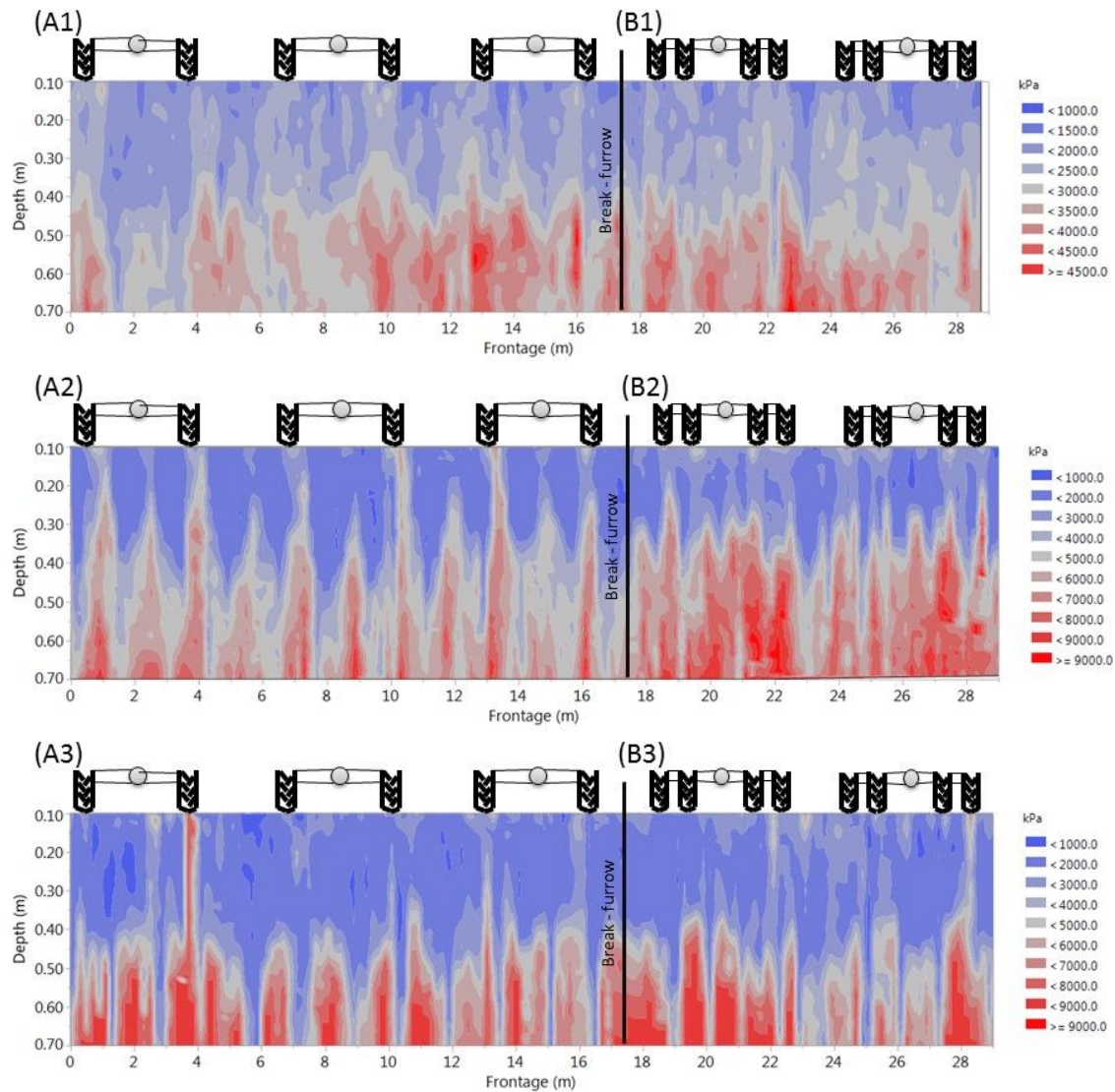
Figure 7. Penetration resistance maps for (A) the 1.5 m row spacing CTF JD7760 system, and (B) the 1.0 m row spacing standard JD7760 system across 12 plant rows at (1) post JD7760 traffic April 2014, (2) post JD7760 traffic May 2015, and (3) prior wheat harvest traffic November 2015. The break furrow represents the transitions from the 1.5 m to 1.0 m row spacing system.

The penetration resistance map in Figure 7 A3 and B3 represents A2 and B2 after a wheat crop, no further irrigation and no heavy harvest traffic. Generally, the top 0.4 m of the soil profile has undergone a reduction in soil strength. This can be partially attributed to high rainfall at harvest, but the resulting GMC is no more than that in A2 and B2. Some cultivation occurred, but not to a depth >0.2 m. Given the observation of soil cracking, and subsequent swelling due to harvest rainfall, it is possible that some remediation has occurred.

Figure 8 shows a comparative analysis of critical penetration resistance by system for each time of measurement. A penetration resistance of 1490 kPa is used as the critical threshold, as this represents the standardised pressure at which plant roots cease exploration (McKenzie & McBratney 2001); standardised from 2500 kPa (Taylor, Roberson & Parker 1966) for a 2.0 mm diameter, 30˚ cone angle, and insertion velocity of 0.0083 mm/s using the approach of (Fritton 1990).

For all three sampling periods, the CTF system had a significantly greater percentage of soil depth with penetration resistance less than the critical threshold. Significant decreases in non-critical penetration resistance are observed between the 2013/14 and 2014/15 seasons, which is in keeping with increased impact for both systems, although the difference between systems is doubled from 6.68% to 13.67% in favour of the CTF system. Differences between the 2014/15 and Wheat 2015 results support remediation for the CTF and standard JD7760 systems. However, the extent of remediation in the standard system is confounded by a significantly wetter soil profile, thus it is likely that the difference between systems is greater than the observed 7.81%.
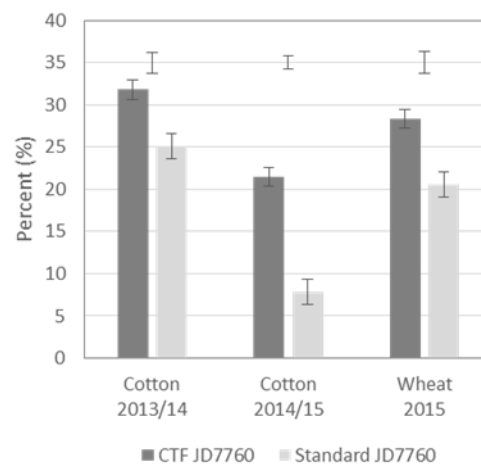

Figure 8. Comparison of percentage normalised soil depth having a standardised penetration resistance less than 1490 kPa by controlled traffic (CTF) and non-controlled traffic (Standard) John Deere 7760 (JD7760) system. Error bars (p<0.001) on columns represent least significant difference within the respective system, whilst least significant difference between systems pertains to error bars above treatment pairs.

Yield

The 2013/14 yield (Table 2) compares yield of the 1.0 and 1.5 m row systems independent of JD7760 compaction, as the soil is compacted as the yield is measured. Thus 2013/14 compaction affects the 2014/15 yield. The 1.5 m row spacing resulted in a significantly (*p*<0.05) lower yield per ha in 20013/14, although, due to less inputs required to manage this system, resulted in a comparative gross margin to the 1.0 m row spacing system. After imposed JD7760 compaction under either CTF (1.5 m system) or standard (1.0 m system) JD 7760 configurations, the difference in yield between the 1.0 and 1.5 m row spacing systems decreased from 1.8 to 0.69 bales/ha. This represented a significant increase in yield within the CTF 1.5 m row spacing system, as compared to the 1.0 m standard system. Hence, yield was comparable between the systems in 2014/15 resulting in a higher gross margin in the 1.5 m CTF system.

The subsequent wheat crop was grown on the same planting density and wheat row spacing, irrespective of the cotton row spacing system, thus inputs were equal. The resultant yield represents the total yield normalised for the area planted and was not replicated due to logistical constraints. However, there is a 0.49 t/ha (60%) yield difference between the standard and CTF systems in favour of CTF, which is a substantial difference at approximately $120/ha based on regional wheat prices in 2015.

Discussion

Traffic system compaction impact

Significant increases in soil compaction, measured as increased bulk density and penetration resistance, occurred under both systems. This is an expected result given the wheel and axle loads of the machines (Keller et al. 2007; Soane, Dickson & Campbell 1982). The obvious difference between the standard and CTF system was a 17% reduction in furrow traffic for the CTF system. This traffic reduction represented a significant decrease in penetration resistance under cotton hills, increased gross margin, and increased wheat yield, presumably due to greater water availability in the CTF system (Alaoui & Helbling 2006; Horn 1994).

The inner dual-wheel of the standard JD7760 is trailed by the rear wheel of the machine, which has significantly more load on the soil at the wheel (Bennett et al. 2015), but both the inner and outer dual produced similar impact in terms of soil compaction throughout the profile depth. This was consistent for all periods of measurement, which suggests that the impact of the front wheel contact pressure is sufficiently great that sequential wheeling of the rear tyre at the respective moisture content has little further impact for this soil. The first pass of a wheel with significant contact pressure is documented as causing the majority of compaction with subsequent immediate wheeling having little further consequence (Cooper et al., 1969), although repeated wheeling in the order of several passes can still cause a measureable difference (Hamza and Anderson, 2005). Where significant compaction was observed in the topsoil, the conditions were always close to optimum for soil compaction, thus it is suggested that the front wheel contact pressure sufficiently exceeds the precompression pressure of the Vertosol soil (Kirby, 1991) causing structural failure prior to rear wheel contact.

Table 3. Yield by system two irrigated cotton crops and a subsequent dryland wheat crop. Yield units are bales for cotton and tonnes for wheat; * represents significant difference between systems within a particular season, while values followed by different letters between seasons represent significant differences within systems. Difference in yield uses the standard system as a benchmark, thus negative values represent higher comparative yield in the CTF system.

System	Yield (unit/ha)	Gross margin ($/ha)	Difference (unit/ha)	Seasonal difference (bales/ha)
Cotton 2013/14				
Standard	11.52a	=		–
CTF	9.72*a	=	1.8	–
Cotton 2014/15				
Standard	12.33a	<		0.81
CTF	11.64b	>	0.69	1.92
Wheat 2015[†]				
Standard	0.85	<		–
CTF	1.34	>	-0.49	–

[†] N.B. Wheat data is a single value representing the total yield for each system, thus could not be statistically compared

Both traffic systems result in reduction of subsoil heterogeneity and appear to increase soil strength in the subsoil, as compared to other furrows. In terms of observed subsoil impacts, the total wheel load is more important than wheel contact pressure (a function of surface contact area). Raper and Kirby (2006) indicated that a heavier machine will induce deeper compaction than a lighter one when soil stresses at the surface are the same. Hence, it is deduced that for this soil the outer dual wheel of the standard machine has sufficient wheel load to cause changes in soil structural arrangement to a depth of 0.8 m. In the standard JD7760 system the furrows are sufficiently close that a compaction pan is able to be observed at 0.4 m, resulting from the wheel load. This is not so in the CTF system where the space between traffic furrows is sufficient to protect the soil structural arrangement under the row. There appears to be the potential for a very serious JD7760 subsoil compaction legacy if this is not addressed throughout the industry.

Row-spacing, controlled traffic and yield
The 2013/14 data refers to the system prior to compaction and is therefore a comparison of row spacing and yield performance. Results indicate that without imposing compaction from the JD7760 that the 1.0 m system produced better yield, although benefits gained in the CTF system in terms of less inputs offset this loss of yield and result in equal gross margin. However, as current cotton picking technology has a clear impact on soil compaction, this direct comparison is only useful for inferring the difference in systems where innovative picking technology has contact pressure and wheel loading well below the precompression stress; small automated vehicles might be applicable to this, for example.

Once a single pass of the JD7760 occurred and compaction was imposed, the yield between the CTF and standard traffic systems was statistically comparable. The 2014/15 season was a better season compared to 2013/14 season according to Auscott, but only the CTF system was able to take advantage of this and respond in terms of yield. This suggests yield detriment as a result of compaction, which is supported by changes in bulk density and penetration resistance. A more detailed analysis of row-spacing and the associated economics is provided in the subsequent Chapter.

It is apparent that CTF has real value in protecting crop yield longevity, or realising gains beyond current yields. The row spacing assessed here for CTF was 1.5 m, but ultra-narrow rows (Brodrick et al. 2010; Brodrick et al. 2013) and the use of 3m track CTF in a 1.0 m row spacing system should be considered. It is estimated that less than 20% of the Australian agricultural industries utilise true CTF, with adoption issues generally associated with uncertainty in the cost-benefit of conversion, and the requirement to remodel the entire farming system (Tullberg et al. 2007). Hence, it is advised that an industry effort is required in extending very clearly how the cost-benefit compares to the current system (Guerin 1999). Furthermore, to facilitate this it is likely that further CTF trial sites in multiple regions will be required.

Wheat rotation to alleviate soil compaction as affected by traffic system
Rotation crops at Auscott Warren following cotton tend to be sown in less than favourable conditions, as for the 2015 wheat. Based on Auscott analysis, there is a great agronomic trade-off between the systems where the cotton becomes the main beneficiary at the sacrifice of the wheat crop. The wheat is sown to provide expected bio-ripping, as well as other benefits such as pest breaks, herbicide rotation, organic and carbon return benefits. The wheat takes advantage of moisture and nutrition remaining after the cotton crop (i.e. is grown as a dryland crop with no inputs), therefore markedly increasing cropping and resource efficiencies at the field level, and as part of the holistic CTF approach. Such practice is essentially best practice advice of SOILpak for cotton growers (McKenzie 1998), but not necessarily common practice throughout the Australian industry where wheat rotations are often still managed for peak production, thus not allowing adequate soil profile moisture drawdown.

Such an approach aims to utilise the shrink-swell nature of smectitic clays dominating Vertosol soils, relying on soil moisture drawdown provided by the sacrificial dryland wheat. Figure 4C clearly demonstrates that wheat was more efficient at utilising soil moisture to a depth of 0.8 m in the CTF system for both traffic and non-traffic furrows. On the other hand, in the 1.0 m standard JD7760 system, wheat did not significantly reduce moisture content in the 0.4–0.8 m soil depth, irrespective of furrow. This supports McHugh et al (2009) in refuting the widely held opinion that Vertosol soils self-repair the induced compaction within conventional cotton farming systems. Pillai-McGarry and Collis-George (1990) showed that at least three wet-dry cycles were required to provide sufficient shrink-swell activity for observable differences in compaction to be measured.

Compaction alleviation by wheat appears to only be effective where wheat can penetrate around, or through, compacted zones to encourage internal bulk volume shrinkage (e.g. CTF circumstance). Presumably wheat roots were unable to penetrate beneath the 0.4 m depth under the standard JD7760 system. This raises questions about relying on wheat rotation to address subsoil compaction – is it able to operate on the same scale as the impact operates on, or will the compaction pan continue to rise, irrespective? The results presented here support a continued rise of the compaction pan under the current farming system, even where bio-ripping is employed.

Radford et al. (2001) found that two wheat crops grown in an 18 month period in a dryland Vertosol system were not only sufficient to alleviate imposed compaction, but out yielded the control. In their case compaction occurred with a maximum axle load of 10 Mg, which is less than half that of the JD7760. Subsequently, McHugh et al (2009) found that natural amelioration caused by wet-dry cycles in a Vertosol was only evident after 22 months when converting from conventional to CTF or zero traffic (control) systems. Although, they noted that cyclical compaction from two tractor passes annually was sufficient to overcome any natural amelioration effect. Once again, the JD7760 has axle load much greater than that of the tractor (4.7 Mg). The literature strongly suggests that time (18–22 months) and true wet-dry cycles are required in order for this management approach to be able to address the imposed compaction. As such, and based on the results observed in this study, it is unlikely that a single wheat crop rotation will be able to induce sufficient compaction amelioration.

The stress supplied to the soil by the JD7760 (Bennett et al. 2015) and the likelihood of soil moisture adequate to facilitate compaction when irrigating up to defoliation (Braunack & Johnston 2014) suggests that the best approach to soil compaction management is avoidance. Soil moisture is thus more important than the contact pressure or wheel load of the machine, suggesting that instigating a true drying cycle prior to defoliation and subsequent harvest of cotton be beneficial. This would also aid in maximising any bio-ripping ameliorative effect of subsequent rotation crops.

Conclusion

The standard JD7706 with its 6.0 m frontage and dual wheel front axle configuration has been demonstrated to significantly influence compaction with the major root zone of cotton, and influence soil structural arrangement to the investigated depth of 0.8 m. Importantly, both the inner and outer dual wheel were shown to have similar impact, effectively creating a compaction pan lateral to the full machine frontage at 0.4 m that was impenetrable by a subsequent wheat rotation after only two traffic passes of the JD7760. For bio-ripping to be an effective management practice post-harvest in this system it is highly suggested that soil is sufficiently dry (below the plastic limit) prior to harvest.

In comparison, a CTF approach using a converted CTF JD7760 and 1.5 m row spacing was shown to provide comparative yield to the conventional 1.0 m system after two cotton seasons and one traffic pass of the JD7760. A subsequent wheat crop designed for bio-ripping more effectively accessed water in the CTF system and out yielded the conventional system by ≈60%. It is concluded that a CTF approach provides better protection of the soil resource than the conventional system and will likely have greater productivity in the long-term.

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Comparing yield, water use efficiency, fibre quality and gross margins between 1.0 m and 1.5 m row irrigated cotton

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Introduction

The previous chapter advocates for transition towards controlled traffic farming (CTF) with use of a 1.5 m row spacing. The 1.5 m row benefits water use efficiency (WUE), soil health and enterprise integration. Plants have access to larger volumes of soil water which increases utilisation of rainfall while reducing irrigations, as low plant densities per hectare assist in reducing water input requirements (Enciso-Medina et al. 2002; Brodrick et al. 2012b). Current harvesting and rotation crop machinery usually results in uncontrolled traffic within fields, due to mismatched machine wheel track. This increases compaction and negatively impacts bulk density, mechanical impedance, porosity and hydraulic conductivity (Radford *et al*. 2000; Chan *et al*. 2006). The 1.5 m row-spacing enables Controlled Traffic Farming (CTF) where all machinery is driven on the same 3 m wheel tracks. Compaction is minimised to 15 – 20% of the total land area and allows for the soil structure to recover. Over time, water infiltration and root penetration will expand, demonstrated by an increase in yield (Tullberg 2000; Tullberg *et al.* 2007; Hamza and Anderson 2005; Antille *et al*. in press), and as observed in the previous chapter.

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

In advocating for a CTF approach to Australian cotton production using 1.5 m row spacing, it is therefore prudent to understand yield differences in terms of WUE, as compared to the current industry standard 1.0 m row spacing system. Whilst the previous chapter focusses on the land resource impact of the John Deere 7760 (JD7760) and managing this through CTF with some regard to yield, this chapter assesses the effects of 1.5 m row-spacing on cotton yield, fibre quality and WUE in comparison to the traditional 1.0 m row-spacing system.

Methodology

The experiment was located at the same experimental site as for the previous chapter: Auscott Warren, 31°47'24.4"S 147°44'01.4"E, 195 m above sea level, situated 11 km south-west of Warren, NSW, Australia. This semi-arid region receives 513 mm of annual rainfall. Summers are characteristically hot (mean maximum temperature is 32.5°C) while winters exhibit slightly cooler

conditions (mean maximum temperature is 16.3°C) (BOM 2015). Experimental design and field history is therefore consistent with the previous chapter.

Soil moisture content

A gravimetric water content analysis (GMC; mass/mass) was conducted in the 2014/15 season from three sites in each treatment to determine the initial volumetric soil water at the beginning of the season. This was converted into volumetric soil water content (VMC; volume/volume) and was determined to a depth of 0.9 m at intervals of 0.1 m. Rows subjected to this practice were chosen at random in the top, middle and bottom sections of the field. Samples were oven-dried to determine soil dry weight and field bulk densities used to convert GMC to VMC. The average of these values were used to determine the initial volumetric soil water in ML/ha for each treatment.

Water balance

To determine the WUE of each treatment, net water was calculated in the 2014/15 season through measurement of water inputs and outputs (Figure 1). Water inputs included: irrigation applications and rainfall. Water outputs included: field evapotranspiration, deep drainage and run-off captured in the tail drain. The change in volumetric soil water dynamics throughout the season were monitored in-field with capacitance probes in each row spacing system.

Irrigation occurred separately for each treatment. The amount of water added into the head ditch was measured using a flow meter on the inlet pipe (see ANCID 2015 for more information). Likewise another flow meter attached to the outlet pipe at the end of the head ditch measured water which left the field. An automatic rain gauge measured seasonal rainfall (October2014–April 2015).
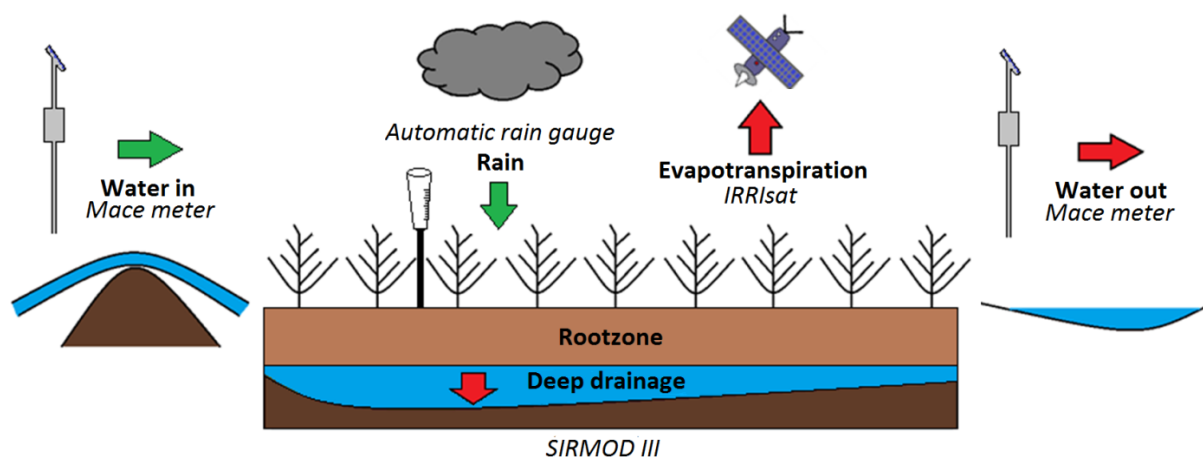

Figure 1. Diagram demonstrating the inputs and outputs of water in a cotton field as well as the methods which were used to measure them.

Evapotranspiration for cotton was determined through the formula:

$$ET_c = ET_o \times K_c$$

Where ET_c is the crop specific evapotranspiration, K_c is the crop coefficient, and ET_o is the standard evapotranspiration value based on the evapotranspiration of fully green alfalfa. IRRIsat was used to determine K_c values using Normalised Difference Vegetation Index (NDVI) and Landsat 8, (see Montgomery et al. 2015 for more information). Evapotranspiration was determined for each treatment block. ET_o values were sourced from the nearby Trangie Research Station. This information was available from the Bureau of Meteorology (BOM) who use the adapted Penman-Monteith equation recommended by the United Nations Food and Agriculture Organisation (FAO56-PM

equation) (Webb 2010). In IRRIsat, ET_c values were determined for each replicate and an average was calculated for each treatment plot.

Deep drainage was estimated using SIRMOD III (Walker 2003) on a single irrigation. The estimated deep drainage from the program was compared against peer-reviewed studies conducted under similar conditions to determine the reliability of the data.

Hand segment picked cotton

Six individual linear metre rows were randomly selected from replicates in each treatment to be handpicked. These samples were further separated into eight plant fruiting segments (Figure 6). Plant numbers were noted per linear metre while boll numbers were recorded per segment. These samples were processed in experimental gins at Cotton Seed Distributors (CSD), Wee Waa, where sample yield and quality characteristics were identified using the High Volume Instrument (HVI) (see Suh and Sasser 1996).

Treatments were compared on a brown hectare rather than green hectare basis. Brown ha refers to the total area required to grow the 1.5 m cotton in hectares. Green ha refers only to the area occupied by plant rows and does not account for the additional inter-row space. This ensured a fair comparison considering the 1.5 m row spacing treatment had access to a larger area (1.5 m^2) which would present data from this treatment more favourably.

Machine picked cotton

This in-field experiment occurred in an 18.42 ha paddock over two seasons. The 1.5 m cotton occupied 9.68 ha while the 1.0 m treatment occupied 8.74 ha. Each treatment was machine harvested separately using calibrated yield monitors. Cotton lint from each treatment was ginned independently. Ginned cotton yield was used to normalise the in-field yield maps providing broad scale comparison between 1.0 m and 1.5 m row spacing.
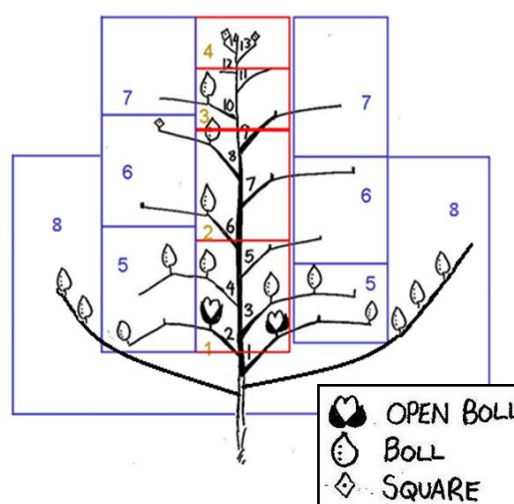

Figure 2. Segment picking diagram outlining cotton fruiting segments 1-8. (1) Mainstem fruiting nodes 1-4 position 1. (2) Mainstem fruiting nodes 5-8 position 1 (3) Mainstem fruiting nodes 9-12 position 1. (4) Mainstem fruiting nodes 13+ position 1. (5) Mainstem fruiting nodes 1-4 position 2+. (6) Mainstem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

Determining WUE

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

Economic analysis

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

determined using the NSW DPI cotton gross margin template for furrow irrigated cotton in central and northern NSW (NSW DPI 2015).

Data analysis

Machine picked (227 kg bales/ha), handpicked yield, bolls/m^2, lint per boll, fibre strength and fibre length were analysed using a one-way analysis of variance (ANOVA). Linear regressions were fitted for lint yield, lint per boll (g), and number of bolls per m^2 for both 2013-14 and 2014-15.
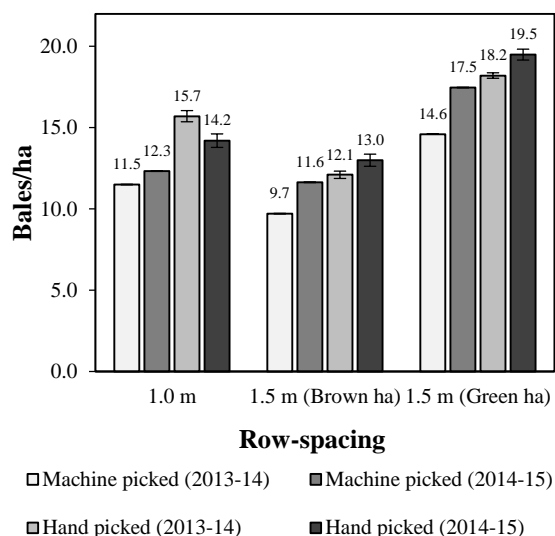
Results

Machine picked and handpicked yields in the 2013/14 and 2014/15 seasons

In both the 2013/14 (significant $p<0.001$) and 2014/15 (not-significant $p=0.68$) seasons, 1.0 m row out yielded 1.5 m row cotton as measured by machine picking and handpicking when compared on a brown ha basis (Figure 3). A 16% (2013/14) and 6% (2014/15) difference was observed between normalised machine yield for the row spacing treatments. This equated to a reduced yield/ha in the 1.5 m row-spacing system of 1.8 and 0.7 bale/ha, respectively, compared with 1.0 m row. This difference was significant in the 2013/14 season ($p<0.001$) and statistically similar for the 2014/15 season.

A similar trend was observed in the handpicked cotton with a 23% (2013/14) and 9% (2014/15) lower yield in the 1.5 m row compared with 1.0 m row. However, differences were significant ($p<0.001$) for both seasons.

Both seasons (2013/14 and 2014/15) experienced below average (283 mm) in-season rainfall at 206 mm and 160 mm, respectively. Accumulative day degrees for the cotton growing

Figure 3. Cotton lint yields (227 kg bales) by machine and by hand from cotton grown on 1.5 m and 1.0 m row spacing in the 2013/14 and 2014/15 seasons. Brown ha refers to the total area required to grow the 1.5 m cotton in hectares. Green ha refers only to the area occupied by plant rows and does not account for the additional inter-row space. Error bars represent standard errors of the mean. Some error bars are not visible due to low standard errors (below 0.02).

season were 1814°Cd (degree days) for 2013/14 and 1897°Cd for the 2014/15 season. These data do not account for comparative system differences and changes in between seasons, hence it is noted that the 2013/14 yield pertains to direct system comparison without any JD7760 potential compaction influence, whilst the 2014/15 season includes this.

Figure 4 demonstrates the ginned yield normalised for distribution of yield (bales/ha) across the experimental site. These maps clearly demonstrate linear features running from the southern to the northern end of the field, which relates to the row-spacing treatments and confirms the compiled results in Figure 3, whereby the differences (ability to detect linear features) are reduced in the 2014/15 season as compared to the 2013/14 season.
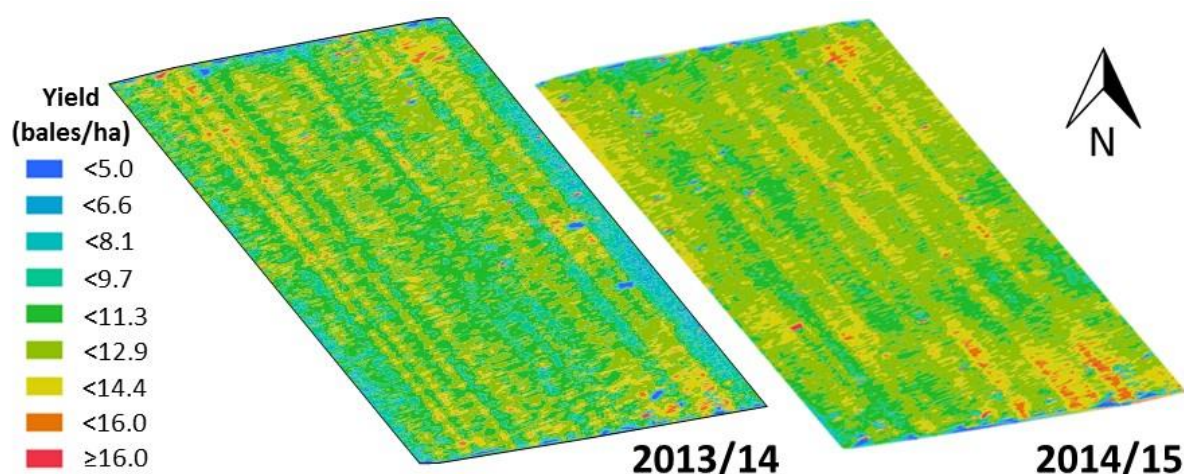
Figure 4. Yield maps normalised for ginned yield from the 2013/14 and 2014/15 cotton season including both 1.0 m and 1.5 m row-spacing to demonstrate the field and experimental treatment spatial and temporal distribution of yield.

Water balance and use efficiency

The water balance and use efficiency was conducted for the 2014/15 season as this pertains to the full system; i.e. it includes the traffic differences associated with 1.0 m (uncontrolled traffic) and 1.5 m (controlled traffic) row spacing systems. The 1.0 m treatment experienced a deficit of 1.66 ML in net available water compared with the 1.5 m row spacing, with 1.0 ML/ha of this ascribed to remaining soil moisture differences between the 1.0 and 1.5 m systems post 2013/14 cotton season. The difference in water outputs (deep drainage and evapotranspiration) between the two treatments was minimal. The 1.5 m row spacing captured more rainfall per unit of cotton, as it covered a larger area than the 1.0 m row spacing. One linear metre of 1.5 m cotton occupied a 1.5 m^2 area while a linear metre of 1.0 m cotton only occupied a 1.0 m^2. Compensating for this, the applied irrigation was slightly more for the 1.0 m row spacing. The 1.5 m row-spacing water requirement was less per hectare to maintain crop productivity (Table 1).

Table 1. Total treatment inputs and outputs of the 2014/15 season water balance in ML. Accounting for initial soil moisture and displaying total available water for each treatment in ML/ha.

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

More water was available per hectare for the 1.0 m treatment (0.84 ML/ha) which resulted in a greater yield (12.3 bales/ha) compared to 1.5 m system (11.6 bales/ha). However, the 1.5 m row-spacing achieved a slightly greater yield per ML (Figure 5), equating to a slight difference in WUE (bales/ML) in favour of the 1.5 m row spacing. When irrigation efficiency was compared based only on applied irrigation water there was a greater difference between 1.5 m and 1.0 m row spacing, in favour of the CTF 1.5 m row spacing.
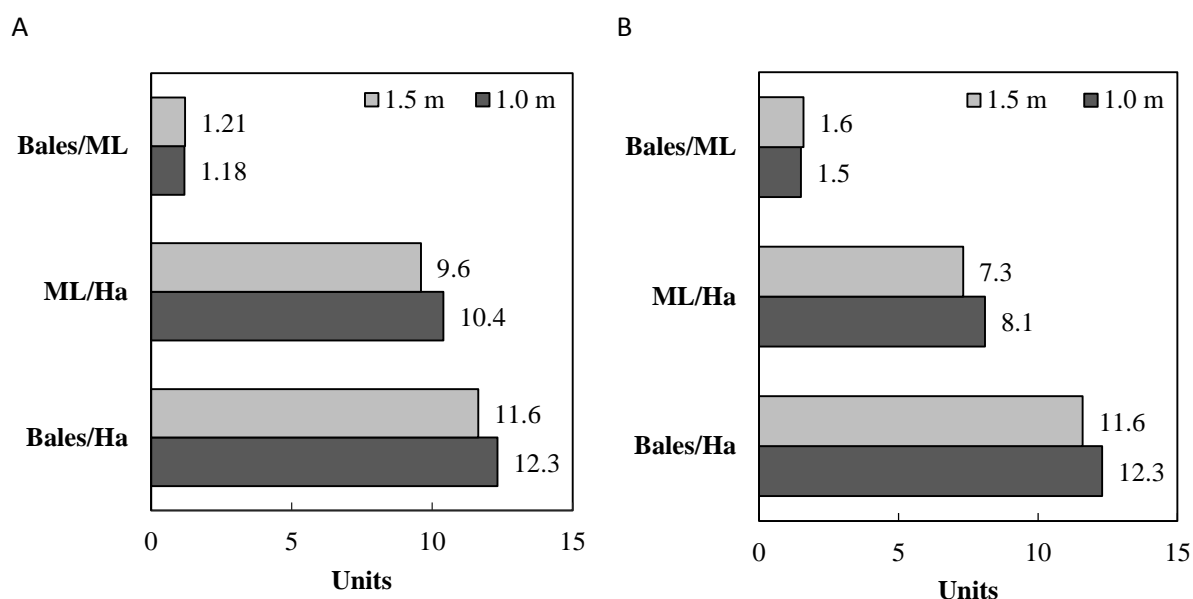
Figure 5. Difference between 1.5 m (light grey) and 1.0 m (dark grey) row spacing cotton yield in bales/ML, total ML/ha and bales/ha (227 kg bales) when (A) incorporating a full water balance (inputs and outputs), or (B) considering only applied irrigation water. Units refers to the respective y-axis units.

Comparison of boll position and subsequent yield

The majority of the lint yield on the 1.0 m row spacing was found on fruiting positions 1-8 with some fruit on the lower vegetative branches. Yield on the 1.5 m row spacing was primarily established on the vegetative branches (Figure 6 and Figure 7). The number of bolls per square meter for each fruiting segments followed this trend (Figure 8). There was an increased amount of vegetative fruit on the 1.5 m cotton in 2014-15. More cotton was found on 2nd position in the 2013-14 season compared with the 2014-15 season.

The average weight of bolls in the first position from each fruiting segment was spread fairly evenly amongst both the 1.5 m and 1.0 m row spacing treatments. However, 1.5 m row spacing had slightly more lint in second position fruit in fruiting branches 1-12 (Figure 9). Boll numbers in 1.0 m row cotton were reduced in 2014-15 compared with 2013-14.

Figure 6. Example of the difference in plant vigour and boll count and position for two cotton plants with 1.5 m (Left) and 1.0 m (Right) row spacing; 50 cm rule for scale.

A strong correlation was observed between the number of bolls per fruiting segment and the lint yield per fruiting segment ($R^2 = 0.99$) (Figure 10) whereby linear trends for both row spacing systems are in good agreement. Relationships for 1.5 m row and 1.0 m row cotton between lint per boll and lint yield per fruiting segment, as well as between the number of bolls and lint per boll, were effectively parallel for the two systems. However, for the 1.5 m row spacing system there was consistently more lint per boll in terms of number of bolls and lint yield per fruiting segment.
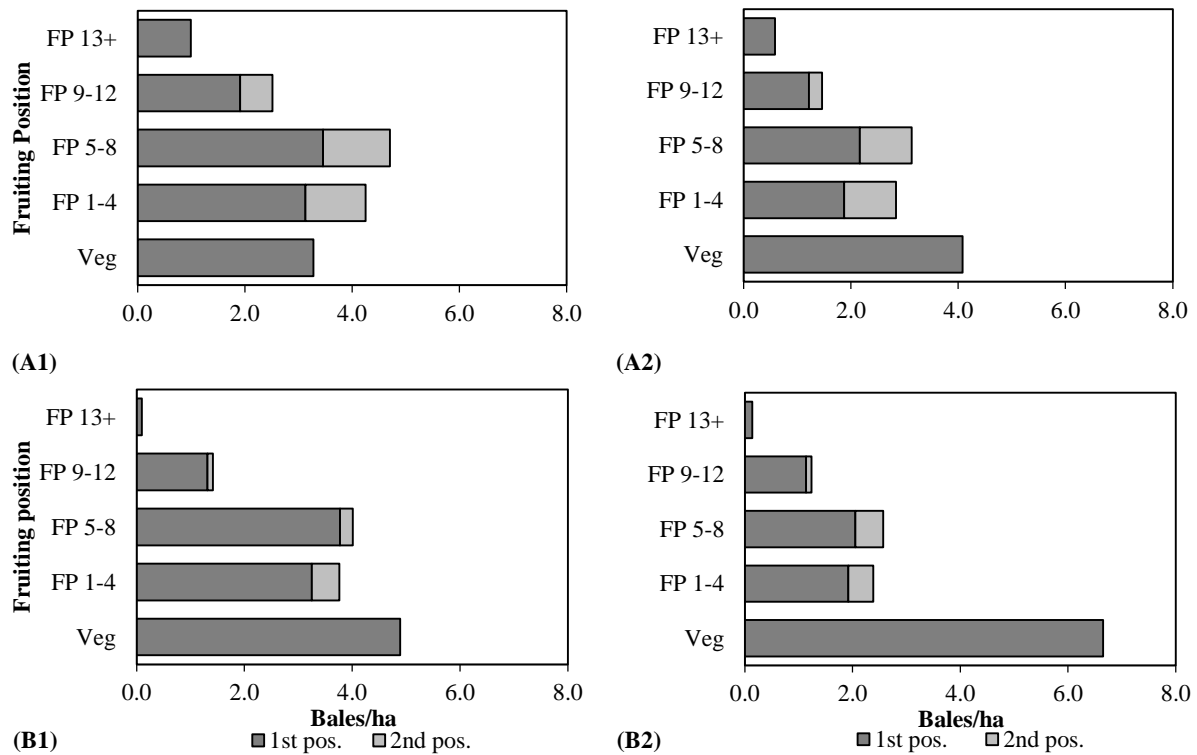
Figure 7. Yields in bales/brown ha (227 kg bales) of handpicked cotton separated into fruiting segment for the (A) 2013/14 and (B) 2014/15 season by (1) 1.0 m and (2) 1.5 m row spacing system.
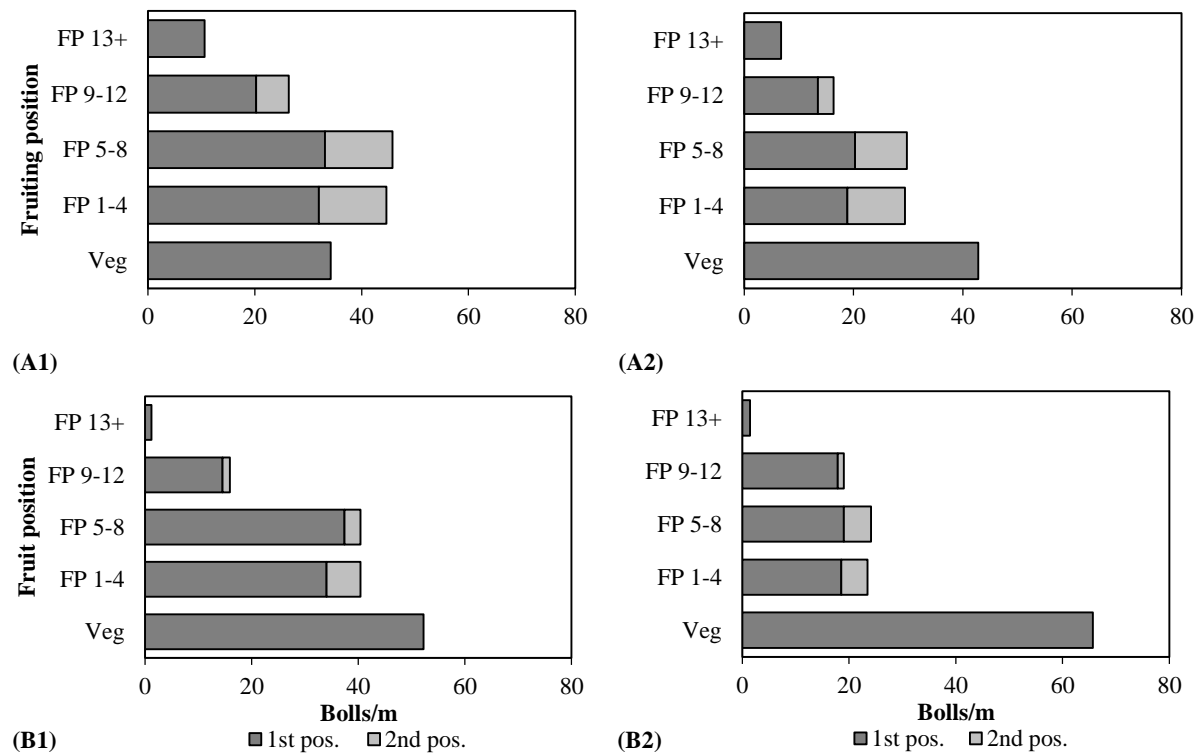

Figure 8. The number of bolls per metre of handpicked cotton separated into fruiting segment for the (A) 2013/14 and (B) 2014/15 season by (1) 1.0 m and (2) 1.5 m row spacing system.
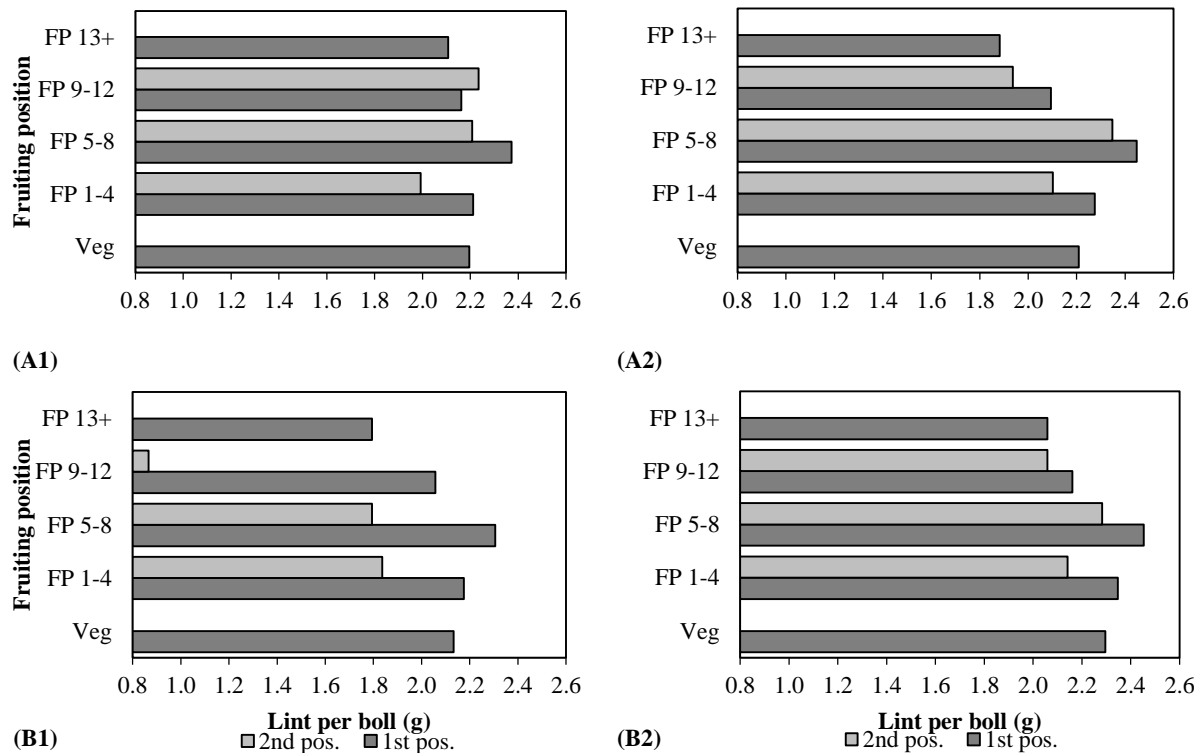
Figure 9. The average weight of lint per boll in grams for handpicked cotton separated into fruiting segment for the (A) 2013/14 and (B) 2014/15 season by (1) 1.0 m and (2) 1.5 m row spacing system.
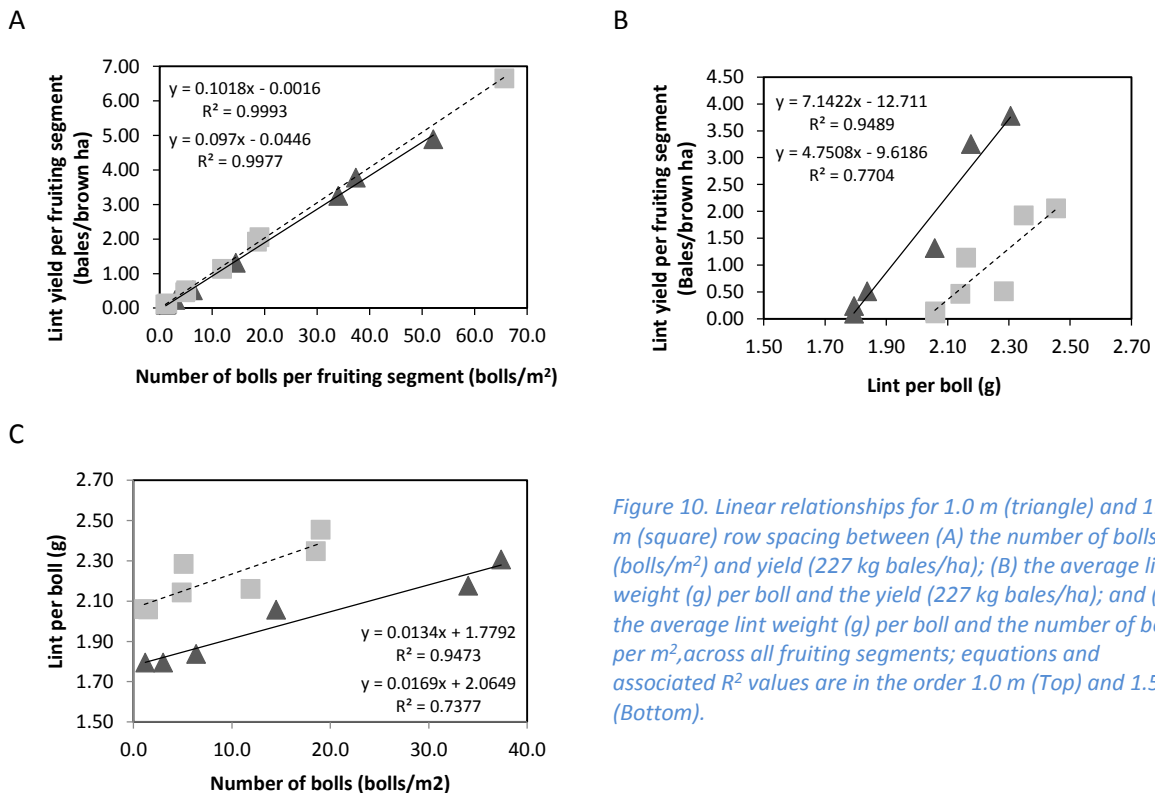

Figure 10. Linear relationships for 1.0 m (triangle) and 1.05 m (square) row spacing between (A) the number of bolls (bolls/m²) and yield (227 kg bales/ha); (B) the average lint weight (g) per boll and the yield (227 kg bales/ha); and (C) the average lint weight (g) per boll and the number of bolls per m², across all fruiting segments; equations and associated R² values are in the order 1.0 m (Top) and 1.5 m (Bottom).

Fibre quality of the handpicked cotton from 2014-15

Fibre length in the first and second position fruit was longer in all fruiting segments below fruiting position 13 in the 1.5 m row compared with the 1.0 m row spacing (Figure 12). In 2013-14 1.5 m cotton fibres were longer than 1.0 m cotton fibre (p=0.031). This occurred again in 2014-15 (p=0.022).

Marginally stronger fibres were observed in each fruiting segment aside from fruiting positions 1-4 in the 1.5 m compared with the 1.0 m cotton. Bolls on the vegetative branches of 1.5 m cotton had significantly stronger fibres than the 1.0 m cotton (33 g/tex and 30 g/tex, respectively) (Figure 13). In 2013-14, 1.5 m fibre was stronger than 1.0 m fibre (p=0.020). This occurred again in 2014-15 (p=0.037).

Economic analysis

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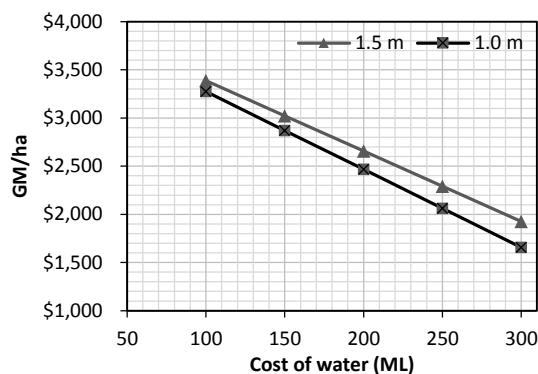

Figure 11. A sensitivity analysis demonstrating the sensitivity of gross margins to variable water prices in 1.5 m and 1.0 m cotton production systems. All other input and output prices remained constant (e.g. $500/bale).

Discussion

Water use efficiency

Water has been identified as the most limiting factor to production in the many Australian cotton producing regions (Roth *et al*. 2013). Hence, employing strategies to improve WUE is vital. Coupled to this is protection of land resource whereby methods to sustain/improve the extent of stored moisture will be vital as water-allocations become more restricted, due to competing industry pressure. Thus, the 1.5 m CTF system appears attractive, even at the cost of a slight yield loss per hectare, as the increase in gross margin ($/ha) compensated for yield loss. The 1.5 m row-spacing required less water per hectare to produce a similar yield to that of the 1.0 m row-spacing (1.21 bales/ML and 1.18 bales/ML, respectively). Overall, 1.0 m cotton received more water than the 1.5 m cotton per ha. The biggest differences in inputs were rainfall and initial soil moisture, although the differences in irrigation compensated for this.

WUE increased with reduced traffic, and Irrigation Water Use Index (IWUI) was found to increase in 2014/15. As traffic was controlled, soil compaction was reduced (as shown in the previous chapter), and water infiltration was maintained (McGarry and Chan 1984; McGarry 1990; Braunack *et al*. 1995; Chan *et al*. 2006). Compaction is clearly documented as reducing pore diameter, thus limiting infiltration (Assouline *et al.* 1997), so the moisture holding capacity of the 1.0 m uncontrolled traffic system would have had lower comparative plant available soil moisture as compared to the
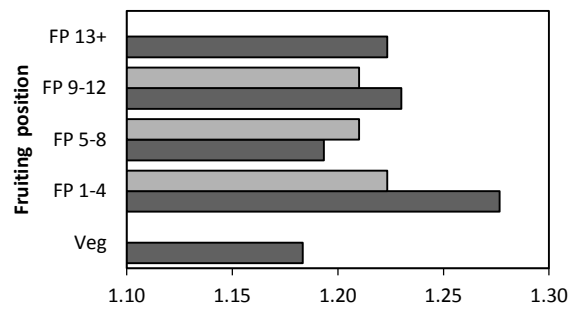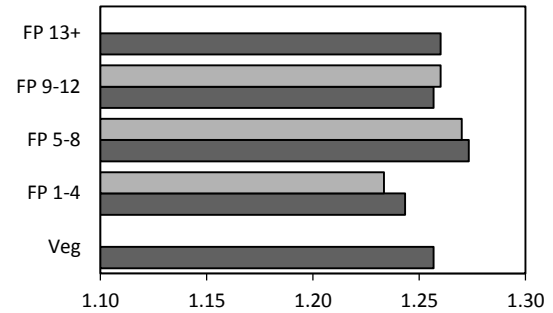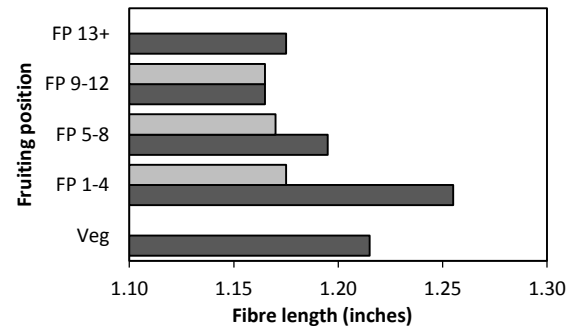
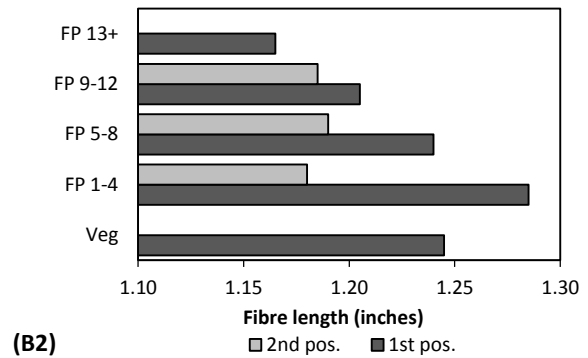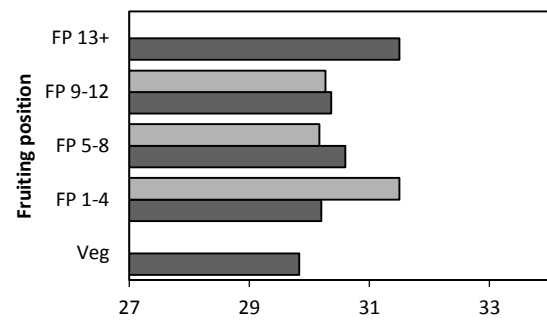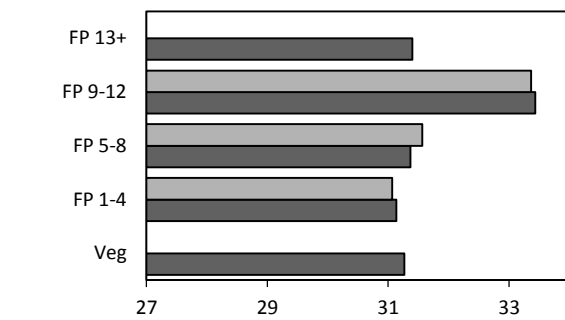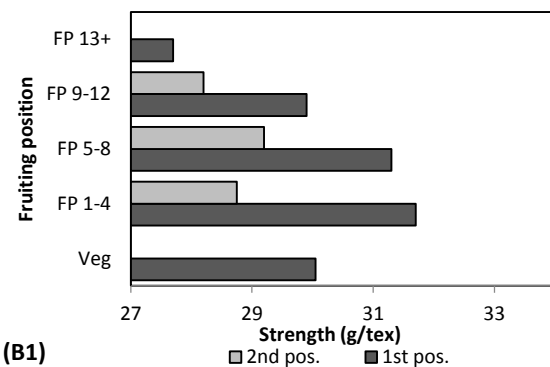*Figure 12. Fibre length (1 inch = 25.4 mm) of handpicked cotton separated into fruiting segment for the (A) 2013/14 and (B) 2014/15 season by (1) 1.0 m and (2) 1.5 m row spacing system.*

Figure 13. Fibre strength (g/tex) of handpicked cotton separated into fruiting segment for the (A) 2013/14 and (B) 2014/15 season by (1) 1.0 m and (2) 1.5 m row spacing system.

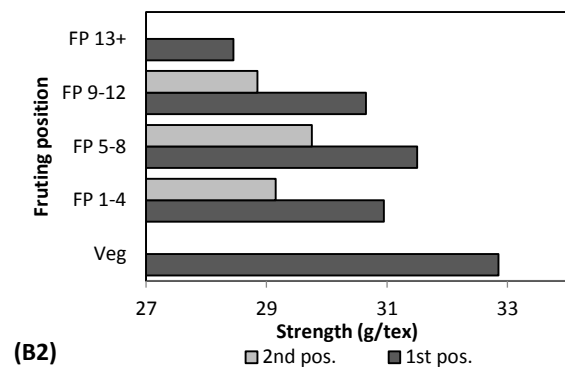controlled traffic 1.5 m system. A compaction influence on WUE would not have been evident in the 2013/14 seasonal data as there had not been any heavy machine (JD7760) traffic.

The Australian cotton industry places importance on cotton yield produced per unit of water. Benchmarks are determined every few years as technology and management practices improve, with two main indicators: (1) Gross Water Use Index (GWUI), which compares yield against all water inputs on farm; and (2) IWUI, which measures the amount of cotton produced per volume of irrigation water applied (Montgomery and Bray 2014). Industry WUE has increased over time (Figure 14). In the space of 10 years there has been an increase of 40% in GPWUI and IWUI. The GPWUI in both the 1.0 m and 1.5 m treatments in this experiment is greater than industry averages observed in other studies, with 1.5 m cotton obtaining the highest GPWUI. IWUI of the two treatments (1.0 m and 1.5 m) in the current study was similar to the industry average over the last six years.

The greatest water saving was in applied irrigation water in both seasons (2013/14 and 2014/15). The importance of this being that cotton crops grown on 1.5 m row-spacing require smaller irrigations or employ longer water cycles. Additionally, 1.5 m cotton was the only treatment above the industry IWUI average of 1.5 bales/ML obtained from Tennakoon et al. (2004) data, which suggests that the 1.5m system provides better WUE than the industry standard system, provided the influence of heavy machinery is controlled. Hence, the 1.5 m system is most likely better suited to a drier climate, or where water availability is uncertain, as compared to the industry standard 1.0 m row spacing system.
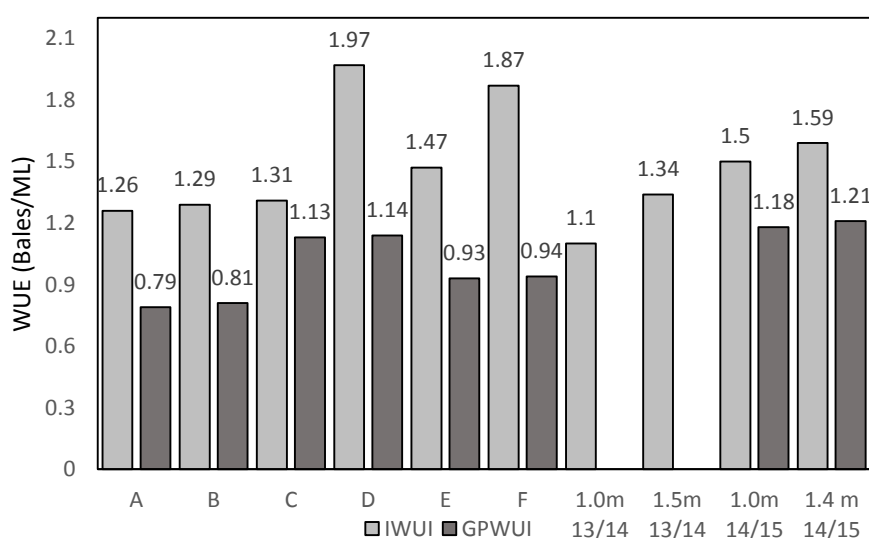
Figure 14. Change in WUE (bales/ML) (227 kg bales/ha) in the last fifteen years on the basis of Irrigation Water Use Index (IWUI) and Gross Water Use Index (GPWUI), combining data for (A) 1996/97–1998/99, (B) 1998/99, (C) 2006/07, (D) 2008/09, (E) 2009/10, and (F) 2010/11 cotton seasons, as well as the 1.0m and 1.5 m systems in 2013/14 and 2014/15 . External data sourced from Cameron and Hearn (1997), Tennakoon et al. (2004), Payero and Harris (2007), Williams and Montgomery (2008) and Wigginton (2011).

Wide row configurations aim to conserve soil water alongside each planted row. During periods of rain this will extend plant growth, especially in regions where soils (e.g. Vertosols) have a high water holding capacity. Each plant has access to a larger volume of soil water (larger bucket) and requires less irrigation to maintain optimal plant growth and development (Bange et al. 2005). Coupling this with a controlled traffic program, such as that employed in the 1.5 m system, serves to enhance this benefit (Bennett et al. 2015).

Yield, fibre quality and fruit segment distribution

Row-spacing potentially has a large impact on yield performance as it influences the number of plants per hectare. An obvious concern is that green hectares have been reduced thereby the perception is that wider row spacing will result in less overall yield. In 2013/14 the yield results of the 1.0 and 1.5 m systems were not influenced by prior compaction from the JD7760 and residual compaction from the previous cotton picking system was provided 3 years fallow, a flood and a wheat crop (bio-ripping contribution). Hence the 2013/14 season provided a fair comparison of the two row spacing systems from which it was found that yield was greatest for the 1.0 m industry standard cotton system (by 18%). However, after one year of JD7760 intervention yield was comparative for the two systems (6% difference), which was primarily attributable to CTF as the traffic basis of the 1.5 m row-spacing cotton. This suggests that yield loss in the 1.5 m row-spacing cotton system, comparative to current standard growing practices (1.0m row-spacing), may not be a concern provided a CTF approach is also used.

Yield in each fruiting segment (bales/brown ha) in both the 1.0 m and 1.5 m row-spacing treatments was directly correlated (R^2=0.99 and R^2=0.99 respectively) with the number of bolls per fruiting segment (bolls/m^2). Increasing the number of bolls/m^2 has a positive impact on yield (Constable *et al*. 2001). The 1.5 m row spacing produced cotton plants which were wider and taller than their 1.0 m counterparts. Brodrick *et al*. (2010) observed the opposite in UNR cotton compared with 1.0 m cotton. Individual plants in UNR cotton were shorter and had fewer mature bolls past the 1st and 2nd positions. This was attributed to lower light interception, a result of a denser canopy. Cotton plants tend to invest resources only in bolls which they intend to keep, meaning boll weight is an indication of which fruiting positions were prioritised (Jackson and Gerik 1989). Hence, as 2nd position bolls were heavier than in 1.0 m cotton, it is deduced the 1.5 m cotton plants had less competition for soil water and nutrients. Furthermore, the majority of the lint from 1.5 m cotton was found on the vegetative positions (branches) while in 1.0 m cotton the majority of the yield was found on fruiting positions 1 to 8. Thus plants in the 1.5 m row-spacing matured slower as faster maturing plants tend to have the majority of their lint in the higher fruiting positions (Brodrick *et al*. 2010).

Greater fibre length and strength in the 1.5 m compared with 1.0 m row-spacing was found. Final fibre length is determined at the end of the fibre elongation period. This occurs around 25 days after flowering and pollination (Bange *et al*. 2009). Water stress during this time can have a detrimental effect on fibre length (Hearn 1976; Constable and Hearn 1981). The 1.5 m cotton has access to a larger profile of soil water which sustains plants through drier periods, alleviating water stress, resulting in longer fibres. Fibre was significantly better quality in the 1.5 m row-spacing in both strength and length, compared with 1.0 m row-spacing. Fibre strength is a measure of the maximum resistance to stretching forces and measured in grams force, and has a direct correlation to fabric strength and durability. Strength is determined by maturity. Moisture stress in the later part of boll filling can reduce fibre strength. Hence the vegetative bolls had the greatest fibre strength since they were the most mature. One metre cotton row-spacing system fibre is less mature as the majority of the lint appears on fruiting positions 1–8, which occur later in the season (Bange *et al*. 2009; Roth *et al*. 2013). As fibre quality impacts the price per bale growers receive at the gin, quality needs to be within certain parameters to minimise penalties. Both the 1.0 m and 1.5 m cotton was considered "ideal" to "premium" in terms of quality (Bange *et al*. 2009). However, 1.5 m cotton fibre was significantly (p<0.001) stronger and longer on average hence if downgrades occur due to limited water and high plant stress, there is somewhat of an insurance policy against a loss in quality.

The lower yield per ha for both years of the experiment (2013/14 and 2014/15) was in the 1.5 m cotton, compared with 1.0 m cotton, which could possibly be attributed to those plants reaching their seasonal yield potential (as light interception may be limiting due to reduced early season canopy cover). The
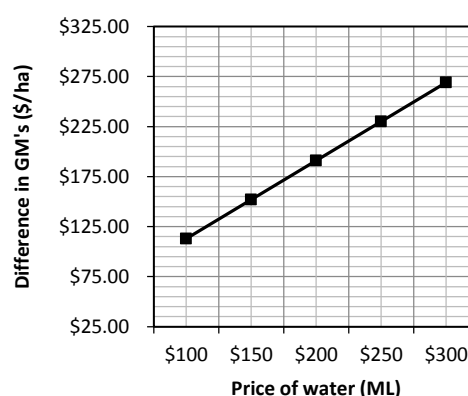
performance of a crop in particular conditions is determined by its genetic potential. Inputs were not necessarily limiting in the experiment, as irrigation and nitrogen were applied as required. This suggests that each plant reached fruiting capacity, hence restricting yield, as demonstrated in Gibbs (1995). Lower plant densities, such as those in the 1.5 m row-spacing system, are known to inhibit yield (Bednarz et al. 2000). However, cotton plants are capable of compensating yield, as was observed in the current project. Where the 1.5 m cotton had reduced plant density in comparison to the 1.0 m cotton, it also produced more bolls per plant, particularly in the vegetative branches. As 1.0 m row-spacing has become standard practice for cotton, numerous cultivars have been developed to suit this system (Clark and Carpenter 1992). Whilst the Sicot 74BRF variety provided good comparative performance for the 1.5 m system, and is the highest yielding variety ever produced (CRDC 2015), further gains could be realised in breeding cotton varieties specifically suited to a 1.5 m system. On the other hand, the yield potential of the Sicot 74BRF variety in 1.5 m row configuration is not well understood from this single experiment and warrants further industry investigation given current reported industry yield potential of 3500 kg of lint/ha (15.42 bales/ha) Sicot 74BRF for 1.0 m row-spacing cotton.

Economic evaluation of the 1.5 m row spacing system

There is a significant difference of $191.30/ha in gross margins between the two row-spacing systems, in favour of the 1.5 m cotton. The 1.0 m cotton received greater yields resulting in a higher gross income but with a higher input cost, whilst the 1.5 m cotton had a lower yield, but a lower cost per ha. Subsequently, the most expensive input cost was water for irrigation although technology fees and ginning costs also had an important impact (Table 2).

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

Figure 15. Sensitivity analysis demonstrating change in gross margins difference between the 1.5 m and 1.0 m cotton as a result of fluctuating water price ($/ML). Differences are in favour of the 1.5 m system.

The price of water is known to fluctuate depending on availability and the region. In a wet year it can be as low as $50 /ML while in a dry year it can reach $300 /ML. The price of water had the most significant impact on the gross margin. Through consultation with various growers and consultants in the Macquarie Valley a $200/ML value was used as the average water price (Pers Comm Sustainable Soil Management, Auscott Warren, NSW DPI). A sensitivity analysis revealed that the difference in gross margins between 1.0 m and 1.5 m cotton increased with an increasing water price (Figure 15). This was due to a greater WUE in the 1.5 m cotton which reduced the irrigation requirement compared to the 1.0 m cotton. This suggests that 1.5 m row-spacing is more economically sustainable production system in regions where water is limiting.

Table 2. The expected gross margins of 1.0 m and 1.5 m row-spacing (using NSW DPI cotton gross margin template for Central & Northern NSW 2014-15).

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

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

Cost benefit analysis of the a 1.5 m controlled traffic system

The increased gross margin for the 1.5 m row-spacing under controlled traffic is $191.30 /ha, which is largely attributed to irrigation water use efficiency achieved through maintaining the soil porosity, in comparison to the 1.0 m row-spacing with uncontrolled traffic. Furthermore, the previous chapter showed that a subsequent dryland wheat rotation with comparative input costs, planted at the same density and row spacing irrespective of the cotton system, resulted in 0.49 t/ha loss of yield potential for uncontrolled traffic and 1.0 m row-spacing. This equated to $120 /ha gain in the 1.5 m system, as compared to industry standard. Hence, within a cotton-wheat rotation the cumulative profitability of the CTF 1.5 m row-spacing cotton system is $311.30 /ha.

The conversion cost of a JD7760 from its standard dual-wheel configuration and 2 m internal track width, to a CTF configuration with a 3 m internal track width is ~$68K (Pers. Comm. Jamie Grant; Vanderfield Pty Ltd). This includes altering the tool bar to handle 6 heads at 1.5 m, widening the track of the front and rear axles, and enhancing the structural stability to avoid weak points in the drivetrain. Hence, at the calculated profitability of the 1.5 m CTF system this would represent 355.46 ha of cotton, 566.66 ha of wheat, or 218.43 ha of cotton-wheat rotation to pay back the cost of conversion. Importantly, these costs are paid back out of system gains, rather than current profits.

However, these figures were obtained by commencing with a system prior to dual-wheel JD7760 inception. The time to increased gross margin due to a 1.5 m CTF system for a system currently using 1.0 m row-spacing with uncontrolled JD7760 is unknown. It is likely some energy costs in soil profile renovation would be required, and that rotation with wheat over a number of seasons to dry down the subsoil, as observed for the CTF system in the previous chapter, would be required to realise the reported gross margin. Therefore, a conservative estimate to recovering cost of conversion could reasonably be within 2–3 years.

Conclusions

This experiment demonstrated that 1.5 m cotton had a greater WUE by producing 0.09 more bales per ML ($20.43 /ML; $500 /bale), compared with 1.0 m cotton. This small difference meant a lower irrigation requirement resulting in 1.5 m cotton outperforming 1.0 m cotton in terms of gross margin ($2657.50/ha and $2466.20/ha, respectively). This outweighs the fact that 1.0 m cotton out yielded 1.5 m cotton by 1.8 bales/ha (16%) in 2013-14 and by 1.09 bales/ha (6%) in 2014-15, and reinforces the fact that yield should be considered in terms of system inputs.

Segment picking revealed that the majority of the fruit from the 1.0 m cotton was from fruiting positions 1-8, while the majority of the lint yield for 1.5 m cotton originated from vegetative branches. This suggests that the 1.5 m row spacing cotton matures more slowly, which led to stronger and long cotton fibres on average for the 1.5 m row spacing system, with an overall better fibre quality than the 1.0 m row spacing system.

On the basis that the 1.5 m row spacing CTF system had no fibre quality penalties and improved gross margin, compared to the current 1.0 m row spacing industry standard, the cost of CTF conversion was analysed against these benefits. If fields are virgin, or being converted from previous basket picking systems, then the cost could reasonably be recovered within one cotton season. However, if converting from a standard dual-wheel JD7760 system, the conversion cost were conservatively estimated to be recovered in 2–3 years.

The use of 1.5 m row-spacing cotton appears to be best suited to water limited environments based on its ability to enhance WUE. It should be noted that much of the Australian cotton industry is historically categorised as water limited in terms of both irrigation allocation and rainfall. Hence, there is benefit in future research replicating this experiment in other major cotton regions to inform row-spacing suitability. If new experiments are setup, then ultra-narrow cotton in a CTF system should also be considered side-by-side. Importantly, the 1.5 m system lends itself to incorporation of true CTF capable of integrating with the majority of current farming machinery that has 3 m wheel track.

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The influence of tyre inflation pressure on soil compaction caused by the John Deere 7760

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Introduction

Cotton is relatively sensitive to compaction and research suggests that root growth is significantly affected when soil mechanical strength is higher than approximately 2 MPa (Taylor and Ratliff, 1969). Above this threshold, water and nutrient uptake by the plant are restricted, which therefore compromises crop yield. Soil compaction is significantly affected by soil moisture, clay content, and soil strength prior to traffic (Saffih-Hdadi et al., 2009). From the perspective of the machine–soil interaction, compaction is influenced by axle load, wheel slip, and contact area, which depends on tyre inflation pressure and, therefore, contact pressure at the tyre–soil interface, and tyre deflection (Soane et al., 1980–1981a-b). These parameters can be manipulated, depending on soil moisture conditions at the time of traffic, in order to minimise compaction.

Soane et al. (1979, 1982) developed a conceptual framework, which considered options for controlling compaction (see Figure 5 in Antille et al., 2016 quoted from the earlier work by Soane et al.). This framework proposed that equipment with axle loads >20 t be banned from field traffic. The John Deere 7760 (JD7760) cotton picker has approximately 21 t on the front axle, which therefore exceeds the proposed limit of 20 t to restrict compaction to relatively shallow depths (e.g., <0.3 m). The picker also carries 12 t in the rear axle that, given tyres size and configuration, can cause additional compaction in comparison to the leading dual tyres. The overall load of the machine explains the need for dual tyres on the front axle, which occurs at the expense of increased footprint. However, the cyclic loading means that total weight increases to ≈37 t when the picker is fully loaded (i.e., when carrying two round bales, fuel and hydraulic fluids) and the weight distribution changes to ≈55% and 45% on the front and rear axles, respectively, compared to about 65% and 35%, respectively, at the beginning of the cycle (Bennett et al., 2015). This large axle loads transfer compaction to depths of 0.6 m, or greater, depending on the soil condition, which is cumbersome to rectify and it is also non-economical. This leaves the following as potentially viable options, ignoring controlled traffic farming (CTF), for managing compaction: (*i*) increased tyre size (section width, overall diameter or both to allow for reduced inflation pressure), and (*ii*) reduction in contact pressures by using tyres at the lowest (safest) operating pressure. This latter option may be assisted by the use of central tyre-inflation-pressure control systems so that inflation pressure can be adjusted 'on-the-go' i.e., slip-controlled, controlled through optimization of tractive efficiency or controlled by tyre deflection (Lyne and Burt, 1987; Koolen and Kuipers, 1989; Sharifi et al., 2007).

In clay soils, in order to maximise traction and reduce wheel slip, greater benefits result from increased contact area because of the cohesive component of shear force (Micklethwaite, 1944). However, if weight cannot be reduced, an increase in contact area is required to minimise contact pressure. This can be achieved by increasing tyre diameter, section width or both, although the former is preferable, and also by operating at the minimum allowable tyre inflation pressure. An increase in contact area through increased tyre diameter is preferable to section width because it will minimise rut width and reduces rolling resistance (Crossley et al. 2001; Kurjenluoma et al., 2009). Increased contact area will also reduce slip and therefore rolling resistance (Komandi, 1999).

The contact pressure at the tyre-soil interface can be reduced by operating the tyres at low inflation pressure, which also provides improved tractive performance and reduced soil deformation beneath the tyre (Keller and Arvidsson, 2004). This is because the average soil contact pressure under the tyre is approximately equal to the inflation pressure plus the pressure caused by tyre carcass stiffness (Way et al., 1997). This approach has primarily been used for low to medium weight agricultural vehicles. Given machine/crop-related incompatibilities within cotton systems, an alternative solution to CTF may be the use of low ground pressure (LGP) tyre systems (Godwin et al., 2015; Antille et al., 2016). LGP systems can operate at about 40%-50% lower inflation pressure than conventional tyres thereby reducing contact pressures significantly. The study reported in this chapter was conducted to gather preliminary information about the effectiveness of these systems in reducing soil stresses and therefore compaction from cotton pickers, but using conventional tyres at lower than the manufacturer's recommended inflation pressure.

Method

The study was conducted at a commercial farm located in Jimbour, Queensland, on a black Vertosol, which had been managed under controlled traffic for >15 years. The soil was wetted-up using an irrigation grid to achieve near-uniform moisture content (field capacity and 50% of FC, respectively) throughout the profile to a depth of 0.8 m. Subsequently, the soil was trafficked using a JD7760 cotton picker (unladen) fitted with 520/85R42-R1 and 520/85R34-R1 for standard dual (front) and rear axles, respectively. Tyres were inflated to the manufacturer's recommended inflation pressure (front: 0.25 MPa, rear: 0.32 MPa) and 50% lower, respectively, to represent a low ground pressure system. A CTF-compatible JD7760 cotton picker modified to match a 3-m track width CTF system and fitted with single tyres (front: 620/70R42, inflation pressure 0.34 MPa, rear: 520/85R34-R1, inflation pressure: 0.32 MPa) was used as a comparison with the standard picker fitted with dual tyres.

Soil bulk density (SBD) measurements were performed to the full depth (80 cm) before and after traffic (centreline of tyre) to determine how the depth of compaction was affected by tyre inflation pressure. Cone penetrometer resistance was measured by pushing a cone (125 mm^2 base area, 30° apex angle) into the soil to a depth of 0.75 m at constant speed, and digitally recording the force at 0.01 m depth increments based on ASAE Standards (1999). Measurements were conducted along transects perpendicular to the direction of travel at 0.2 m spacing to capture differences in soil penetration resistance within wheeled and non-wheeled soil. Shear strength indicates the maximum strength of soil at which point significant plastic deformation occurs due to an applied stress, and it was measured using a torsional shear vane (Franti et al., 1985). Soil pits were excavated and torsional shear strength measured on the wall of the pit based on a grid sampling technique with measuring points spaced at 0.1 m both laterally and at depth (depth range: 0-0.8 m). Surface soil strength was also assessed using a drop-cone penetrometer (Godwin et al., 1991). The technique consists of releasing a 2 kg, 30° apex angle cone from a height of 1.0 m, and measuring its penetration into the soil (n=10). Measurements of soil bulk density, penetration resistance, and torsional shear vane and drop cone penetrometer were taken from trafficked and non-trafficked soil. Soil moisture content was also determined to aid interpretation of soil strength measurements (Ayers, 1987). Rut profile measurements were conducted using a profile-meter based on the approach reported in Vero et al. (2014).

Results and discussion

This investigation was conducted to evaluate the merit of tyre deflation in managing soil compaction. In implementing this technique John Deere dealers strongly advised that we not reduce the tyre pressure of the JD7760 at all as the machine already operates close to the tyre limits. Thus, results

below should be used to infer the usefulness of low ground pressure tyre systems for a machine of this weight, rather than for implementation with standard tyres.

Soil bulk density

On average, over the measured depth, a single pass of the picker increased SBD by approximately 8% and 2% when tyres were operated at the recommended and reduced inflation pressures, respectively (Figure 1). Overall changes in SBD after traffic were only significant in the 0-0.25 and 0-0.50 m depth intervals for the reduced and standard pressure tyres, respectively. However, the inner tyre of the dual configuration, operated at the recommended inflation pressure, induced a significant increase in SBD to 0.8 m deep compared to that prior to traffic but differences before and after traffic were progressively smaller at greater depths. It was also observed that the rear tyre caused additional compaction to that of the leading (inner) tyre even when these were operated at reduced inflation pressure. This may be attributable to the high load on the rear axle and the tyres dimensions. This effect was not observed when the leading inner tyre was operated at the recommended inflation pressure because the compaction caused by this tyre was relatively high and therefore prevented the rear tyre from causing additional damage. Despite this, overall compaction caused by the inner (front) tyre at reduced inflation pressure was lower compared with the same tyres at standard pressure. For the outer tyres, reduced inflation pressure significantly reduced the depth of compaction to approximately the top 0.2 m of the soil profile. The implication of this observation is the additional tillage energy (draught) that would be required to remove deeper compaction prior to establishing the following crop when tyres are operated at relatively higher inflation pressure.
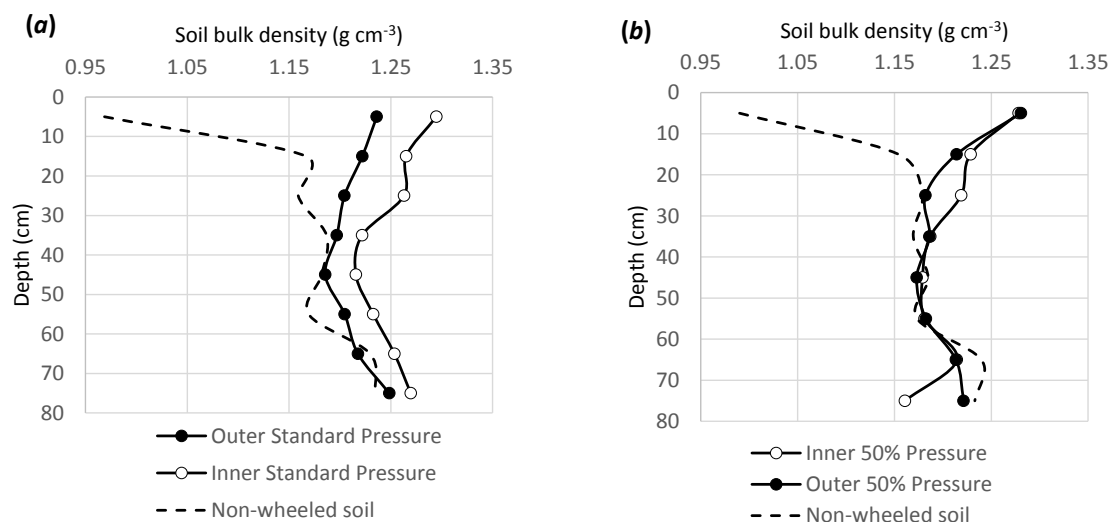
Figure 1. Soil bulk density changes after a single pass of a JD7760 cotton picker fitted with tyres at (a) the recommended and (b) reduced inflation pressure, respectively.

Soil strength

Shear strength measurements conducted with the shear vane are shown in Figure 3. There were significant differences ($p<0.05$) in shear strength depending on the tyre configuration used. Overall, shear strength measurements conducted at the centreline of the rut were higher ($p<0.05$) in permanent traffic lanes (single-wheeled machine) compared with the dual tyres arrangement, which is explained by consolidation of wheel lanes over multiple passes with farm vehicles. Overall, shear strength was higher when dual tyres were used at the manufacturer's recommended inflation pressure compared with reduced pressure (Figures 3a-d). However, differences were significant within the 0-0.4 m depth interval on both soil conditions (p-values <0.05). Below that depth, differences in shear strength were non-significant regardless of the soil moisture condition (p-values >0.05). A single
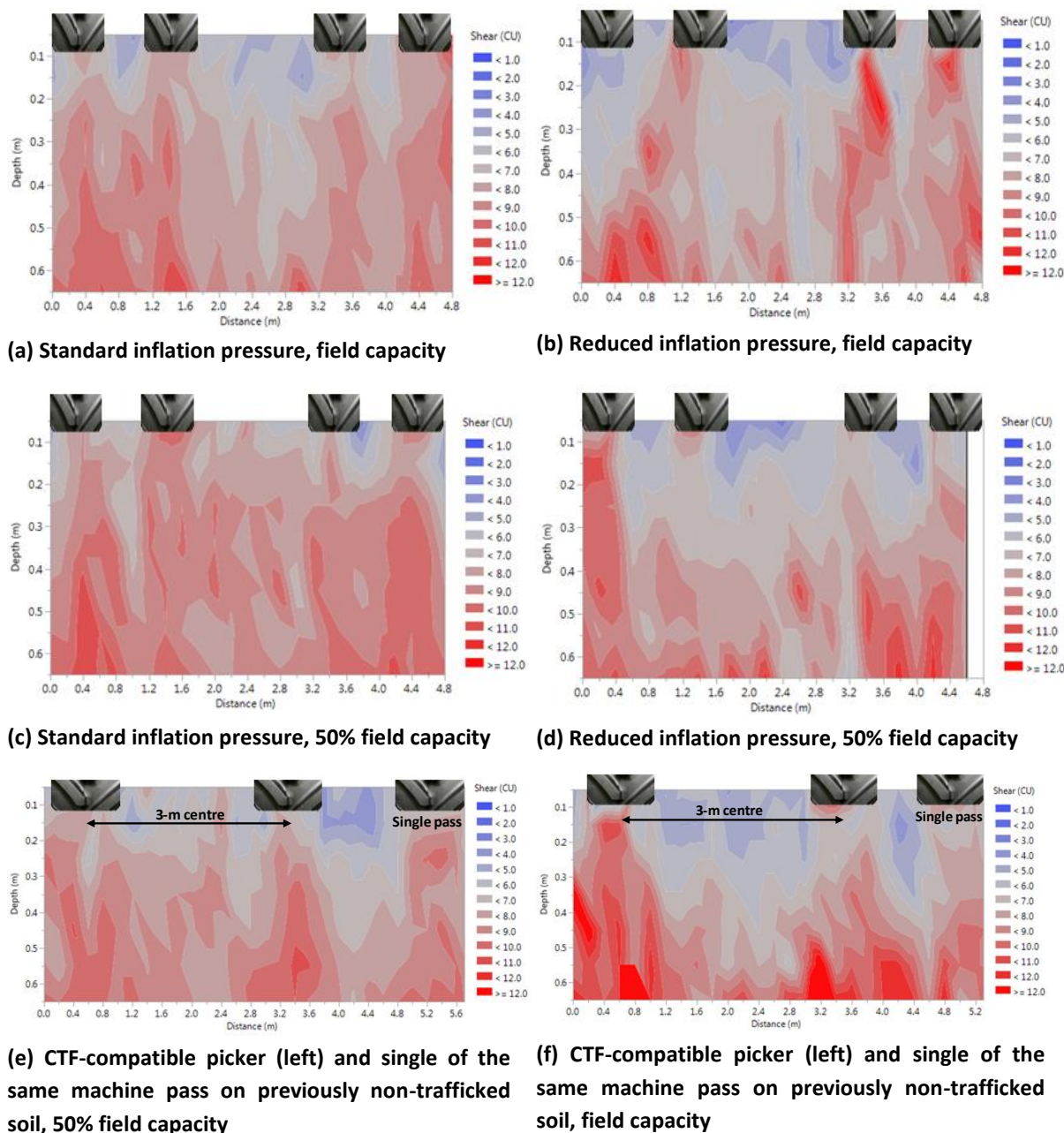
pass of the CTF-compatible machine over a non-wheeled soil resulted in similar ($p>0.05$) shear strength compared to that recorded on permanent traffic lanes. This was observed after traffic on both the field capacity and 50% field capacity soil moisture conditions (Figures 3e-f). This result reinforces observations reported in earlier studies in that most of the traffic-induced compaction can occur after a single traffic event (e.g., Fekete, 1972; Raghavan et al., 1976; Raper, 2005). The rate of change in soil strength before and after traffic is also dependent on the initial strength prior to traffic (Paz and Guérif, 2000; Ansorge and Godwin, 2007), which in our study is equivalent to that of the non-trafficked soil.

The results presented in Figure 3 show that differences in soil strength between trafficked and non-trafficked soil were greater when the soil was trafficked at field capacity compared with the drier soil condition, which had a relatively higher carrying capacity. The effect of traffic at depth greater than about 0.40 m appears to be relatively less dependent on tyre inflation pressure and due mainly to the high axle loads (Raper et al., 1995a-b). Changes in shear strength recorded at the centreline of the machine (between tyres) were not influenced by tyre inflation pressure. Therefore, lateral soil displacement was only significant at locations near-the-edge of the tyres, which agrees with related studies (e.g., Antille et al., 2013).

Measurements of surface soil strength determined with the use of the drop-cone penetrometer were consistent with values recorded with the shear vane. The highest strength at/near the surface was recorded after a single pass of the CTF-compatible picker over the untrafficked soil, which yielded similar ($p>0.05$) values to those recorded on the permanent traffic lane (mean penetration: 3.6 cm, moisture content: 44.7% v/v). Differences in surface soil strength between-tyres at the standard and reduced inflation pressures were only significant for the inner tyres of the dual configuration ($p<0.01$). This may be explained by additional compaction caused by the rear tyre when the picker was operated at the standard pressure. Similar conclusions are reported by Ansorge and Godwin (2008) for combine harvester tyres.

The non-wheeled soil between-tyres showed differences in drop-cone penetration depending on the inflation pressure at which the dual tyres were operated ($p<0.05$). The lower inflation pressure system exhibited higher drop-cone penetration between-tyres compared with the standard pressure system. These differences were not observed with the torsional shear vane and suggested that this method is more sensitive to small changes in strength possibly cause by lateral soil displacement near-surface. Similar observations were reported by Godwin et al. (1991) and attributed the benefits of the drop-cone device to the relatively larger volume of soil that is displaced in every drop compared with the shear vane, thereby providing a more reliable measure.

(a) Standard inflation pressure, field capacity

(b) Reduced inflation pressure, field capacity

(c) Standard inflation pressure, 50% field capacity

(d) Reduced inflation pressure, 50% field capacity

(e) CTF-compatible picker (left) and single of the same machine pass on previously non-trafficked soil, 50% field capacity

(f) CTF-compatible picker (left) and single of the same machine pass on previously non-trafficked soil, field capacity

Figure 3. The effect of tyre configuration, tyre inflation pressure and soil moisture conditions on soil strength following traffic with a JD7760. Note that in (e) and (f), the single-wheeled machine (CTF-compatible) was driven over permanent traffic lanes. An extra pass was also performed to determine the effect of this tyre configuration on previously non-trafficked soil, which is denoted by the 'single pass' treatment shown on the right-hand side of the picture.

Implications for tillage draught

Draught (horizontal force) increases significantly and in a near-linear fashion with increasing tillage depth (Wheeler and Godwin, 1996; Tullberg, 2000). The relationship between tillage draught and depth for high clay content soil (≥60%) is shown in Figure 2 based on simulated results derived from the application of a tillage force prediction model developed by Godwin and O'Dogherty (2007). Although this model has not been validated for Vertosols, these results serve to exemplify the relative tillage effort that may be required to remove either shallower or deeper compaction for a soil with similar mechanical properties.
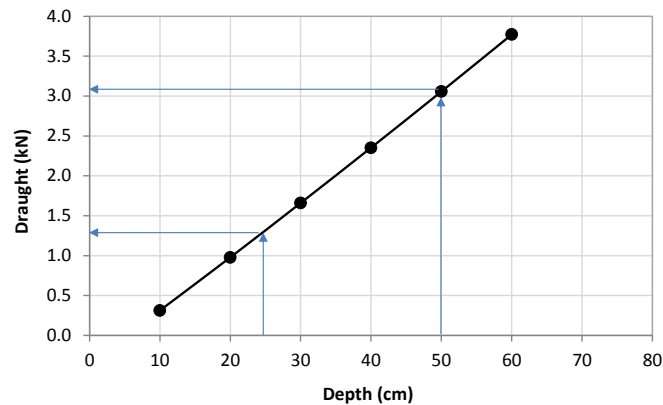
Figure 2. The relationship between predicted tillage draught and depth of tillage for a high (60%) clay content soil based on the tillage force prediction model developed by Godwin and O'Dogherty (2007).

Soil disturbance

The cross sectional areas of the ruts created by tyres operated at the standard and reduced inflation pressures, and the tyres used in the machine compatible with the CTF system are shown in Figure 4. Overall, there were significant differences in the ruts' cross sectional areas depending on the tyres' settings and configurations ($p<0.05$). The dual tyres operated at reduced inflation pressure provided increased flotation compared with the same tyres at the standard pressure. Increased tyre deflection at lower inflation pressure marginally increased the width of the rut but reduced its depth at the centreline of tyre ($p<0.05$). Therefore, cross sectional area remained smaller compared with the same tyre at the standard pressure. Relative differences between-tyres were similar in both soil conditions (field capacity and 50% of FC, respectively). The tyres used in the CTF-compatible picker were operated at the standard pressure in both the front and rear axles, respectively. The relatively large cross sectional area in this treatment is explained by multiple passes with farm vehicles, including tractors and planter, sprayer, and picker and trailer, and by increased section width (0.62 m) compared with the dual tyres (0.52 m). Despite this, the area affected by traffic on a field-scale basis compared with the dual tyre configuration operated at the standard pressure is approximately half. A single pass of the CTF-compatible picker over previously non-trafficked soil produced similar disturbance to that observed with dual tyres at the recommended pressure, and effectively the same cross sectional area to the permanent traffic lanes of the CTF system. This result agrees with shear strength data and highlights the risk of damage to the soil when high axle loads are used on relatively soft soil conditions.
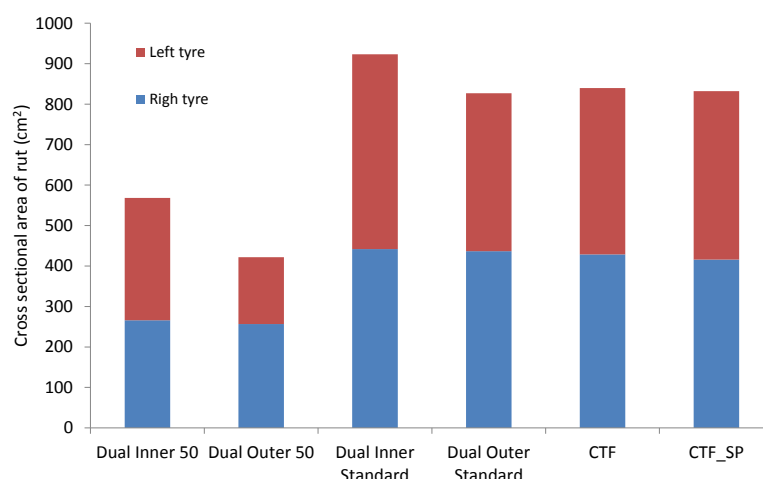
Figure 4. *The effect of tyre inflation pressure of cross sectional area of the rut after traffic with a JD7760 cotton picker. Use n=3, p<0.05, LSD (5% level) =64.6 cm². Nomenclature: Dual Inner 50 and dual outer 50 (reduced tyre inflation pressure to 50% of recommended by manufacturer), dual inner and dual outer standard (inflation pressure recommended by manufacturer, CTF is permanent traffic lane of a 3-m centre controlled traffic system, and CTF_SP is a single pass of the CTF-compatible picker over previously non-trafficked soil.*

Conclusions and future research requirements

The main conclusions derived from this work are:

- The main benefits of the controlled traffic system appear to be the significant reduction in soil disturbance. The single tyres arrangement produced similar cross sectional area to the dual tyres configuration however the footprint at the field-scale is approximately half. Additional benefits may be expected from reduced rolling resistance and wheel-slip due to traffic on consolidated wheel lanes compared with the dual tyre system on relatively softer soil, which has been reported for combine harvesters (e.g., Luhaib et al., 2016),

- Reduced tyre inflation pressure showed some advantages in terms of compaction alleviation compared with tyres operated at the standard pressure. The main advantages were reduced soil disturbance (cross sectional area of rut) and reduced soil strength, particularly at relatively shallow depths (<0.3 m),

- Measurements of soil bulk density generally agreed with soil strength and soil disturbance but suggested that benefits gained by lowering contact pressure may be offset by high axle loads, particularly the rear axle. This is due to the cyclic loading and high weight transfer onto the rear tyres, which are smaller and therefore operate at higher inflation pressure. This, in turn, increases contact pressure and results in additional compaction to the dual leading tyres,

- The practical and safety aspects of operating tyres at lower than the pressure recommended by manufacturers need to be observed, including increased wear and tear. However, future developments in tyre technology may enable safe operation at lower inflation pressure, potentially used in conjunction with central tyre inflation control systems.

- The use of low ground pressure systems may be a cost-effective alternative to CTF, particularly if they can be used together with shallow or minimum tillage techniques. For cotton, this may be a practical engineering solution to manage compaction given the incompatibilities that exist between crop row/rotation and machine configurations, which may create a barrier to adoption of CTF.

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Efficacy of delaying defoliation to mitigate compaction risk at wet harvest

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Introduction

Soil compaction susceptibility is governed by its mechanical strength, which is most sensitive to soil moisture and clay content (Al-Shayea 2001), whereby compaction susceptibility is greater with increased clay content and increasing to optimum soil moisture. Australian cotton is predominantly grown on Vertosol soil (Isbell 2002; McKenzie 1998) with clay content >>30%, meaning that small changes in soil moisture will result in large changes in compaction risk.

Unfortunately, there is perceived pressure on farmers to traffic soils at less than ideal field moisture conditions, in order to overcome the financial implications of delayed operations. The resulting soil degradation however can be highly detrimental to the farming operation. In irrigated fields, soil moisture can be controlled via irrigation regime to be sufficiently dry prior to harvest, while in dryland systems the soil is usually sufficiently dry by virtue of the season and climate. However, where unforeseen rainfall events occur the soil can be rewet substantially within the major rooting zone, presenting high-risk condition for soil compaction due to traffic. Strategies that deal with managing soil moisture to reduce the compaction risk need to be investigated.

Moisture is removed from the soil profile in three processes, namely: deep drainage, evaporation and transpiration. Due to the high frequency of meso- and micro-pores within Vertosol soils, it is not viable to rely on drainage for removal of rain-induced soil moisture prior to traffic. Therefore, the combined effects of evaporation and transpiration (evapotranspiration) are the largest contributing factor to soil moisture removal under such circumstances. By utilising the natural moisture demands of a cotton crop towards the mature end of the season, it may be possible to harness the plant as a pump to dry down the soil profile and reduce compaction risk. Thus, this chapter investigates a novel approach whereby cotton defoliation is delayed at harvest in high-risk weather conditions, allowing evapotranspiration to dry down the soil profile as a strategy to minimise detrimental soil compaction from harvesting operations.

Methodology

Field Trial

The site selected for the trial was located on the Darling Downs at Aubigny, QLD, (27°28'30.17"S 151°37'41.72"E). The topography of the site consisted of a shallow slope and was located on an alluvial floodplain. The dominant soil type was a Black Vertosol high in 2:1 clay minerals, which is the predominant cotton growing soil in Australia (McKenzie 1998). Supplementary irrigation was used on-site due to limited rainfall, which resulted in two irrigations being made during the season. These occurred as a i) pre-sowing event, and ii) within-season event.

Experimental Design

The original experimental design consisted of a 2x2 completely randomized block design, which was replicated once down the full length of the field. The treatments were developed such that the proposed management strategy of postponing defoliation could be assessed against the conventional management strategy of defoliating the crop prior to a rainfall event. The applied treatments were binary in the sense that the levels of the first treatment were i) defoliated, and ii) not defoliated; and the levels in the second treatment were i) rainfall, and ii) no rainfall. After a significant rainfall event

of 145 mm occurred on the site three days prior to the planned simulated rainfall event, the 'no rainfall' treatment was removed. The 'no rainfall' treatment was therefore omitted, which resulted in the trial consisting of 2 treatments (defoliated and undefoliated). This resulted in doubling the number of replicates for each treatment to 4.

The treatments were randomly assigned to the experimental units to reduce the chance of biased results. The block was replicated once down the field, which allowed each treatment group to be replicated a total of 2 times. The experimental units were blocked in a way to reduce the within-group variability, due to the spatial variations in soil properties and a possible moisture gradient down the field (an artefact of irrigation). The plots were designed such that they captured the full frontage, and thus impact, of one pass of the John Deere 7760 (JD7760) cotton picker (i.e. 6 rows, 7 furrows). The constructed plots were also sufficiently wide enough in the direction of JD7760 travel to reduce the edge effects. The final experimental design is shown in Figure 1.

In order to measure the soil moisture drawdown in each plot, Decagon® EC-5 moisture sensors were installed at depths of 10 cm, 30 cm and 60 cm. The sensors were installed in the center of each plot underneath the differential furrow (furrow where the machine differential passed over), which was thought to be most representative of the entire plot. The sensors used were selected due to their research grade accuracy and the availability of factory calibration curves. The sensors could measure volumetric water content with an accuracy of 3-4% (Decagon, 2015). The sensors were installed earlier in the season on the 28/03/2015. This allowed sufficient time for the sensors to settle, as well as giving them the opportunity to capture as much soil moisture drawdown data as possible. The sensors within each plot were connected to a Decagon® Em50 data logger that was setup to log data at hourly intervals. The data was retrieved from the loggers using a USB link and Decagon software.
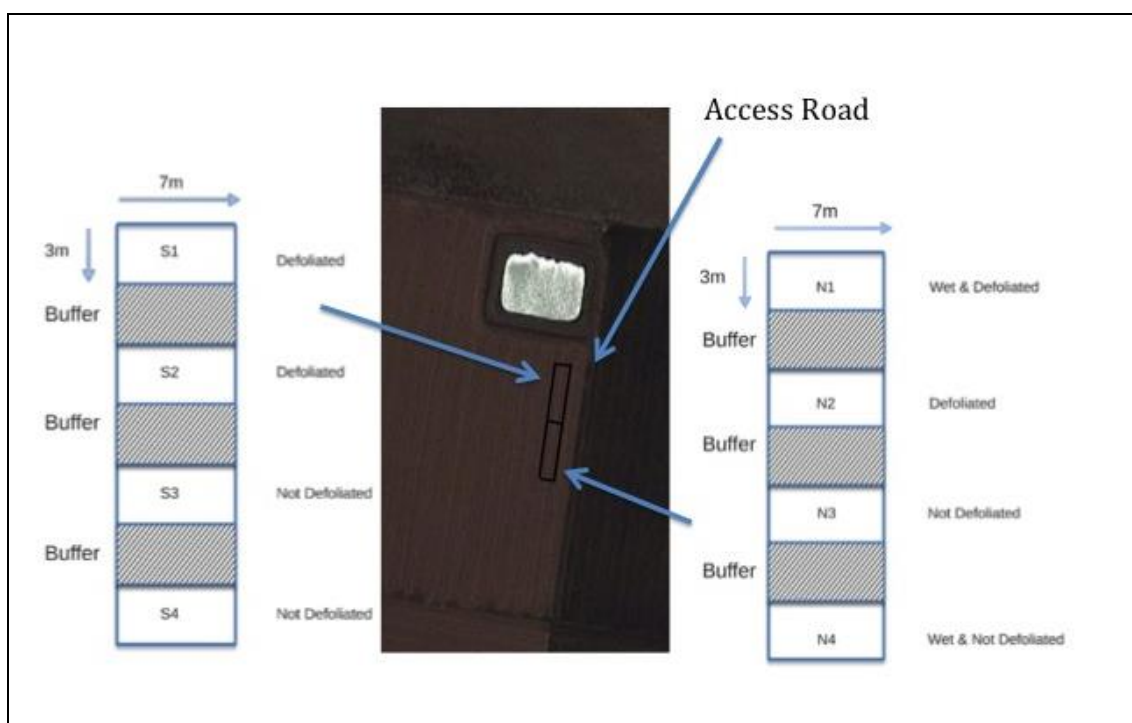

Figure 1 Trial site layout of experimental blocks and treatment plots. Trial code 'Nx' represents trial plots within the north block and trial code 'Sx' represents trial plots within the southern block. 'x' pertains to the treatment and replicate number. (Google Earth 2013).

In order to simulate the postponed defoliation for the corresponding treatments' plots, whilst not impacting the grower's field operations, tarps were used to manually cover the corresponding plots.

This created a 'defoliation black-out', which was done such that the spray mist could not reach the leaf surface and the plants were therefore left unaffected. Figure 2 shows photos of this, with the covered plots on the left hand side and the visual results on the right hand side. The tarps were installed a day prior to the defoliation and removed the day following. The crop was defoliated twice, first by a ground based spray-rig on the 24/04/2015 and secondly via crop-duster (plane), 12 days later on the 6/05/2015.

(A)   (B)

Figure 2 (A): Manual defoliation 'black-out' by covering up treatments. (B): resulting effects from (A), i.e. Undefoliated plots in a defoliated crop

Soil Moisture Modelling

The primary purpose of the field experiment was to obtain a soil moisture dataset that could be used to validate APSIM in modelling the proposed management strategy over time and in a number of cotton growing regions. The APSIM model was the primary model used in the approach to simulating soil moisture conditions in an irrigated cotton scenario. This approach was chosen as it provided specific information for cotton and related moisture drawdown specifically to the plant. APSIM was selected to simulate the proposed management strategy after consultation with industry professionals (J Whish 2015, Pers. Comm 14 May) from CSIRO (Commonwealth Scientific and Industrial Research Organisation).

The climate data selected for use within the model was obtained from the Queensland Government's enhanced climate database, SILO (Long Paddock), which is hosted by the Science Delivery Division of the Department of Science, Information Technology and Innovation (DSITI) (Queensland Government 2015). One of the benefits of using SILO climate files is that there is a range of infilling techniques present which use other sources of data to infill the missing data for the chosen site.

Once the model was developed and validated, it was used to simulate the proposed management strategy over an extensive period of time for the Aubigny site. The model was also used to simulate the soil moisture dynamics towards the end of season at various other cotton growing locations to assess the proposed management strategy. These sites were Goondiwindi (QLD), Moree (NSW) and Warren (NSW), which represent major centres within the Australian cotton industry. The simulation was run for all years where climatic data was available from SILO, which resulted in a 116-year simulation between 1900 and 2015 at daily time steps. The purpose of the simulation was to assess the merit of the proposed management strategy in years where field moisture conditions at 15–30 cm depth were highest at the time of harvest. Therefore, the simulation's output identified the years which possessed the top 20% of field moisture conditions at cotton harvest. Once ascertained, these years were simulated once again, using the delayed defoliation date instead. From this, the difference in field moisture conditions were investigated. The climate and soil files for each site were obtained from SILO and APSIM's APSoil on the merit of the most appropriate soil parameters. These files are shown in Table 1.

Table 1 Site-Specific Soil and Climate Files

Location	APSoil File	Primary SILO Station
Aubigny, QLD	Black Vertosol-Mymbilla (Bongeen No001)	Oakey Airport
Goondiwindi, QLD	Grey Vertosol (Goondiwindi No 219)	Goondiwindi Post Office (41038)
Moree, NSW	Black Vertosol (Moree No 235)	Moree Airport
Warren, NSW	Medium Clay (Warren No 705)	Warren Auscott

Results

Soil Moisture Drawdown and Resulting Bulk Density After Traffic

From the soil moisture drawdown data presented in Figure 3, the rainfall event on the 2&3/05/15 is clearly evident. The moisture data prior to the rainfall event suggests that the undefoliated and defoliated cotton treatments maintained their relativity prior to defoliation. However, the rainfall event effectively equilibrated the system, recharging all depths to be highly comparative at the respective treatment and depth. After the rainfall event, there was greater soil moisture drawdown at shallower depths than deeper ones, as would be expected. This is evident across all treatments. Given the climatic conditions, the drawdown at the 30 cm depth behaves similarly between treatments.
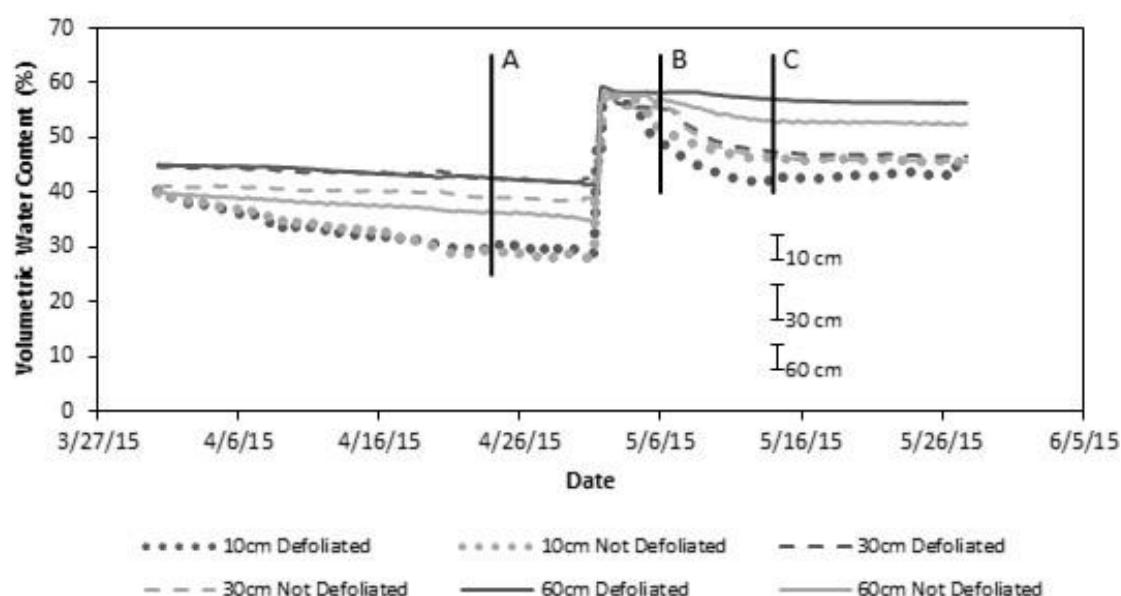

Figure 3 Soil moisture drawdown across treatments at depth. Where point (A) represents the date of first defoliation, (B) represents the data of second defoliation and (C) represents the date of harvest. The error bars presented are for an ANOVA at 95% confidence interval.

This suggests that there is a balance between the evaporation effects in the defoliated treatment and transpiration effects in the undefoliated treatments. At the 10 cm depth however, the moisture content at harvest was greater in the undefoliated treatments, suggesting that moisture loss due to soil evaporation in the surface layer was reduced in these treatments; likely due to foliage cover. The lack of foliage in the defoliated treatments would have allowed for a greater amount of radiation and wind to reach the ground, thus increasing the evaporative potential.

The soil moisture drawdown at the 60 cm depth appeared to be greater in the undefoliated treatments, suggesting that the main component of soil moisture removal was due to transpiration affects. Although this difference was identified, it did not prove significant at the 90% confidence level.
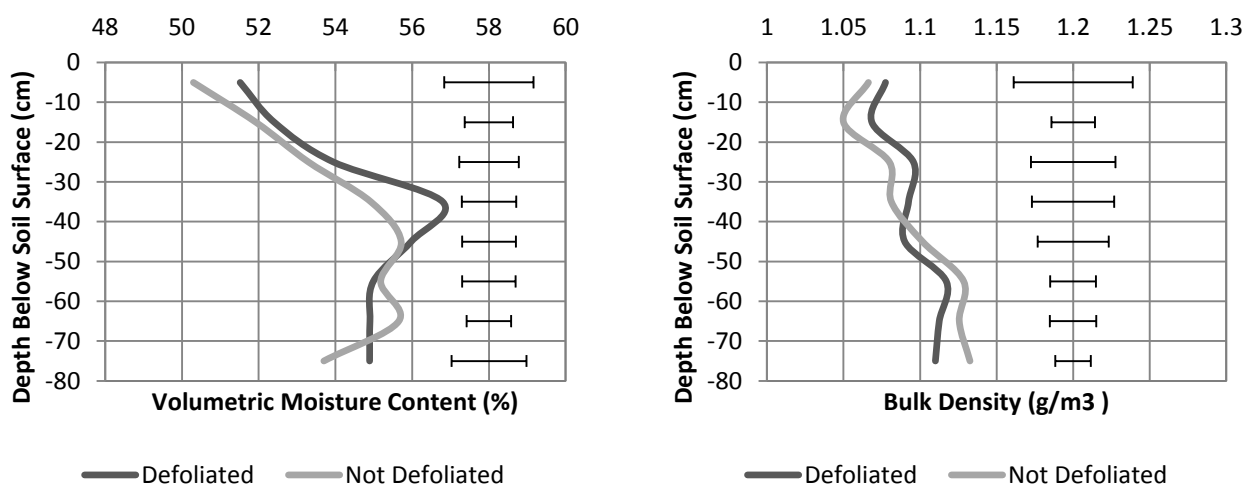
(A)   (B)

Figure 4 (A) Volumetric moisture content at depth between treatments before traffic. Bars located at depth increments are Tukey's HSD error bars at 95% confidence interval (α=5%). (B) Bulk density at depth between treatments after traffic Bars located at depth increments are Tukey's HSD error bars at 95% confidence interval (α=5%).

Figure 5 (A) depicts the soil moisture immediately prior to harvest as measured directly. On average, the soil moisture content in the undefoliated treatments were always less than the defoliated treatments in the upper soil layers of 0–45 cm, which while not a significant result is worth noting. The soil core data effectively reinforces the lack of significance in soil moisture drawdown between the treatments at the 10, 30 and 60 cm depths. From Figure 5 (B), it appears that the mean bulk density in the undefoliated treatments was less than that of the defoliated treatments in the upper soil layers (0–40 cm), which again whilst not a significant result, is worth noting. The lower depths appear to be relatively more comparable in terms of bulk density between treatments, with the exception of the 75 cm depth, where the average bulk density of the undefoliated treatments appeared to less than that of the defoliated treatments. The soil bulk density data by treatment therefore reflects the results for soil moisture at the time of traffic, whereby no significant difference in soil moisture resulted in no significant difference in resultant traffic induced soil bulk density, whilst a difference was still detected. Interestingly, the correlation between soil moisture prior to traffic and the resulting bulk density following traffic at all depths was found to be R^2=0.85, which proves a strong correlation.

Changes in Soil Structure due to Traffic

Soil pit face images for the defoliated and undefoliated treatments are presented in Figure 5 and Figure 6 respectively. The images shown are for the first replicate of each treatment. It is important to note that at the time of harvest the soil volumetric moisture content was sufficient to have induced complete swelling of the soil profile. Under the trafficked furrow, the soil structure appeared to be massive, with granular structure less evident to a depth of ≈40 cm, as compared to the untrafficked treatment. Pit observation suggested a reduction in the distribution of the macro pores, in comparison to the soil profile underneath the untrafficked furrow, which was more friable and had a greater pore distribution. Importantly, the defoliated treatment clearly exhibited platy soil structure in the 40–70 cm depths that was not evident in either the untrafficked soil profile or the undefoliated soil profile

that had been trafficked (Figure 5 (A)). For both of the traffic furrow profiles the structure of the soil was easier to make out from the images, which was as a result of the consolidation of material, as evidenced by ease of cleaning pit faces during preparation for photography.
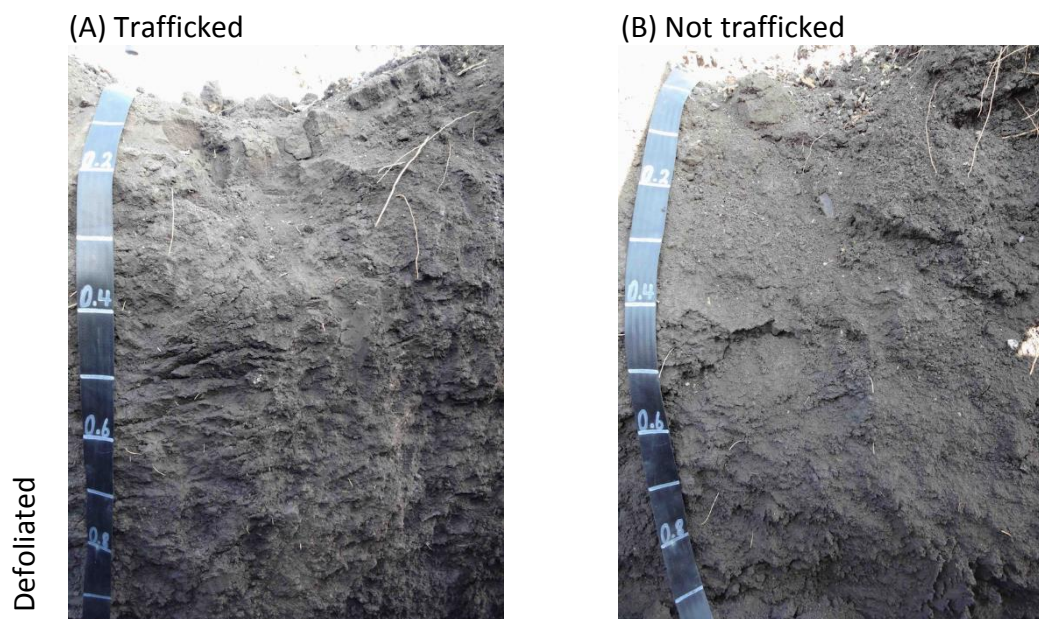
(A) Trafficked   (B) Not trafficked

Figure 5. Pit face images for fist replicate of defoliated treatment – (A) Under inner wheel traffic furrow; (B) Under untrafficked furrow. The tape measure in the image has units of meters
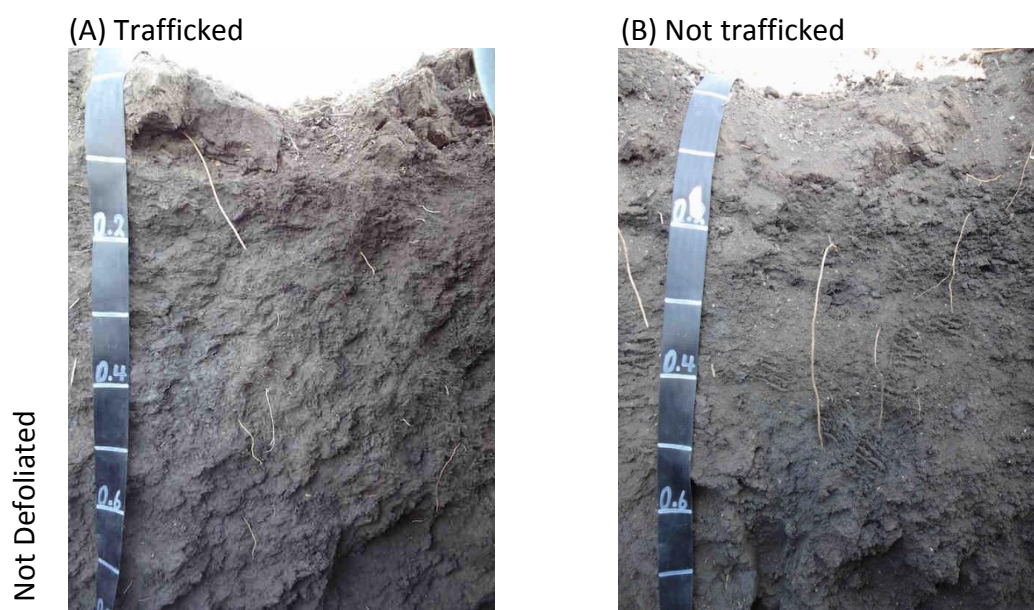
(A) Trafficked   (B) Not trafficked

Figure 6 Pit face images for fist replicate of undefoliated treatment – (A) Under inner wheel furrow; (B) Under untrafficked furrow. The tape measure in the image has units of meters.

Rut Depth Resulting From Traffic

The average rut depth results presented in Table 2 show a significant increase in rut depth after traffic in both treatments under the inner wheel traffic furrow, as would be expected. However, a moderate significant difference was detected between the treatments after traffic, when testing at the 85% confidence interval. Although the confidence interval of 85% is not conventional, it was considered to be acceptable due to highly variable field conditions (Webster 2007). This suggests that the observed reduction in soil moisture in the top 45 cm of the undefoliated treatments resulted in a reduced rut depth after traffic; and whilst the extent of this is minimal (i.e. <2 cm on average), it is a significant result in itself. An increase in rut depth means the soil profile was compressed, thus resulting in a reduction in void spaces and production of a massive soil structure, reflecting the visual results obtained from the soil profile images, which display a massive soil structure caused by compression.

Table 2. Average rut depth for inner wheel traffic furrow by treatment. '' in rows identifies a significant difference in rut depth at p<0.05 whilst 'b' in columns identifies a significant difference in rut depth at p<0.15*

Treatment	Before	After
Defoliated (cm)	12.48	19.44*a
Undefoliated (cm)	12.29	17.88*b

Soil Strength as Influenced by Traffic

A number of penetration resistance maps were created for each of the replicates, however for convenience, two penetration resistance contour plots are produced in Figure 7 below. No difference was detectable between treatments however there was generally an increase in soil strength directly below trafficked furrows to depth, which contrasts clearly with adjacent untrafficked furrows. Wheels showed a clear impact for both treatments to a depth of ≈25 cm with indication that soil strength increases directly under the wheels to a depth of ≈65 cm. Interestingly, associated with traffic rows is an expression of low soil strength at ≈67–70 cm, irrespective of treatment.

Soil Moisture Drawdown Modelling

For all sites, the soil moisture for the wettest 20% of years at harvest appeared to increase rapidly just prior to harvest, suggesting that rainfall events had occurred just prior to the original harvest date (Figure 8 to Figure 11). By delaying the defoliation and therefore harvest date by two weeks in these years, it was evident that that on average, a reduction in soil moisture could be achieved (refer to Table 3). The magnitude of the reduction in soil moisture over these two weeks varied, however, with depth and location. At all locations, the reduction in soil moisture appeared to gradually increase from the lower layers to the upper layers of soil, with the 0–15 cm depth experiences the largest drawdown across all locations. This may suggest that soil evaporation is the largest contributing factor to soil moisture removal for both the defoliated and undefoliated plants.

A combined effect between soil evaporation and plant transpiration would be expected in the 15–30 cm depth, due to the increased root density and therefore plant water uptake. This combined affect however has less of an influence on the soil moisture drawdown in comparison to the upper layers. At the lower depths (30–60 cm), the effect of evaporation is significantly reduced and the primary source of moisture removal is due to plant water uptake and deep percolation. The magnitude of drawdown at this depth across all locations was quite small (0.41–1.35%; refer to Table 3), which suggests the plant water uptake at this time of year does not have a significant effect on soil profile dry-down over a 2-week period.
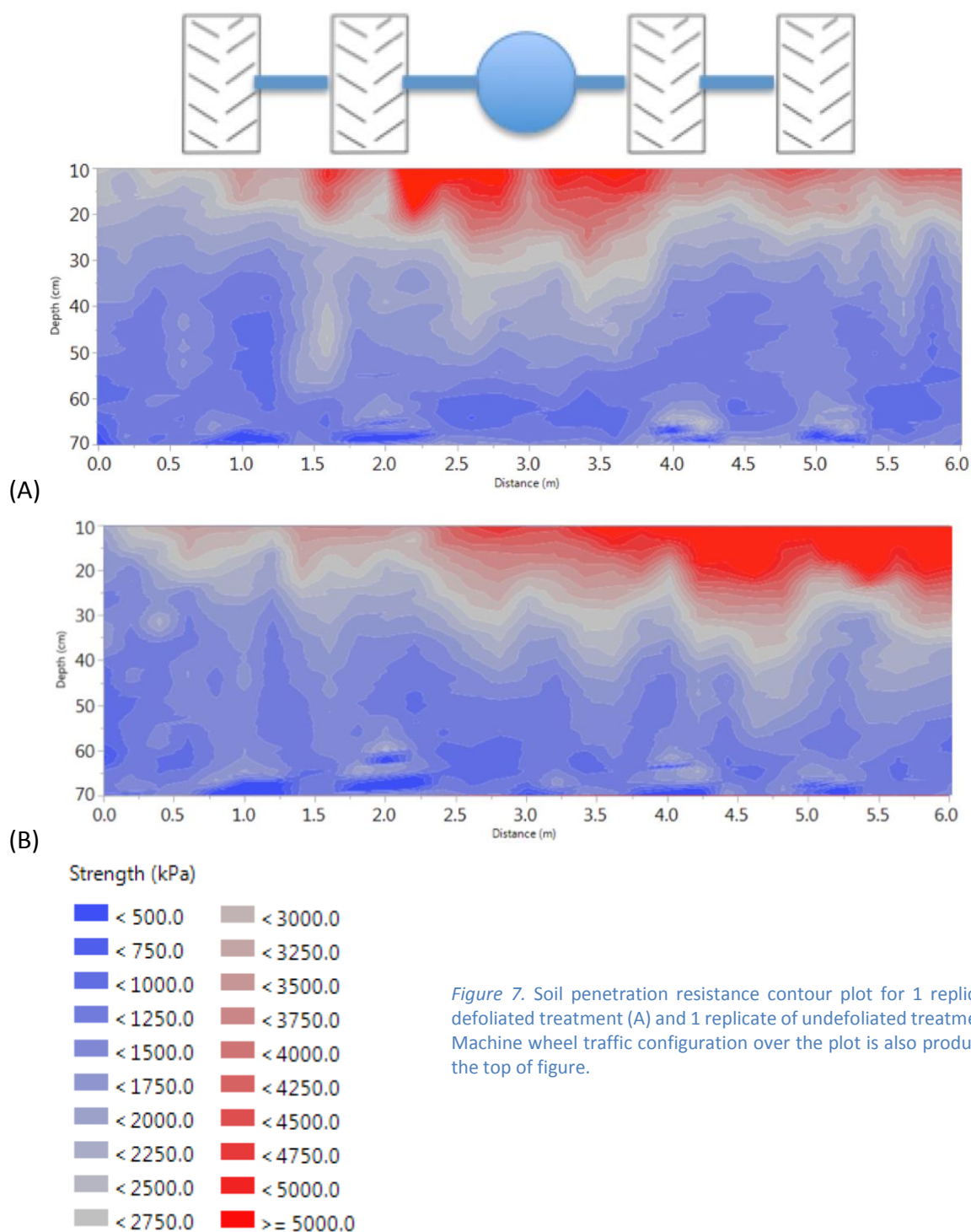
Figure 7. Soil penetration resistance contour plot for 1 replicate of defoliated treatment (A) and 1 replicate of undefoliated treatment (B). Machine wheel traffic configuration over the plot is also produced on the top of figure.

A strong relationship was observed when comparing the magnitude of the soil moisture drawdown across locations to the average climate statistics presented in Table 4. From this table, it was shown that soil evaporation in the upper layer of soil (0–15 cm) increased with increases in daily average maximum temperatures. In general, this affect was also seen at all depths across all locations. This effect would be expected as increases in temperature results in increases in evaporative demand (Allen, Pereira et al. 1998).
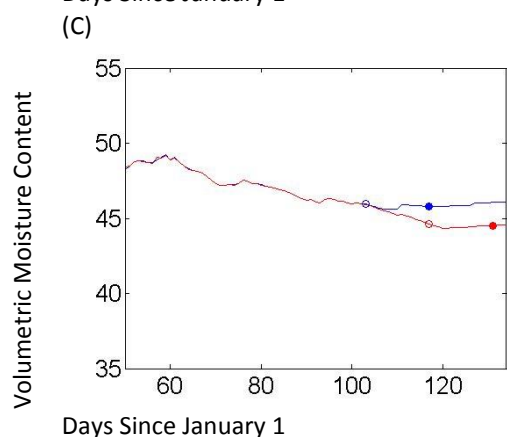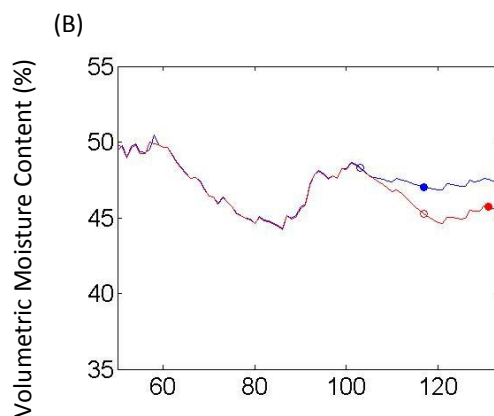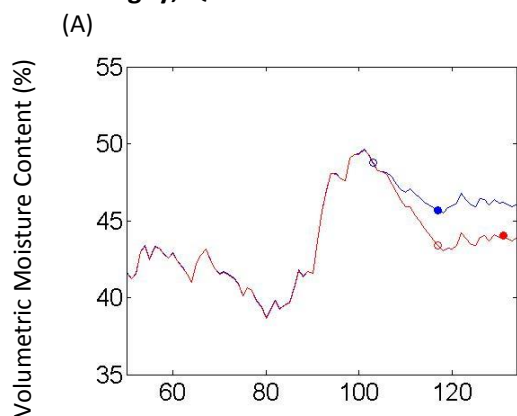
Aubigny, QLD

(A)

(B)

(C)

Figure 8. Average soil moisture conditions of the wettest 20% of years during the mature stage of the growing season at Aubigny, QLD. Where —— is soil moisture for original defoliation date, —— is soil moisture for delayed defoliation date, • is postponed harvest, º is postponed defoliation, • is original harvest, º is original defoliation for (A) 0–15cm, (B) 15–30cm and (C) 30– 60cm depths

Goondiwindi, QLD

(A)

(B)

(C)

Figure 9. Average soil moisture conditions of the wettest 20% of years during the mature stage of the growing season at Goondiwindi, QLD. Where —— is soil moisture for original defoliation date, —— is soil moisture for delayed defoliation date, • is postponed harvest, º is postponed defoliation, • is original harvest, º is original defoliation for (A) 0–15cm, (B) 15–30cm and (C) 30– 60cm depths

Moree, NSW

(A)
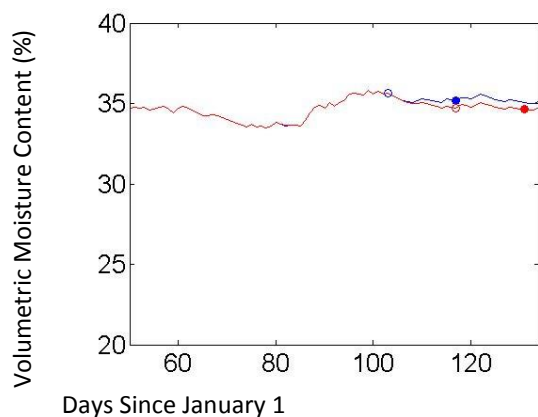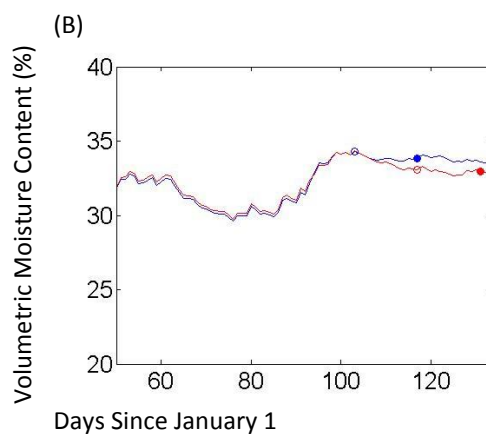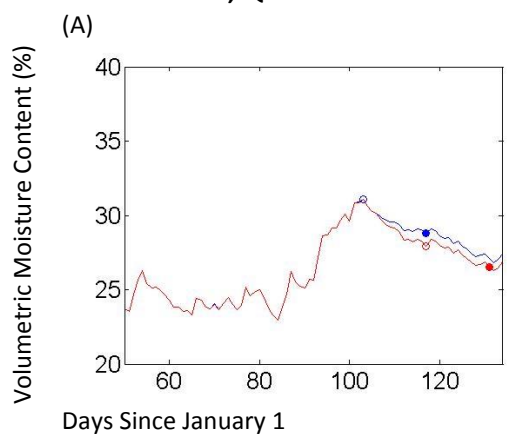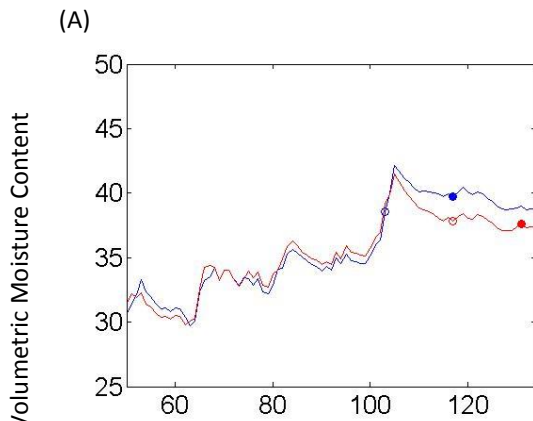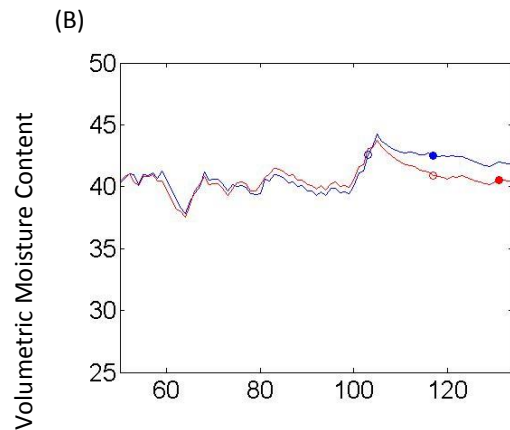

(B)

(C)
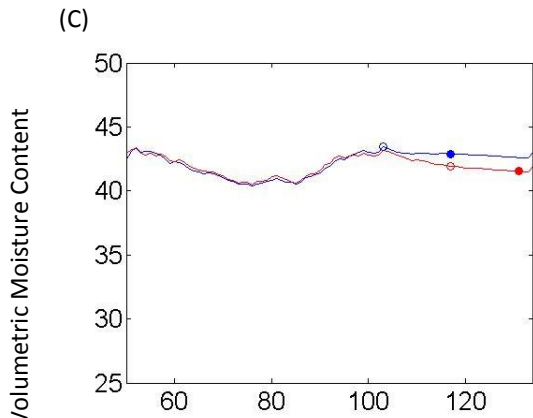
Figure 10. Average soil moisture conditions of the wettest 20% of years during the mature stage of the growing season at Moree, NSW. Where —— is soil moisture for original defoliation date, —— is soil moisture for delayed defoliation date, ● is postponed harvest, º is postponed defoliation, ● is original harvest, º is original defoliation for (A) 0– 15cm, (B) 15–30cm and (C) 30– 60cm depths

Warren, NSW

(A)

(B)

(C)
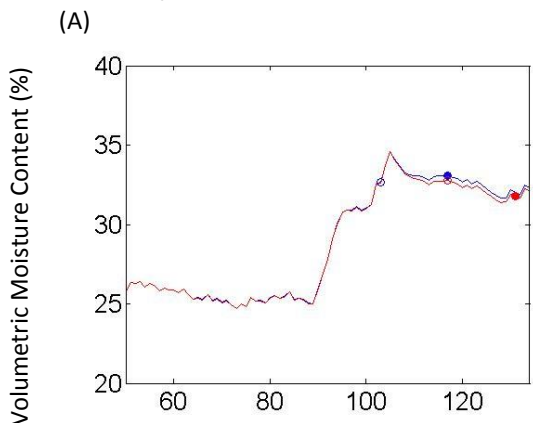
Figure 11. Average soil moisture conditions of the wettest 20% of years during the mature stage of the growing season at Warren, NSW. Where —— is soil moisture for original defoliation date, —— is soil moisture for delayed defoliation date, ● is postponed harvest, º is postponed defoliation, ● is original harvest, º is original defoliation for (A) 0–15cm, (B) 15–30cm and (C) 30– 60cm depths
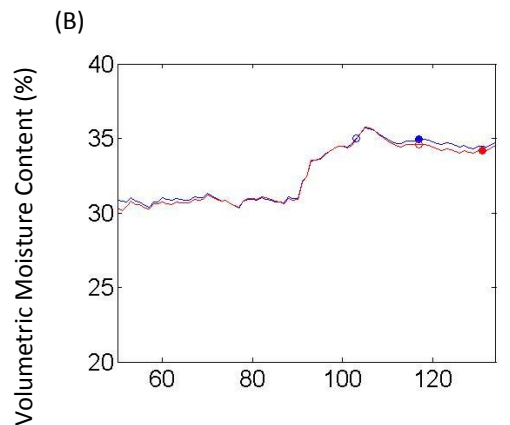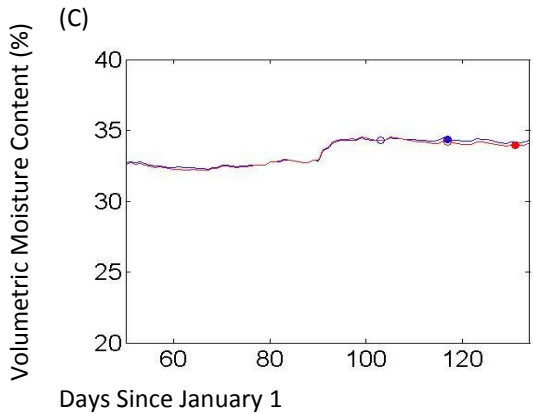
Table 3. Average volumetric moisture content at depth at original harvest date and postponed harvest date by region, as well as the volumetric moisture content (VMC) reduction associated with the undefoliated cotton management strate

Depth (cm)	Moisture Content at Original Harvest (VMC %)	Moisture Content at Postponed Harvest (VMC %)	Difference (VMC %)
Aubigny			
0-15	45.66	44.04	1.62
15-30	47.03	45.72	1.31
30-60	45.8	44.53	1.27
Goondiwindi			
0-15	28.77	26.53	2.24
15-30	33.85	32.97	0.88
30-60	35.19	34.64	0.55
Moree			
0-15	39.76	37.63	2.13
15-30	42.54	40.56	1.98
30-60	42.88	41.53	1.35
Warren			
0-15	33.09	31.79	1.3
15-30	34.94	34.18	0.76
30-60	34.38	33.97	0.41

Table 4 Average climate statistics for April by modelled region. Mean number of clear days refers to the average number of clear days in a calendar month

Region	Mean Daily Maximum Temperature (°C)	Mean Daily Minimum Temperature (°C)	Mean Number of Clear Days
Aubigny, Qld	25.8	11.8	7.8
Goondiwindi, Qld	26.9	13.2	15.3
Moree, NSW	27	13.2	13.9
Warren, NSW	25.7	10.3	N/A

Discussion

Effect of Observed soil moisture drawdown on compaction Risk

Different magnitudes of observed soil moisture drawdown were detected across all treatments and depths, and thus, a difference in the resulting bulk density was also detected. It was identified that the treatment had a direct effect on distribution of moisture removal throughout the profile, with a greater moisture removal in the 0–45cm depth of the soil profile for the undefoliated treatments. Whilst this result did not prove to be significant, it identified that given the climatic conditions, the effect of delaying defoliation can result in a reduction of soil moisture. In the undefoliated cotton, where soil moisture was lower, the compaction risk was decreased, albeit to a small extent, and the resulting observed changes in soil structure were less impeded where this occurred. Furthermore, in support of these observed trends, a strong correlation (R^2=0.82) between soil moisture and resulting bulk density was observed for the 0–45 cm depths after traffic. With such a small difference in average moisture content affecting the resulting bulk density after traffic, the sensitivity of compaction risk to soil moisture is clearly highlighted, and is also supported by previous research (Koolen 1983, Ayers 1987, Soane and van Ouwerkerk 1995).

The reduction in bulk density in the undefoliated cotton was also supported by a reduction in rut depth on average and therefore soil compression. The undefoliated cotton had a rut depth 11% less than that for defoliated cotton. Given the strong correlation between soil moisture and bulk density in the 0–45 cm depth, this is a meaningful result. Furthermore, the effects of increased rut depth in the defoliated treatments were observed when assessing the soil profile structural arrangements. The

wetter soil profile (defoliated cotton) prior to traffic resulted in a more massive pedology towards the surface, as well as clear platy soil structure in the major rooting depth below the massive layer. Platy soil pedology is a clear indicator of soil compaction effects within the soil profile (McGarry 1987, McGarry 1990). Furthermore, the depth range of this platy structure (0–55 cm) was comparable to depth range of the wetter soil profile (0–45cm) in the defoliated treatments. Platy structure was not identifiable in the undefoliated treatments, suggesting that the resulting soil structure of the proposed management strategy was more ideal than the conventional management strategy. Hence, as platy structure was only observed under the traffic furrows, and where defoliated cotton was the treatment, it is deduced that this is an artefact of cotton harvest in 2015 using the JD7760 and that there was greater risk of compaction effects on subsequent crops in this treatment due to the observed changes in pedology.

Creating a platy soil structure should be avoided at all costs as the effect on growing conditions can be highly adverse, whereby soil infiltration can be significantly reduced (Lipiec and Hatano 2003). Occurrence of platy structure is a latent effect, and only identifiable where a soil pit has been dug and visual assessment is able to be made of the soil profile. As observed, the platy soil structure was identified deeper in the soil profile than conventional tillage would be able to address ($\approx$30 cm). Hence, infiltration for subsequent rainfall and irrigation events would be expected to be reduced throughout the profile (Horn and Rostek 2000, Keller and Arvidsson 2004) although the shrink-swell attributes of Vertosols may provide some alleviation (Sarmah, Pillai-McGarry et al. 1996). Efforts to manually remediate the platy layer would require deep ripping to at least 60 cm depth. However, the cost of this may be greater than the benefit, suggesting avoidance of the issue is still the better option.

Furthermore, this project did not assess the change in soil porosity with increase in bulk density. So, whilst platy structure was observed in the defoliated cotton only, results clearly suggest significant compaction in the undefoliated treatment also. This was further observed for the undefoliated cotton, albeit to a lesser extent than the defoliated treatment, in the soil pit observations. Therefore, whilst compaction risk clearly appears to have been reduced for the undefoliated cotton, the extent of reduction does not limit compaction effects (before and after comparison of bulk densities within treatments) to occur only within the cultivation depth. This means that compaction effects will continue to compound throughout subsequent harvest at this site irrespective of employing the delayed defoliation management strategy.

Management Strategy Potential effect for Wider Cotton Industry
The use of real historic data provided a true sense of the range of temperatures that a crop would have been subjected to, towards the mature end of the growing season in wetter years. The modelled data proved a significant reduction in soil moisture for the proposed strategy over all locations, however the magnitude of this drawdown was minimal, and was comparable to the results obtained from the field trial at Aubigny. This suggested that perhaps in these wetter years, the weather system that had caused the significant increase in soil moisture also resulted in reduced average daily temperatures and radiation, which are known to have a direct link to the plant evapotranspiration demand (Allen, Pereira et al. 1998). Much like the conclusions drawn from the field data, the modelled data suggests while although a significant reduction in soil moisture can be obtained by delaying defoliation, the extent of this reduction is minimal.

SoilFlex (Keller et al. 2007) was used to estimate soil deformation at the relative soil moisture condition (defoliated/undefoliated) for the respective site. The modelled reductions in soil moisture as a result

of the proposed management strategy across all locations reduced the resulting bulk density occurring from simulated JD7760 traffic. In the upper 40 cm, a reduction of 2% gravimetric moisture content resulted in an approximate reduction of 4.5% in bulk density at all depths. Hence, achieving a small soil moisture drawdown may be expected to result in a meaningful compaction risk reduction. However, compaction was still predicted to occur due to wheel traffic at all sites, irrespective of management.

Efficacy of the Proposed Management Strategy

It is evident that the proposed management strategy of postponing defoliation at times where field moisture conditions impose a large soil compaction risk is effective in reducing soil moisture and the associated risk. This is supported by both the field observations and the results obtained from the modelling exercise. However, although a reduction in soil moisture, and thus compaction risk was identified, the extent of this was relatively small. Furthermore, both observed and predicted results demonstrate that compaction is expected well below the feasible cultivation depth. This suggests that the proposed management strategy is not overly effective in significantly reducing the soil compaction risk at cotton harvest when considering systems with heavy machinery. This is likely due to a combination of effects between reduced plant water requirements towards the end of the season (due to plant maturity), climatic conditions associated with increasing soil moisture towards the end of season (i.e. rainfall events causing more cloud cover and less evaporation), and the magnitude of the wheel load. Recent irrigation management trends observed within the industry suggest that growers generally irrigate right up to defoliation to drive yield, which means that there is stored moisture in the profile come harvest traffic. It is possible that the proposed delayed-defoliation strategy could have more impact in wet years where the soil profile was dried down substantially prior to defoliation. Furthermore, as lighter harvesting innovations are realized, this strategy could be revisited.

With such rapid adoption of the JD7760, large concerns exist within industry as the full impact of the new machines isn't completely understood and there is a significant lack of effective soil compaction management strategies for these heavy machines (Bennett et al. 2015; Antille et al 2016). Therefore, it is just as crucial to identify which strategies are and aren't effective in reducing the compaction risk associated with the current cotton harvest system. Identifying strategies that don't work avoids growers causing significant degradation in their soil resource where they may be of the opinion (incorrectly) that compaction is being managed.

Although the proposed strategy was not found to have an extended effect on the resulting bulk density after traffic, the sensitivity of rut depth to soil moisture at the upper end of the soil moisture range was identified to be quite large. This suggested that small decreases in soil moisture result in a large decrease in the rut depth associated with traffic. Hence, achieving floatation, as opposed to significant reduction in compaction, might be a useful outcome of this work for growers. Whilst postponing defoliation does not appear to greatly reduce the resulting bulk density, there is good evidence from both the field investigations and the modelling approach suggesting floatation is increased substantially with small decreases in soil moisture. Whilst flotation does not reduce compaction *per* se it reduces energy use (enhanced traction), reduces requirement for reforming of ruts and decreases smearing shut macropores responsible for the majority of water infiltration. Hence cotton growers must weigh up whether the penalties of rut formation and lost energy at wet harvests that are offset by managing for flotation using a delayed-defoliation strategy are not subsequently lost in yield quality downgrades, or lost yield from open bolls.

Conclusions

This study investigated a novel approach to soil compaction risk reduction, whereby defoliation of cotton was delayed in high risk weather conditions to reduce the soil compaction risk at harvest via transpiration moisture drawdown. The conclusions drawn from the study indicated that the proposed management strategy of delayed defoliation reduced soil moisture and thus the resulting soil compaction risk at cotton harvest, although the extent was not sufficient to deem this an effective management strategy.

Although moisture dry down towards the mature growth stage of cotton was limited, the study found that changes in observable compaction were detectable with small differences in soil moisture. These conclusions were supported by the data obtained from the field investigations as well as the historic data that was obtained from the modelling exercise. However, as demonstrated for modelled and field data, the benefit of the strategy was only a minor decrease in resultant bulk density, which may not outweigh potential costs in yield parameters (if theses exist). Furthermore, compaction from heavy machinery such as the JD7760 was shown to have compaction effect well beyond the feasible cultivation depth (to 80 cm), irrespective of treatment strategy. Hence, this strategy would not mitigate against long-term risks of heavy machinery.

It would be highly beneficial to industry if a software package was developed that could accurately predict the compaction risk associated with the timing of traffic, that operates on a soil profile with both moisture content and bulk density initial gradients with depth, rather than an isotropic medium. This would allow growers to better manage soil compaction in their operation.

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Optimal planting dates of cotton to reduce soil compaction at harvest

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Introduction

In Australia, the risk of soil compaction during cotton harvest is high, particularly in surface irrigated systems. As discussed in previous chapters, this is due to the overall weight of recent editions of cotton pickers (21 t and 12 t for the front and rear axles, respectively) coupled with relatively soft soil conditions that are common in autumn when harvesting operations are conducted. The soil carrying capacity and trafficability (field access) at the time of harvest are influenced by the seasonal effect of weather, the cut-off time of irrigation water that is applied near-terminal stages of the crop cycle, and the timing of defoliation. Where irrigation cut-off and defoliation are capable of being managed for optimal traffic conditions (soil moisture less than the plastic limit), the effects of unforeseen wet weather can undo such management and render traffic conditions sub-optimal, resulting in soil compaction.

Manipulating the planting date may accommodated avoidance of unsuitable soil moisture conditions at harvest allowing for reduced risk of soil compaction and improved trafficability, whereby historical rainfall data could be used to plan for harvest traffic to occur during low rainfall probability periods. However, changes in planting date must not lead to yield or financial penalties. These may result from growing the crop under suboptimal eco-physiological conditions, particularly radiation and temperature, by increasing the risk of crop losses (quality) or market opportunities (price) and therefore profitability from improper harvest timing. Cotton yield is known to be relatively sensitive to changes in planting date (Porter et al., 1996; Boquet and Clawson, 2009; Huang, 2015). However, the effect of shifting planting date within the optimal window to allow for improved soil trafficability conditions at harvest are not well understood for Australian cotton-systems.

This chapter reports the results of a preliminary modelling exercise, which was conducted to provide some understanding of the above relationships and explore the feasibility of shifting planting date in irrigated cotton. Therefore, the objectives of this study were to: (1) Determine if planting date can be used as a strategy to avoid rainfall and therefore unsuitable conditions for traffic at harvest, and (2) Examine the relationship between cotton yield and planting date to determine likely changes in potential yield. Improved understanding of these interactions will assist the assessment of soil compaction risks within cotton-farming systems in Australia (Antille et al., 2016).

Methodology

The use of a process modelling approach was chosen to quantify the likely impact of changes in planting date on crop yield, harvest date, and likely rainfall within five days prior to harvest. Rainfall influences soil moisture, which has a direct effect on load-carrying capacity (Earl, 1997). The Agricultural Production Simulation (APSIM) model (Keating et al., 2003; Holzworth et al., 2014) has been developed to simulate biophysical processes in farming systems and has previously been used to determine relative changes in resource use efficiency (radiation, temperature, water, fertiliser) as affected by planting date (Braunack et al., 2012). A similar approach to that of Braunack et al. (2012) was followed. In this study changing planting dates and associated effects on soil conditions at harvest were investigated for two major cotton-growing areas in Australia; namely, Jondaryan (Queensland) and Narrabri (New South Wales).

The soil water balance model within APSIM was used to determine the effect of soil type and management practices on cotton yield, and soil moisture based on long-term (115 years) climate data. The window available for planting cotton within the main growing region in Australia is between 30 August and 30 December. For the two areas investigated, the irrigation strategy used in the APSIM model was to initiate irrigation when soil water was 50% of field capacity (FC) in the top 1-m of the soil profile. This equates to a water deficit of about 100 mm within that soil depth. Irrigation was set to continue until soil moisture levels reached FC within the same depth interval. The final irrigation event was assumed to be when 60% of bolls were open. Soil properties representative of Vertosols occurring in the two growing regions of interest to this study were taken from the APSoil database (Dalgliesh and Foale, 1998; Padarian et al., 2014). These soil properties have been used in previous field and simulation studies (e.g., Huth et al., 2002) and they are representative of soils typically found in Jondaryan and Narrabri, respectively, were cotton is grown. The database includes specification of soil bulk density (SBD), saturation water content (SAT), drained upper limit (DUL) and lower limit (LL, 1500 kPa) water contents. No adjustments were made to the soil parameter sets.

Soil parameters and rainfall

The plant available water capacity (PAWC) for the soil at Jondaryan (Figure 1) was 290 mm over the rooting depth (1-m). The reference soil used for Narrabri had similar hydraulic properties however differences between the two sites are in accord with rainfall regimes and evapotranspiration. PAWC is equivalent to the amount of water stored in the soil profile that can be used by plants, and is estimated as the difference between the upper and lower limits of water contents over the rooting depth.
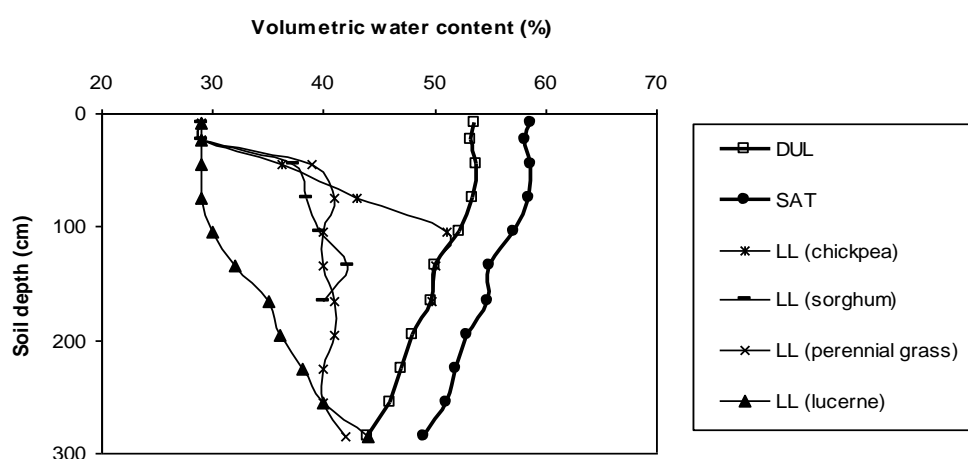
Figure 1. *Drained upper (DUL) and crop lower (LL) limits for a black Vertosol representative of soils where cotton in grown, and used to parametrise the model.*

The drained upper limit (DUL) is defined as the moisture content after a soil is fully saturated and drainage has ceased, also referred to as field capacity (FC). Saturation (SAT) corresponds with the maximum amount of water that can be held in the soil before drainage takes place. SAT approximates the total porosity of the soil (η), which is related to density properties but is slightly lower than η due to entrapped air (McKenzie et al., 2002).

Based on long-term meteorological data for both sites, the probability of rainfall occurring on the harvest date is dependent on the planting date. In up to 20% of years, rainfall occurs on the harvest date, except when cotton is planted between 15 and 30 Oct where the probability of rainfall at harvest is 100%.

Results and discussion

Figure 2 shows the relationship between planting date and cotton yield for the two growing regions investigated. Based on the APSIM simulations, it appears that the optimum window for planting cotton is between late September and late October in Jondaryan, and between early October and early November in Narrabri. However, this information should be treated with caution as the OZCOT simulation model (Hearn, 1994) used within APSIM has not yet been updated to incorporate Bollgard II®, which is widely used at present (Bange et al., 2008). Similarly, the yield potential of modern varieties of cotton is higher than older varieties such as those used in OZCOT (Constable and Bange, 2015).
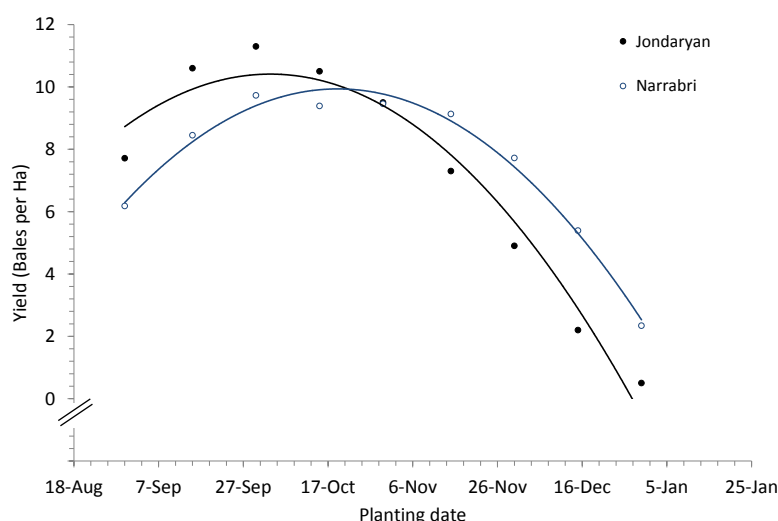

Figure 2. APSIM-predicted relationships between planting date and cotton yield for Jondaryan (Queensland) and Narrabri (New South Wales), respectively.

Figure 3 shows the relationship between planting date and average days to harvest. The implication of this relationship is the associated shift in harvest date, potentially leading to increased risk of soil compaction due to rainfall at/around harvest. Additional impacts from improper harvest timing are associated with loss of crop yield, quality and profitability as mentioned in several other studies (e.g., Bednarz et al., 2002). Cumulative rainfall influences trafficability conditions (field access) and increases the risk of soil compaction at harvest. Such rainfall changes soil water content, which affects bearing capacity (Chancellor and Schmidt, 1962). Table 1 shows that by planting between 15 Oct and 15 Nov the risk of significant rainfall immediately before harvest is relatively low. For Jondaryan, the early part of this window is preferred to avoid potential yield penalties whereas for Narrabri a slightly later planting date may be recommended (Figure 2). These deductions assume that lower mean rainfall is representative of lower probability of unforeseen large magnitude rainfall events.
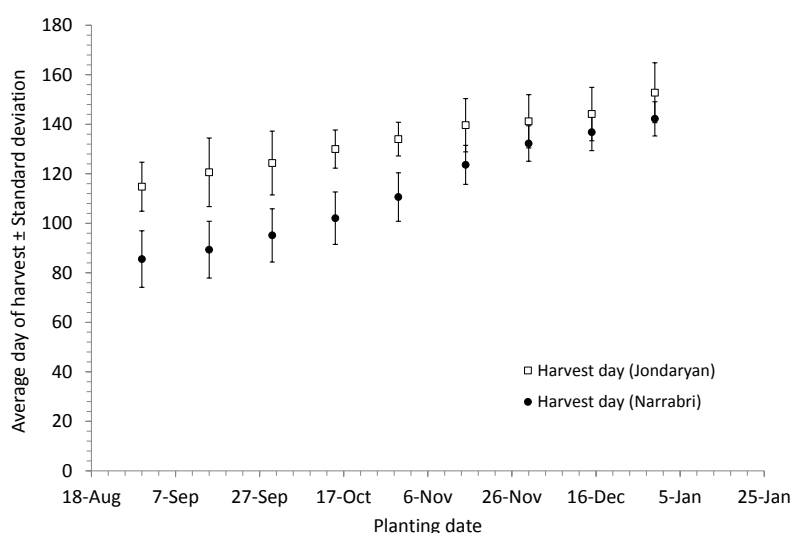
Figure 3. The relationship between planting date and APSIM-predicted day of harvest for Jondaryan (Queensland) and Narrabri (New South Wales). Error bars denote ± standard deviation of average day of harvest.

Whilst the value of cumulative rainfall alone may be limited, this information can be supplemented with estimates of soil water content (moisture deficit) to support decision-making about harvest-trafficking (Antille et al., 2016). Previous studies (e.g., Earl, 1997) have shown that relatively small rainfall events may be sufficient to induce significant changes in soil moisture and consequently restrict the opportunities for traffic, particularly with heavy vehicles. Approaches such as used in the study of Vero et al. (2014) based on soil moisture deficits appear robust, yet simple, to establish thresholds for limits to trafficability with cotton pickers (Antille et al., 2016).

Table 1. Mean cumulative rainfall within five days prior to cotton harvest in Jondaryan (QLD) and Narrabri (NSW) based on long-term (115 years) meteorological data.

Site	Jondaryan (QLD)		Narrabri (NSW)	
Planting date	Harvest day	Cumulative rainfall (mm)	Harvest day	Cumulative rainfall (mm)
30-Aug	115	6.7	86	9.6
15-Sep	121	6.3	89	11.0
30-Sep	124	10.4	95	12.8
15-Oct	130	6.9	102	7.8
30-Oct	134	6.2	111	4.0
15-Nov	140	7.7	124	7.9
30-Nov	141	7.4	132	6.6
15-Dec	144	7.7	137	10.4
30-Dec	153	7.8	142	10.0

Summary

The model showed that optimal dates for planting cotton are between late September and early November depending on the region. However, a window planting between middle of October and early to middle of November is likely to minimise the risk of soil compaction at harvest without a significant compromise on crop yield. For planting within the suggested window, cumulative rainfall in the five days prior to harvest are also likely to be small, which may increase the efficiency of harvesting operations. Further research is required to validate the outcomes and preliminary conclusions derived from the modelling work reported in this chapter. This modelling work also requires integration with the set of recommendations and practical approaches to minimising traffic compaction indicated

elsewhere in this report and earlier publications (Bennett et al., 2015; Antille et al., 2016) such as adjustments to picker's running gear.

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6. Diagnosing traffic based soil compaction with an EM38

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Introduction

Soil compaction is a worldwide issue for agricultural production (Soane & van Ouwerkerk 1995) and is considered the utmost impact of modern agriculture on the environment (McGarry 2003). Controlled traffic farming techniques – where all machine traffic is constrained to permanent tracks (tramlines), machines and implements operate on inline wheels (i.e. no requirement for dual wheel configurations) and these wheels are at a matched width between wheels on an axle – are proven to reduce this impact (see Tullberg, Yule & McGarry 2007). However, such systems have been slow to be adopted, with many landholders indicating that they can't see compaction and its effect, so it is a forgotten issue most often. This highlights the importance of providing a graphic representation of impact and being able to produce this at low cost and high resolution of farm coverage.

The use of electromagnetic induction (EMI) survey technique provides the required resolution and can be undertaken relatively rapidly, resulting in reasonable cost. Numerous studies have indicated that EM38 sensors (EMI technology) are capable of detecting increases in soil density due to anthropogenic intervention (soil compaction). However, while previous investigations using an EM38 to determine soil compaction have shown merit, they have in majority focused on highly contrasting densities such as existing plough-pans (subsoil compaction) (Hoefer & Bachmann 2012) or imposed low density zones in effluent pond, maximum dry density clay liners (Guyonnet et al. 2003). Additionally, the majority of studies have occurred in coarse textured soil at low moisture content.

These studies use the standard Geonics EM38 with a 1.0 m transmitter and receiver spacing, allowing a 1.5 m and 0.75 m depth of interrogation in the horizontal and vertical mode of EM38 operation. Given the integrated nature of EC_a measurement (see "Theoretical concept" section), dilution of compaction effect in the EM38 response at either horizontal or vertical dipole configuration is likely to have occurred, which could also have affected the ability to detect changes in soil compaction. However, Geonics newer EM38-MK2 includes two receiver coils spaced at 1.0 and 0.5 m from the transmitter, providing data from effective depth ranges of 1.5 m and 0.75 m respectively (vertical dipole orientation), and 0.75 m and 0.375 m respectively (horizontal dipole orientation). Hence, our study sought to investigate the ability of an EM38-MK2 to diagnose traffic based soil compaction at a range of soil moisture contents, with relatively low density contrast, and in high clay content Australian Vertosol soils.

Theoretical concept

The electromagnetic induction (EMI) survey technique induces alternating currents within the soil that are linearly related to the soil electrical conductivity (EC) using a varying magnetic field (McNeill 1980). The below-ground response is then analysed to determine electromagnetic fields and the ramification of differences depending on the depth response of the instrument. EMI instruments use a transmitting and receiving coil to interrogate electromagnetic field response, whereby the transmitting coil is excited using sinusoidal current, creating a time-varying magnetic field that induces eddy currents (secondary magnetic field within the primary magnetic field) within the soil (Lamb, Mitchell & Hyde

2005). It is the magnitude of these eddy currents that is proportional to soil EC, and the receiver intercepts a fraction of these which are returned as an amplified summation in the form of an output voltage.

While this method is considered a measure of EC, it is actually measuring the apparent EC (EC_a) which is the EC integrated throughout the depth of measurement; a depth weighted EC according to the theoretical respective depth response functions (McNeill 1980). Hence, at any single point of measurement, the EC_a returned by the instrument is an integration value determined by both the depth related sensitivity and the predominant, depth dependent, drivers of the soil EC (Hossain et al. 2010; Sudduth, Drummond & Kitchen 2001). Considering this, the EM38 MKII provides four maximum depth weighted responses over which to assess soil electrical conductance, with the data from the smallest depth included in the depth weighted integrations of greater depth assessments.

As explained by Roades et al. (1989), and depicted in Figure 1, the current flows through three pathways: 1) a liquid phase pathway (soil pore water and its salt content); 2) a liquid-solid phase pathway; and, 3) a solid pathway (direct, continuous contact between soil separates). However, the soil matrix does not usually provide sufficient direct, continuous contact between soil separates for continuous current flow.

The EC of a soil is governed by multiple soil properties (McKenzie et al. 2008), predominantly: 1) Pore network characteristics (primarily defined by clay content and type) and connectivity; 2) Water content with depth; 3) Concentration of dissolved salts in the soil water; and, 4) Temperature and phase of the pore water (phase referring to frozen/unfrozen). Hence, soil bulk density (and compaction) is considered to affect EC_a measurement (Corwin & Lesch 2003, 2005; Hossain et al. 2010).

When considering a given volume (V), where a soil is compacted into that volume, more soil solids are contained in V, than for the same soil when not compacted. The volume of soil (V) is described by:

$V = V_S + V_A + V_w$

where V_S is the volume of solids, V_A is the volume of air, V_w is the volume of water, and $V_A + V_w$ is the soil pore volume. Thus, if V is to remain constant, as per the consideration, as V_S increases $V_A + V_w$ must decrease. Additionally, if soil pore space is decreasing, the diameter (d) of the soil pores must be decreasing also. This is important because as soil pore diameter decreases the suction required to remove water from a pore increases (i.e. more work must be done to remove water).

Pathways of Electrical Conductance
Soil Cross Section

Figure 1. Conductance pathways; d, is pore diameter, V is volume and W, S and A refer to water, solid and air, respectively (modified from Corwin and Lesch 2005)

In considering how compaction would be expected to affect electrical conductivity, we can use Figure 1. The likelihood of pathway 3 being responsible for conductance is increased. Where gravimetric moisture content (mas of water per mass of soil) and soil solute concentration are not changed, we would expect the volumetric water
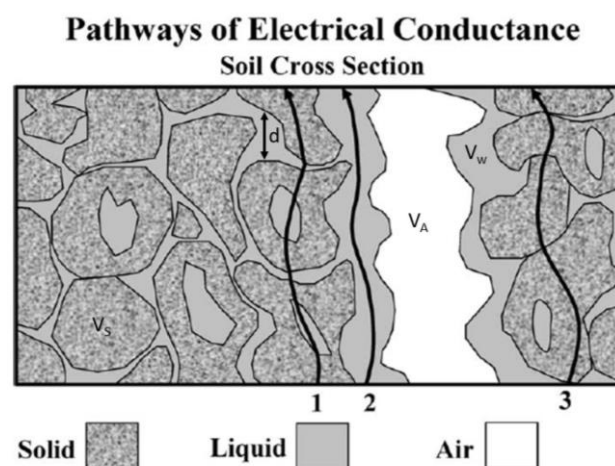
content (volume of water per volume of soil) to be increased if the soil is not moisture saturated. Thus, we would expect an increase in soil conductivity due to the volumetric moisture and soil solid contact increases. Where a crop is included in the scenario, we might expect the compacted zone to exhibit further contrast in terms of high EC_a due to the effect of increased suction (plants must work harder to access water from the compacted zone).

Methods

Vertosol soils were used in the investigation. Investigations were carried out on 1) a long term controlled traffic paddock and 2) on a paddock never subject to traffic. Investigation 1, like the numerous previous studies, allowed a stark contrast in bulk density between traffic lanes and un-trafficked field. Unlike previous studies, this also allowed a high clay content soil at numerous soil moistures to be investigated over time. This site was located near Jimbour, Queensland. Two sub-sites were used in this location, whereby the first had recently come out of crop, and was thus drier than the second, which had been in fallow. This allowed greater assessment of the moisture range. The sub-sites were located within 400 m of one another.

Investigation 2 was conducted to assess the capability of the EM38 MKII to detect soil compaction of a single pass of a standard, dual wheel front axle John Deere 7760 cotton picker. EM38 assessment was undertaken by hand prior and post traffic to assess natural variation.

For both investigations, soil bulk density was determine every 10 cm to a depth of 80 cm. These samples were also used to determine soil moisture content. Soil strength was assessed using a constant insertion velocity cone penetrometer. Whilst this device is strongly influenced by soil moisture, measurements were taken directly before and after traffic, so relative differences indicate differences in soil strength due to soil compaction. These data are not shown in this article for brevity.

Results and discussion

Investigation 1

The fieldwork undertaken for investigation 1 resulted in 40 EC_a response maps: 2 different sites x 4 different positions x 5 different measurement timings. The response maps for the V0.5 position (0.75 m depth) for the first three measurement timings are presented in Figure 2. It is observed that over time as the soil dried out, lower EC_a values were measured, reflecting the importance of soil moisture as a factor influencing EC_a. Within the maps linear horizontal features with higher EC_a values can be distinguished, correlating to the wheel tracks (WT) as observed on the surface. Noteworthy, between map A and B there was a single pass from agricultural traffic (spray rig), resulting in a clear feature at the top of maps B and C. Similarly, a linear feature is found at the bottom of map F at Site 2. This highlights the effect of a single traffic pass, even on soil zones subject to high traffic loads, and indicates the volumetric moisture content effect discussed in the theoretical concept section.

The average gravimetric soil moisture content for the 0.75 m depth was 32, 29, 22, 38, 34, and 27% for A, B, C, D, E and F, respectively. The bulk density for the traffic lanes was 1.59, while it was 1.24 for the non-traffic zones, on average over depth and sites. This bulk density was obtained from soil near field capacity. Vertosol soils have shrink-well characteristics that affect bulk density with soil moisture, which is likely to affect EC as well, but is not considered here. Thus, it can be seen that the EM38 MKII is capable of diagnosing high contrast soil compaction at a large range of soil moisture contents in soils with high clay content.
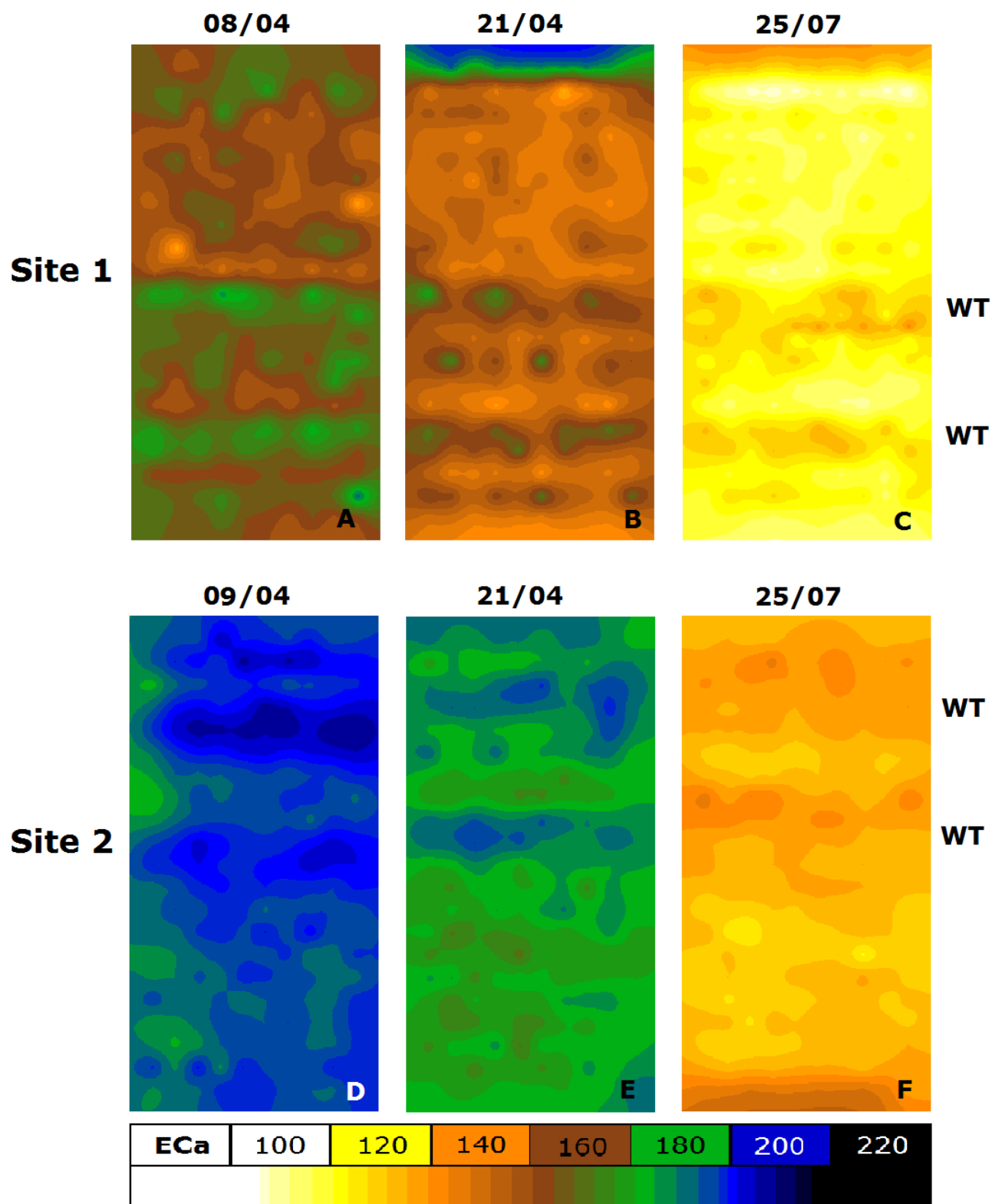
Figure 2: Maps of EC_a (mS/m) as measured by the EM38 in the V0.5 position. Numbers above each map indicate date of measurement. Assessment occurred in the year 2014.

It was also noted that high EC was strongly correlated with bulk density and moisture corrected soil strength (data not shown). Furthermore, the linear features representing soil compaction from wheel tracks (high EC_a) were more pronounced in the Horizontal 0.5 m configuration, but are not shown here;

the Vertical 0.5 m configuration is shown instead to provide a similar depth of investigation to previous studies.

Investigation 2

A summary of results for investigation 2 is shown in Table 1. In this case, interpolated response maps have not been used to depict results in order to statistically and simply show the compaction effects. Between traffic and non-traffic furrows it can be seen that there is a significant increase in EC_a where traffic has occurred for V0.5, H1.0 and H0.5 instrument configurations. This indicates that the EM38 MKII has been able to diagnose compaction due to wheeled traffic. The results are different for the H1.0 and V0.5, which can be attributed to the depth weighted integration for vertical and horizontal configurations (this being different with weighting placed slightly deeper in the horizontal mode).

This data further shows that the difference in EC_a is more substantial where the interrogation depth is shallower, which is as to be expected considering the stress load effect is greatest at the soil surface. Such a result confirms the issue of impact dilution as the depth of interrogation is increased.

The compacted bulk density for 0–38 cm and 0–75 cm was 1.52 and 1.56, respectively, whilst for non-traffic furrows it was 1.41 and 1.50, respectively. Hence, the EM38 MKII was capable of diagnosing less contrasting compaction effect. These data were again strongly correlated with soil bulk density and soil strength (data not shown).

Table 1. Apparent electrical conductivity for the four interrogation depth configurations of the EM38 MKII. Numbers in the same column followed by different lowercase letters indicate significant differences at $p<0.05$. Traffic furrows include data from all four machine tracks, differential furrow refers to the untrafficked furrow beneath the centre of the machine, whilst the guess furrow is the furrow not trafficked, but between two machine frontages.

Furrow	EM38 configuration			
	V1.0	V0.5	H1.0	H0.5
	1.50 m	0.75 m	0.75 m	0.38 m
Traffic	113.0	89.0a	79.3a	61.3a
Differential	117.7	85.7b	70.3b	51.3b
Guess	116.7	84.3b	69.3b	48.7b

Conclusion

Use of an EM38 to diagnose compaction has merit and should provide a more cost effective way by which to demonstrate graphically the effect of machine traffic on the soil resource. The Geonics EM38 MKII has proven capable of diagnosing soil compaction in high clay content soils at a moisture range of 38–22% gravimetric soil moisture

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7. Recommendations and Future directions

The following recommendations are made in considering this work as a whole:

Avoidance of traffic in sub-optimal conditions

If there is one single major recommendation of this work, it is that avoidance of traffic with the JD7760 at soil moisture content near or above the plastic limit occur at all costs. Mechanical parameters for Vertosols suggest that the wheel load and contact stress of the JD7760 should cause irreparable damage to the soil resource even at considerably low moisture contents in comparison to the plastic limit. This was observed for every site the JD7760 traversed. Hence, all results advocate controlled traffic farming as the best management practice. If traffic with the JD7760 is not addressed, then there could be substantial soil compaction legacy effects; this may perhaps be the next inter-generational challenge if not addressed throughout the industry. Bio-ripping and cultivation as management options are discussed further below, but suffice to say bio-ripping cannot be relied upon for short-term fallow systems, and cultivation possibly cannot address sufficient depth of soil to avoid long-term compaction pans. Additionally, tillage to depths of 0.8 m would have further ramifications for soil structural, microbial and nutrient dynamics that could not be conducive with optimal soil resource function. Further work to understand the effect of compaction on soil porosity and water infiltration dynamics in order to model these interactions will be invaluable in estimating long-term impacts.

Controlled traffic farming conversion

Controlled traffic farming is advised as the best management practice for controlling soil compaction, especially under heavy machinery such as the JD7760. If controlled traffic is to be adopted by the industry, there is an apparent requirement that the industry move as a whole to protect contractor availability and the ability to offset purchase/investment costs via the ability to supply a contracting service. Furthermore, row-spacing in association with conversion to controlled traffic requires further investigation in a larger number of climatic regions to help with speculation of results to applicable regions. Row spacing investments by CRDC have been made in recent history, but the incorporation of traffic systems in this has not been provided adequate consideration.

Additionally, cultivation regimes and bio-ripping (evapotranspiration wet-dry cycles) should be investigated as interacting factors with controlled traffic and best management practices developed on this basis. Growers appear concerned that CTF systems with different row spacing will not be able to provide equivalent yield/ha, although the emphasis should be placed on gross margin, this must be addressed to communicate the full benefits. Additionally, there is a view that high yield results from cultivation depth (requires investigation; see below), which stems from not being able to adequately compare the CTF approach long-term benefits to high yielding cotton systems. This is because long-term sites do not exist in abundance, and where they do exist, information is not communicated to the required extent. A combination of more research and good communication will be required.

The replacement of dual by single tyres in the front axle (and axles extension) of recent editions of cotton pickers to accommodate to permanent traffic lanes with 3 m centres may be at the expense of increased inflation pressure. Whilst some loss of tractive efficiency may be expected (e.g., increased wheel-slip and rolling resistance) under relatively soft soil conditions, the effect may be marginal on consolidated wheel-lanes. However, this requires further investigation together with optimal design of traffic lanes (length, slope), particularly within irrigated systems to reduce concentration of runoff potentially leading to increased erosion risk.

Cultivation and viability of spent energy

Deep ripping/ significant cultivation is often ignored as a management strategy due to high energy input costs per hectare, which usually outweigh any perceived yield increase. This is a common reported outcome of reduced tillage research. For that reason, this management practice was ruled out at the commencement of the current project, in favour of management strategies with lower per hectare costs. However, a base trend observed in energy impact assessment after one year, and anecdotal evidence revealed at 2015 discussion forums, appears to suggest that increased tillage depth has a positive relationship with increased yield. In all reported cases, the increase in yield justified the energy cost based on a price of cotton at ≈$500 /bale and wholesale cost of diesel at ≈$1.20 /L. Such a relationship should be explored on a wider basis to determine limitations and to factor in commodity price sensitivities. Importantly, it will be key to understand if increased yield is a mechanism of improved hydraulic function (infiltration and plant availability), rooting interactions, and/or nutrient mineralisation. As per the Brigalow Catchment Study (Cowie et al 2007) clearing of land and the subsequent tillage is known to provide greater access to previously unavailable nutrient, resulting in nutrient run-down in the longer term.

The results from Toobeah, Qld, after one year actually suggest that there is space to optimise the energy inputs. Ignoring the relatively high commodity price of cotton, the pupae busting only treatment (current minimum tillage) provided greater yield production per unit of input energy. Thus where energy input costs approach parity with cotton commodity prices, reduced tillage presents as the optimal system. In the circumstance of energy investigations in this work all other system inputs were managed to be equal, but over time it would be prudent to optimise irrigation uniformity and water use efficiency, as well as nutrient use efficiency management plans, if reduced tillage systems were to be used. Furthermore, reduced tillage research suggests that the long-term environmental cost of intensive tillage is high. Thus, the environmental cost also needs to be factored into the long-term farming system. With Bollgard® III the requirement for pupae busting is removed provided crops are defoliated prior to the end of March. This essentially means that cotton could be grown on a zero/minimum till system on average (climate affected) and with careful management. Hence, reduced wheel traffic will likely become more important. For this reason, long-term controlled traffic farming systems should be compared to any cultivation management plans within the balance of environmental cost.

Data collection

One of the major issues with attempting to conduct an economic assessment of moving from the basket picking system to the JD7760 system was the incompleteness of data. Growers could generally provide total production system performance in terms of yield/ha or yield/ML, but could not break this down to a paddock scale. System inputs were similarly accounted for in total, rather than on a spatial scale. As machines all moves towards digital communication and rapid data collection, precision agriculture data collection BMPs should be produced. The identified data required in this work that was substantial missing was field scale production, inputs, yield, and in-field energy consumption. All of these are relatively simple to capture with existing technology on agricultural implements and machines.

Intelligent decision support systems

Identification of soil compaction impacts on the wider aspects of farm economics to aid decision-making (Kirby, 2007). This requires the development of decision support systems (DSS), which need to incorporate the economics of managing soil compaction and provide advice on options available to

specific farming systems (farm-scale analysis) including conversion to CTF coupled with adoption of precision agriculture technologies, use of (ultra) low ground pressure tyres and precision tillage. The wider aspects of farm economics include impacts of compaction on:

a. Water (rainfall and irrigation), and fertiliser use efficiencies. The latter includes reductions in recoveries of applied nutrients and yield-to-nitrogen responses,

b. Energy use efficiency to account for total energy input for the crop. This includes (excess) energy spent on tillage repair treatments, and (reduced) recovery of fertiliser and water in crop yield. Therefore, development of DSS needs to incorporate models that optimise energy output-to-input ratio. In grain cropping (clay soil), fuel may be reduced by up to 50% when CTF is used but work is needed to determine these potential savings for cotton,

c. The above research may apply similar approaches to those employed in grain cropping (e.g., Kingwell and Fuchsbichler, 2011; Blackwell et al., 2013; Gasso et al., 2014), including life cycle assessment and environmental audits, and incorporate modelling approaches for simulating the effects of changes in land-use and management practices.

Soil compaction prediction at field-scale

Prediction of soil compaction risk at the field- or subfield-scale based on soil type and soil water content would be a highly valuable planning and educational tool (non-CTF systems only). Approaches such as that used in the studies of Earl (1997) and Vero et al. (2014) appear to be robust, yet simple, tools to determine soil moisture deficit (SMD) thresholds for limits to trafficability with heavy equipment. Site-specific information on trafficability conditions used in conjunction with central tyre inflation systems may enable for 'on-the-go' adjustments of running gear. Subsequently, site-specific compaction may be corrected based on the principles of 'precision tillage' (spatially- and depth-variable). Other methodologies, such as that developed by Troldborg et al. (2013), may be also readily applicable in terms of data inputs and offer the advantage of accounting for uncertainties in the assessment of compaction risks.

SoilFlex (Keller et al 2007) provides a good means by which to calculate the contact stress of a machine based on the tyre and load characteristics, but utilises an analytical solution to calculating compaction impact. It is possible that the contact stress calculation could be incorporated into a finite element model such as HYDRUS to help determine consolidation effects simultaneous to soil moisture impact. This would then allow compaction to be discussed using a WUE metric, which is currently not able to be done. This would require some broad characterisation of soil water potential characteristics, in a similar fashion to Kirby's (1991) survey of regional Vertosol mechanical characteristics.

Greenhouse gas emissions in relation to uncontrolled traffic

The potential of controlled traffic to mitigate greenhouse gas (GHG) emissions and reduce loss of SOC appears to be under-researched within cotton work. Much of the effort on reducing GHG emissions in cotton cropping appears to be centred on reducing N application rates, and more recently on the role of advanced N formulations coupled with improved irrigation management and fertiliser placement. It is hypothesised that:

a. The need to reduce N application rates may be less critical if improved soil conditions in the absence of field traffic allow for enhanced N use efficiency (increased uptake and recovery, reduced N_2O emissions from fertiliser, and increased CO_2 capture in crop biomass) and effectively translate into higher yield, and

b. Reduced need for tillage helps protect SOC levels, which contributes to maintain adequate supplies of soil N and to reduce reliance on synthetic N fertiliser.