Managing field moisture to reduce the soil compaction risk at cotton harvest

A dissertation submitted by:

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Abstract

A recent rapid change in the cotton harvesting system due to the inception of the John Deere 7760 round bale module builder as increased the soil compaction risk within the cotton industry due to the increased weight of the new machines (i.e. >36Mg). Due to the implications soil compaction has on farm productivity, it is pertinent to investigate management strategies whereby the compaction risk can be reduced. This project was developed to investigate a novel approach whereby cotton defoliation was delayed at times of high field moisture, allowing the soil profile to be dried down due to the evapotranspiration demands of the crop, thus reducing the compaction risk at harvest. A field trial located at Aubigny, QLD was used to evaluate the merit of the proposed management strategy in the 2014/2015 growing season, and provide a validation data set to be used in a modelling exercise. The modelling component of the project was developed to assess the merit of the proposed management strategy using historical climatic data in a number of cotton regions in Australia. The investigations concluded that the proposed management strategy of delaying defoliation was effective in reducing soil moisture and thus the resulting soil compaction risk at cotton harvest. The extent to which the compaction risk was reduced was however limited, with only small reductions in bulk density after harvest being detected.
University of Southern Queensland
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1 Introduction

With predictions of world population exceeding 9.6 billion by 2050 (United Nations, 2013), there will be an increased pressure on the agricultural sector to sustain the food and fibre demands of a rapidly growing population (de Fraturier, Wichelns D et al. 2007). With increased financial pressures and climatic uncertainty, producers are continually looking for ways to increase field efficiency, essentially reducing operational time in the field. This ultimately leads to the development of larger machines that are capable of high capacity operations, resulting in a greater soil compaction risk.

Soil compaction is regarded as the largest environmental problem caused by conventional agriculture (McGarry 2003), with 68 million hectares globally being affected by compaction-induced soil degradation (Flowers and Lal 1998). The effects of machine-induced compaction within agriculture can be extremely detrimental to crop production and it is therefore pertinent to develop management strategies that reduce the soil compaction risk.

The Australian cotton industry is no exception to the pressures of increased production costs. In 2008, Deere & Co. commercially released a revolutionary cotton picker which fulfilled the requirement of high capacity operations by increasing the effective field capacity to 3.5 ha/hr; 30% greater than the conventional picker (Bennett, Woodhouse et al. 2015). This machine, branded the ‘JD7760’, was revolutionary in the sense that it had the capacity to simultaneously pick, build and wrap modules. This exponentially increased field efficiency and allowed for a continuous harvest. The cost of this continuous harvest, however, is the increase in machine weight, which exceeds 36Mg when fully loaded (Bennett, Woodhouse et al. 2015). With such a large increase in machine weight, comes a significant increase in soil compaction risk.

Soil compaction susceptibility is governed by its mechanical strength, which is most sensitive to soil moisture and clay content (Al-Shayea 2001). In particular, a soil’s
compaction susceptibility is greater with increased clay content and soil moisture. The compaction risk is exacerbated for the predominant cotton growing soil, The Australian Vertosol (Isbell 2002), at times of high field moisture due to its exceedingly high clay content. It is therefore pertinent to develop management strategies at such times, to reduce the compaction risk at cotton harvest.

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. Therefore, strategies that target traffic during high-risk weather predictions, where field moisture conditions may be less than ideal, will have the most impact on picking operations. In particular, strategies that deal with managing soil moisture to reduce the compaction risk need to be investigated.

1.1  Project Aim
This project aims to investigate a novel approach whereby cotton defoliation is delayed at harvest in high-risk weather conditions, allowing evapotranspiration soil profile dry down to occur as a strategy to minimise detrimental soil compaction from harvesting operations.

1.2  Project Objectives
The objectives required to be met in order to achieve this aim are as follows:

1. Investigate the likely soil moisture draw down of mature cotton plants leading up to the time of a typical harvest using soil-moisture-crop computer models
2. Validate modelled results with dry down results obtained from field trials and the subsequent resulting compaction under field conditions
3. Use modelled and observed results to quantify the difference in compaction risk at the different moisture contents associated with the two management strategies (conventional and proposed) for a number of typical Australian cotton regions
4. Evaluate the proposed management strategy in terms of practical/meaningful reduction of the soil compaction risk at harvest

The project specification can be found in Appendix A
1.3 Dissertation Overview

1.3.1 Literature Review
This section will detail the background literature behind that nature of soil compaction within cotton production and the parameters which affects its process. The review will also provide a basic evaluation on the theoretical potential of the proposed management strategy in reducing the soil compaction risk at cotton harvest.

1.3.2 Experimental Methodology
This section will outline the procedures undertaken to obtain results in order to address the project aims and objectives. The section will provide a detailed explanation of the design of the field trials and the modelling exercises that were undertaken.

1.3.3 Results
The results section will detail all crucial findings of the field and modelling investigations in the evaluation of the proposed management strategy. Results will be presented in a number of figures, tables and statistical analyses.

1.3.4 Discussion
The discussion will evaluate the potential management strategy in reducing the soil compaction risk at cotton harvest via the natural removal of moisture from the profile by an undefoliated cotton crop. The proposed strategy will also be evaluated for its usefulness in the wider cotton industry.

1.3.5 Conclusion
This section will conclude on the major findings of the study and provide a final evaluation on the significance of the proposed management strategy.
2 Literature Review

2.1 Introduction

The aim of this literature review is to investigate the soil compaction fundamental background material that currently exists to gain insight for soil moisture and plant dynamics within the harvesting (picking) system. This review will focus on two main sections: 1) The mechanics and influencing factors of soil compaction, and 2) cotton-soil-moisture interaction and dynamics. Reviewing this material will identify the potential for the proposed management strategy of delaying defoliation to more rapidly drydown the soil profile, as well as recognise any knowledge gaps that exist within the topic.

2.2 Nature of Compaction

Soil Compaction is defined by the Soil Science Society of America (1996) as “Increasing the soil bulk density and concomitantly decreasing the soil porosity, by the application of mechanical forces to the soil” which leads to increased soil strength. Compaction has immense negative agronomic impact, due to reduced root growth and plant yield. These are indirect effects of decreased soil porosity, permeability and structure degradation (Clemente, Schaefer et al. 2005). The effects of soil compaction within agriculture have been well documented (Soane and Ouwerkerk 1994, Ishaq, Ibrahim et al. 2001, Lipiec and Hatano 2003, Hamza and Anderson 2005, Défossez, Richard et al. 2014) and it is therefore pertinent to investigate how the detrimental effects of compaction can be minimised or avoided.

Soil compaction has large economic impacts on the agricultural industry, with loss of production being estimated to be $850 million annually in Australia alone (Walsh 2002). It is likely that this figure has increased over the past decade as agricultural machinery has become heavier to accommodate the greater field efficiencies that producers are demanding (Bennett, Woodhouse et al. 2015) Therefore, the cost of compaction is heightened due to the elevated risk. If not properly managed, the effects of soil compaction can severely reduce the long-term production potential of a given soil. In particular, subsoil compaction may be considered to be a greater physical restraint for crop production because of the difficulties associated with the identification and amelioration of it (Håkansson, Voorhees et al. 1987).
There is often limited ability for effective compaction remediation due to the difficulties in trying to achieve it. Vertosol soils do have some ability to repair themselves due to their self-mulching, shrink-swell characteristics. A study conducted by Sarmah, Pillai-McGarry et al. (1996), concluded that Vertosol soils were able to repair their structure after repeated wet/dry cycles. Furthermore, it was concluded that the timeframe required to achieve such natural remediation was greater than the incidence of subsequent compaction in an agricultural setting. Therefore for such soils, this method of remediation is not viable and other methods must be investigated.

Even though it is possible to employ biological methods for compaction remediation, (i.e. crop rotations using deep rooted plants) (Motavalli, Stevens et al. 2003), the most common method is to employ tillage practices in order to reduce the soil’s impendence on root exploration (Hamza and Anderson 2005). However, it must be noted that tillage is quite a costly exercise and overreliance on the practice can also result in detrimental structural decline of the soil (McGarry and Sharp 2001). The cost of tillage is elevated with increased soil strength. This is because greater draft force, and therefore energy, is required to till the soil. A study undertaken by the Department of Industry and Science (2015) concluded that the energy requirement of tillage on predominant cotton growing Vertosol soils at a depth of 350mm ranged from 27.5–31 L/ha, depending on ground speed, engine speed and soil moisture content. The actual cost of such tillage is increased when operational costs such as wages, depreciation and maintenance are accounted for. It must be noted however, that tillage can only provide a limited amount of compaction remediation Therefore the risk of permanent structural decline is inevitable when considering individual aggregates and their microstructure. Hence, it is vital to investigate management strategies that can potentially reduce the compaction risk and avoid this permanent structural decline.

2.3 Source of Compaction

Along with the soil’s mechanical strength, the characteristic of loading is the second factor that determines the degree of compaction, and is considered to be a large contributing factor influencing the soil compaction process (Defossez and Richard 2002, Hamza and Anderson 2005).
2.3.1 Dynamic Sources

Dynamic sources of soil compaction may include the vibration of machinery, trampling by animals (not discussed) and wheel slippage from agricultural machinery due to their dynamic loading conditions (Soane and Ouwerkerk 1994). These dynamic sources ultimately lead to high levels of vibrational forces at the soil surface that are projected into the soil profile, aiding the compaction process (Koolen 1983). Vibration propagates compression and shear waves into the soil (Hamidi, Nikraz et al. 2010), which act to reduce the soil cohesion and internal angle of friction and therefore soil strength (Soane and Ouwerkerk 1994). This is often why vibration rollers are used in civil engineering during the preparation of foundations. When considering agricultural machinery, it has been found that the vibrations induced under wheeled and tracked machines have different frequencies and oscillation patterns (Soane and Ouwerkerk 1994), thus resulting in different compaction impacts.

2.3.2 Static Sources

When assessing the magnitude of static sources, it is crucial to define and differentiate between pressure and force. The machine force may be described as the wheel axle load in kN or kg; whereas the pressure relates to the area in which this force is displaced, and is measured in kPa. These two factors have shown to contribute to soil compaction at different locations within the soil profile, with evidence to show that subsoil compaction may be determined by the axle load however topsoil compaction has a greater relation to surface pressure (Hamza and Anderson 2005).

The machine weight and geometry determines the wheel axle load, whilst the tyre inflation pressure, number of tyres, and tyre dimensions determine the contact pressure. In an agricultural setting, the grower often has no influence over the wheel axle load. However they may have the potential to manage the contact pressure, via the manipulation of tyre pressures, increasing the number of tyres, and/or manipulation of tyre dimensions, which all can increase the contact surface area. It has been shown that these factors have a direct relation to change in soil bulk density (Horn, Way et al. 2003), and are therefore factors that must be considered when managing the soil compaction risk. A compromise exists however, when employing these management strategies to reduce contact pressure by increasing the machine’s surface contact area. Although an increased surface area reduces contact
pressure, it results in a greater proportion of the field being trafficked and consequently a larger percentage of the field will be affected by surface compaction (Hamza and Anderson 2005, Tullberg, Yule et al. 2007). Conversely, reducing the contact area will increase the risk of subsoil compaction, however will decrease the percentage of the field being affected by traffic. Therefore, manipulation of tyre pressures and enlarging contact area by increasing the number of tyres may not necessarily provide an economically and environmentally viable option when aiming to reduce the compaction risk.

This problem exists with the configuration of the JD7760, which has dual wheels on the front axle and singles on the rear. When attached with the factory 6 metre picking head, this results in 66% of the field being trafficked. When considering the individual plant rows, the configuration leads to 33% of the rows being impacted by a wheel track on both adjacent furrows, and a further 66% of the rows being impacted by at least one adjacent wheel track (i.e. 100% of rows will be influence by adjacent wheel traffic to some degree). Thus, there is a large compaction risk associated with the machine in its current configuration.

2.4 Mechanics of Soil Compaction

When a soil medium is impacted by traffic, both axial and shear stresses are propagated through the profile. It is therefore crucial to develop a thorough understanding of the stress and strain relationships that exist for soil. When cultivating an understanding of these relationships, soil is assumed to be seen as an isotropic, homogeneous medium, which means that its properties are continuous across a soil volume and are independent of the measured direction (Soane and Ouwerkerk 1994). This is quite a large assumption as soil properties can change dramatically over short spaces, both down the profile and in the horizontal plane. Due to difficulties in accurately increasing the spatial resolution of soil data however, these types of assumptions are quite common.

Using the said assumptions, Boussinesq (1885) developed an analytical solution which may be used to map the propagation of the major principal stress through an ideal elastic material (Defossez and Richard 2002). When approximating the tyre-soil interaction by a vertical point load being applied to a semi-infinite elastic medium (Koolen 1983), it is possible to calculate the stress propagation through the profile. Boussinesq (1885) equation (Equation 2.1), shows that a point with radius ‘r’ and angle ‘θ’ from the vertical point load
only has principal stresses acting on it which are perpendicular to the radius. This can be represented by Figure 2.1.

\[ \sigma_1 = \frac{3P}{2\pi r^2} \cos \theta \]

Equation 2.1

Where

\( \sigma_1 = \) Applied Principal Stress [Pa]

\( r = \) Polar Coordinate radius [m]

\( \theta = \) Polar Coordinate [radian]

Figure 2.1 Stress in a volume element under point load P (Defossez and Richard 2002)

Boussinesq’s model however, does not account for any soil properties, which is far from ideal. This limiting theory was extended on by Fröhlich (1934), who recognised the need for a factor that accounted for soil strength and its effect of stress distribution (Kolen 1983,
Defossez and Richard (2002). This resulted in the inclusion of a concentration factor, $\nu$, which decreases with increased soil strength. The developed relationship is shown by Equation 2.2. The influence of this concentration factor can be observed in Figure 2.2, which shows the isobars of the stress distribution under a load of 8kN at three stress concentration values of 4, 5 and 6.

\[
\sigma_1 = \frac{\nu P}{2\pi r^2} \cos^{4-2}\theta
\]

Equation 2.2

Where

$\sigma_1$ = Applied Principal Stress [Pa]

$r$ = Polar Coordinate radius [m]

$\theta$ = Polar Coordinate [radian]

$\nu$ = Concentration factor [unitless]

Figure 2.2 Curves of equal pressure as described by (Defossez and Richard 2002) under an 8kN point load at three different concentration factors of 4, 5 and 6. Diagrams adopted from Equation 2.2 under a load using modified vertical point load method

From Figure 2.2, it is evident that the stress propagation under a point load radiates into the soil medium from the point of contact. However, this simplified point load may not be appropriate to describe the stress propagation underneath an agricultural tyre, as the force
is applied over an area rather than a point. Taking this into account, Sëhne (1953) modified the Bousinesq (1885) formulas to calculate the stress distribution under agricultural tyres (Defossez and Richard 2002). In his work, Sëhne (1953) assumed an elliptical surface contact area with a parabolic stress distribution over this area, although this could be altered if required. The stress distribution over a soil medium is represented in Figure 2.3.
Figure 2.3 Triaxial stress propagation under an elliptical surface contact area where $\sigma_1$, $\sigma_2$, and $\sigma_3$ represents the principal stresses acting at an arbitrary point according to (SÈhne 1953). (Defossez and Richard 2002)

Although SÈhne (1953) only accounted for the vertical normal stress, his work was extended by (Johnson and Burt 1990) to account for triaxial stresses due to wheeling (Defossez and Richard 2002). These triaxial stresses are also represented in Figure 2.3. When considering a centre line static load, $\sigma_1$ is vertical (estimated by Equation 2.2), $\sigma_2$ is longitudinal and $\sigma_3$ is tranverse (O’Sullivan, Henshall et al. 1999). It has been identified however that the directions of these three principal stresses rotates during traffic. The major principal stress, $\sigma_1$ is estimated by Equation 2.2, whereas $\sigma_2$ and $\sigma_3$ are determined by the size of the contact area, the shape of the stress distribution and the percentage of wheelslip (O’Sullivan, Henshall et al. 1999).

Using the Johnston and Burt model of triaxial stresses, O’Sullivan, Henshall et al. (1999) fitted regression equations to the outputs obtained and developed Equation 2.3, which can be used to calculate $\sigma_2$ and $\sigma_3$. Similarly to the Johnson and Burt (1990) model, $\sigma_1$ is estimated by Equation 2.3.
\[
\ln \left( \frac{\sigma_1}{\sigma_n} \right) = c_1 z - c_2 A + c_3 \zeta
\]

Equation 2.3

Where

\( \sigma_1 \) = Principal stress [Pa] as calculated by Equation 2.3

\( \sigma_n \) = Principal stress for \( n=2, n=4 \) [Pa]

\( c_1, c_2, c_3 \) = Regression constants

\( A \) = Contact Area [m²]

This literature develops an understanding of how stress is propagated through a soil medium from a static load. From this, it is important to note that stress propagation radiates from the point of contact on the surface. When considering vehicular traffic, it is necessary to consider that the compaction will not be localised to areas directly under the tyre's point of contact but will instead propagate into the surrounding subsoil volume. In an irrigated cotton scenario, where traffic is limited to furrows, this suggests that the stress, and therefore compaction will propagate from the furrows into the root zone underneath the hills.

2.5 Soil Failure Types

Soil failure may occur due to a compression stress, a shear stress or a combination of both. Failure due to shear may be approximated by the Mohr-Coulomb failure criterion, which takes into account the soil parameters of internal friction angle and cohesion. During the development of a model to estimate soil compaction, O’Sullivan et al. (1999) concluded that the main compaction effects were due to the intermediate and minor principal stresses, as opposed to the shear stress (O’Sullivan, Henshall et al. 1999). The main driving force for compaction may therefore be said to be the mean normal stress (Defossez and Richard 2002, Bennett, Woodhouse et al. 2015).

However, failure due to compression may be seen to be the point where irreversible soil compaction has occurred. With the aid of Figure 2.4, it can be seen that soil has an elastic and
plastic stage that will ultimately lead to a point of failure (Defossez and Richard 2002). The elastic stage of soil deformation occurs at stresses smaller than the pecompression stress, $P_c$, which results in reversible compaction. This stage may be represented by the parameter $K$. After the point of $P_c$, the soil begins to deform plastically resulting in irreversible soil compaction, which is extremely detrimental to agricultural production. This rate of plastic deformation may be described by the parameter $\lambda$.

![Isotropic Compression on a natural log scale (Defossez and Richard 2002)](image)

The pecompression stress is an important value that may be used to describe a soil’s susceptibility to compaction (Keller, Arvidsson et al. 2004), and is one of the most important parameters during the modelling of soil compaction. The risk of soil structural decline can be reduced by limiting agricultural traffic such that the applied mechanical stress is kept below the pecompression stress (Keller, Arvidsson et al. 2004). This is however quite unrealistic in modern agriculture, as stress induced by current machinery is much larger than common pecompression stress values. (Kirby 1992) suggested a $P_c$ value of 99 kPa should be adopted for Vertosol soils in Eastern Australia based off average data. When considering the weight of machines such as the JD7760, whose rear wheels support a load of 8441kg each (Bennett, Jensen et al. 2014), given the standard tyre dimensions, induces a total of 165kPa to the soil, and thus greatly exceeds the standard $P_c$ value.
2.6 Compaction Susceptibility

Understanding a soil's susceptibility to compaction is pertinent when making management decisions around the scheduling and execution of farming operations (Ohu, Folorunso et al. 1989, Saffih-Hdadi, Défossez et al. 2009). A soil’s compaction susceptibility is largely dependent on its mechanical strength. This is governed by many intrinsic properties such as soil texture, tilled layer at wheeling state, organic carbon content and the structure and water status. An increase in mechanical strength leads to a decrease in a soil’s compressibility, which refers to a soil’s resistance to volume changes when subjected to a mechanical load (Soane and Ouwerkerk 1994). Compressibility may therefore be described as changes in bulk density, $\rho_b$, which is described by the ratio of the dry soil weight and the soil volume.

It has been noted by (Hartge and Horn, 1984) that increased soil strength, and therefore susceptibility to compaction, is influenced either by the number of contact points between single particles or the shear resistance per contact point. The number of contact points may be influenced by the soil texture. It has been reported that soils with a finer texture, such as the predominate cotton growing Vertosol soils, have a higher compressibility (Soane and Ouwerkerk 1994) and tend to propagate stresses in multiple directions unlike coarser soils (Hamza and Anderson 2005). This is due to the small particle size of clay which has a reduced internal angle of friction, in comparison to coarser soils such as sand. (Tembe, Lockner et al. 2010).

2.6.1 Shearing Resistance

The shearing resistance of a given soil is described by the two parameters: 1) cohesion, $c$; and 2) angle of internal friction, $\varphi$ (Al-Shayea 2001). A soil’s cohesion is due to a number of effects including electrostatic and electro-magnetic attractions, cementation and adhesion due to compaction and capillary suction whereas the internal angle of friction refers to the frictional resistance between particles (Al-Shayea 2001). The Mohr-Coloumn model is widely used to describe the shearing strength of a soil, and is given by Equation 2.4. From this equation, it can be seen that the shearing strength (tau) of a soil is heightened by both an increase in cohesion and internal angle of friction.
\[ \tau = \sigma_n \tan \phi + C \]

Equation 2.4

Where

\( \tau \) = Shear stress

\( \phi \) = Internal angle of friction

\( \sigma_n \) = Normal stress

\( C \) = Cohesion

Al-Shayea (2001) found that both cohesion and internal angle of friction parameters were largely dependent on clay and moisture content. Using a series of triaxial strength tests on a number of different soils with varying clay and moisture contents, Al-Shayea (2001) was able to plot their effects on cohesion and internal angle of friction, as shown in Figure 2.4, (A) and (B) respectively. From Figure 2.4 (A), it can be noted that at a given clay content, soil cohesion peaks at a maximum value before declining with both reductions and increases in moisture. It can be seen that soil cohesion is more sensitive to changes in moisture content at clay contents greater >30% (Australian Vertosol soils for example). Furthermore, for such a clay content, the internal angle of friction appears to become redundant for soil moisture above 25%. It is understood that decreasing the internal angle of friction ultimately leads to reduced soil strength, and therefore an increase in compaction susceptibility, so by extension, heightened soil moisture should also increase the susceptibility.

For a given soil, the clay content may be described as a static value (soil texture changes occur only over large periods of time). Therefore, changes in internal angle of friction and cohesion may be best described by the moisture content.
Figure 2.5 Effects of water content and clay content on (A) soil cohesion and (B) internal angle of friction (Phi) (Al-Shaye 2001)
2.6.2 The Affect of Water

The affects of moisture content on compaction susceptibility have been well documented (Koolen 1983, Soane and Ouwerkerk 1994, Hamza and Anderson 2005). A soil’s compaction susceptibility, and therefore compressibility, may be found using a standard proctor test, which plots the dry unit weight of a given soil at varying moisture contents under a specific load (proximal to that of a sheep’s foot roller used in civil construction). The standard proctor test is often used to find the moisture content at which the maximum dry bulk density can be achieved. The moisture content that achieves the greatest dry density at a given compaction energy is referred to as the optimal water content (OWC) for compaction. Although from a geotechnical engineering standpoint the OMC is desirable, it may also be noted that this is the point where compaction susceptibility is at its greatest, as the most physical damage can occur when trafficking or cultivating the soil (Singer and Munns 2006).

A typical compaction curve that results from a standard proctor is demonstrated in Figure 2.6. It can be seen that initially, increases in soil moisture cause an increase in bulk density. This is represented in between points A and B on the curve where the water is acting as a lubricant between soil particles, thus allowing the individual particles to slip and slide over each other and fill void spaces (Al-Shayea 2001, Das 2009). It can be seen that after certain moisture content however, the soil’s ability to compact further ceases, instead, the bulk density declines under the same loading conditions. This phenomenon may be explained when considering the soil’s three phases: solid, aqueous and gaseous. During the development of a model to predict soil compaction curves, Hilf (1948) assumed that all solid and liquid parts of a soil are volumetrically incompressible, which is a reasonable assumption under the achievable magnitude of typical agricultural loading conditions. Therefore, as air is the only compressible proportion of the soil, it is responsible for the reduction in volume. As moisture content increases however, the air within the pores is replaced with incompressible water, which essentially acts as a hydraulic fluid under compression (A.V and Shah 2003). With a reduced proportion of compressible air, it would be expected that the soil is able to resist compaction.

However, as soil moisture increases, soil begins to act more like a liquid as it approaches the liquid limit (LL) (Keller and Dexter 2012). Although the risk of soil compaction is being reduced, the main concern at such moisture is traffickability and floatation. Trafficking a field at these moisture contents can be extremely detrimental to soil structure, as the
process of smearing shuts off soil pores at the stress-soil interface thus reducing infiltration post-traffic (Soane and Ouwerkerk 1994). Furthermore, larger energy costs are required due to increased wheel slippage and tillage requirements for subsequent seasons.

![Soil Compaction Curve](image)

**Figure 2.6** Soil Compaction Curve where $\gamma_d$ is the point where maximum dry density is achieved (Das 2009).

For high clay content soils, such as Vertosols, the soil moisture status is extremely important as it quickly diminishes soil strength due to the inherent low internal angle of friction with small particle size and the rapid reduction in cohesion with increasing water content. Furthermore, given the negative consequences of field traffic at moisture contents approaching and greater than the liquid limit, it is pertinent to investigate soil-water dynamics and how they might contribute to a reduced compaction risk during timely farming operations.

### 2.7 Managing Soil Compaction

Soil compaction is not a new concept in agriculture, thus it is prudent to investigate the current management strategies. Strategies that target traffic during high-risk weather predictions, where field moisture conditions may be less than ideal, will have the most
impact on cotton picking operations. During such conditions, the timing of traffic plays an integral role in the compaction risk (Bennett, Antille et al. 2015).

### 2.7.1 Soil Moisture Management

As previously established, managing soil moisture has a vital role in minimising compaction risk (Soane and Ouwerkerk 1994). However, achieving the optimal moisture content to minimise traffic effect is no simple task. There is perceived pressure on farmers to traffic soils at less than ideal field moisture conditions to overcome the financial implications of delayed operations. More often than not, wet traffic is chosen to minimise the risk of potential yield loss. As far as cropping is concerned, cotton provides one of the more resilient yields to moisture effects, considering it is largely carbon based, rather than a protein based yield.

Ayres (1987) found that volumetric moisture content was a good indicator for soil compaction vulnerability. Furthermore, detrimental soil compaction can only be reduced once the soil profile is allowed to significantly dry down, because of the due to soil moisture’s integral role in the soil strength process. Under current management practices, this may involve a period of waiting to allow moisture to be removed from the soil profile. As a rule of thumb, however, McKenzie (1998) suggested that harvesting-induced compaction risk is only reduced once the soil-drying front had reached a depth twice as large as the tyre width. Although this has no relation to the machine axle weight, it highlights a recognised need to remove moisture from deep in the profile in order to reduce the compaction risk.

Within the cotton industry, the risk of soil compaction during a wet harvest is exacerbated when considering the weight of the harvesting equipment, which exceeds 36 Mg. SoilPak for cotton (McKenzie 1998) was initially developed to offer the industry a number of Best Management Practices surrounding soil management, in order to optimise crop yields. Section B3 of the document outlines a number of best management practices for minimising compaction from harvesting equipment when soil conditions are less than ideal. It must be noted however, that these practices were developed for the previous basket picking system. Consequently, not all practices have merit under the current system.

The document outlines that there must be a trade-off between a quick harvest and the level of soil damage a grower is willing to accept (McKenzie 1998). Increasing harvester mobility
will allow the crop to be picked more rapidly, but this is at cost to soil degradation. The first suggestion is to increase the ground contact area of the picker, either by increasing the number of wheels or by reducing tyre inflation pressures to achieve machine floatation. Achieving machine floatation does not equate to the complete avoidance of compaction, which is a common misconception of people in industry. Machine floatation may result in decreased rut severity during traffic, however the compaction process is still occurring in the subsoil. Achieving flotation via the increase in contact area also subsequently increases the proportion of the field being trafficked. In effect, whilst the extent of impact in the root zone is reduced, the impact of subsoil compaction is not removed.

Achieving machine floatation via the addition of extra tyres on the JD7760 may not be seen as a viable option due to the field efficiency constraints which require the machine to turn in a tight circle at the end of each run. As the rear wheels on the JD7760 carry the largest axle load, an additional wheel would be required on this axle to attempt machine floatation. This would result in a larger turning circle (as the machine pivots from the front axle) and thus loss of field efficiency.

SoilPak (McKenzie 1998) highlights the importance of planning the picking pattern, such that the least amount of furrows are trafficked and the harvester wheel tracks are aligned with wheel tracks of previous traffic during the season (planter, spray rig etc). In the previous system this may have involved choosing between 4 or 6 row cotton pickers, depending on the width of the planter used. In the current system, this is not an available option as all pickers are 6-row factory standard. This management strategy highlights the importance of a Control Traffic Farming (CTF) system within cotton, which currently is not widely adopted in irrigated cotton due to the perceived difficulties in matching the cotton system with the grains 3 m system. The cause of this has been identified to be due to the requirement for the grower to seek aftermarket modifications of axle widths because of the limitations of the machinery imported from Europe and North America (Bennett, Woodhouse et al. 2015). Furthermore, the adoption of CTF in cotton is also limited due to the current standard 1 m furrow spacing, which does not align with the standard 3 m CTF system that has been adopted for grains. As many growers operate using a winter/summer crop rotational cropping system, it is not viable to have two sets of machinery on with different wheel spacings. Therefore, under current conditions, the only way to achieve CTF farming in cotton is to change the cotton system to 1.5 m row spacings. Although this has
been encouraged using the results of recent studies, it is not supported by the majority of industry (Bennett 2015).

SoilPak also highlights that trafficability improves as the soil drying process advances, for reasons investigated in earlier sections. Therefore, a thorough understanding must be developed of the soil drying process and soil moisture movement in order to increase trafficability and reduce the compaction risk in an irrigated cotton scenario.

2.7.2 Machinery Management

Although growers do not usually have direct control of the axle weight of their machinery, there is some ability to control how this load is distributed across the soil via the manipulation of tyre pressures, addition of dual wheels, manipulation of tyre characteristics, and/or use of a tracked machine (Soane and Ouwerkerk 1994). Manipulation of tyre pressures results in an increased surface area and consequently reduced contact pressure. This may be seen as the most versatile management option to achieve machine floatation as it can be rapidly changed to account for varying field moisture conditions. When considering machines such as the JD7760 however, which is in excess of 36Mg, this may not be a viable option as even the reduced contact pressure is still greater than the soil’s pre-compression stress and therefore detrimental soil compaction is spread over a larger proportion of the field.

Increasing the diameter of the tyre is one option that can increase the contact surface by extending the length of the footprint, which confines the traffic to the traffic lanes. This might be constrained by the configuration of the machine, which may only allow for a maximum wheel diameter.

2.7.3 Agronomic management

Three agronomic practices that have been deemed important in preserving soil structure and compaction resistance include the application of soil conditioners, appropriate choice of cropping systems and retention of organic matter (Soane and Ouwerkerk 1994). Appropriate choice of cropping system may refer to the adoption of Control Traffic Farming (CTF), which has been widely studied in terms of its ability to reduce the effects of soil compaction (Tullberg, Yule et al. 2007). For further information on CTF systems, readers are directed to Tullberg, Yule et al. (2007). Incorporating deep rooted crops into the cropping
rotation may also help the remediation of subsoil compaction layer. McKenzie (1998) recommends the use of Safflower or Lucerne to produce 'biological deep ripping', however this is not widely adopted within the cotton industry likely due to the timescale of the operation (i.e. an entire season) and the magnitude of the effects.

Increasing soil organic matter has also been found to reduce a soil’s compactability (Soane 1990). Furthermore, the sensitivity of soil compaction to organic matter is greatest at high moisture contents (Koolen 1983). As organic matter is difficult to incorporate into deeper layers of the soil profile, it may only be useful for surface compaction and compaction induced by excessive tillage.

2.8 Soil Moisture Movement

The concepts that govern soil moisture movement must firstly be investigated, in order to understand how moisture can be removed from the profile, effectively reducing compaction risk. Soil moisture movement occurs when there is an energy potential gradient, with moisture moving from high to low water potential (Singer and Munns 2006). This potential gradient is a function of pressure ($\Psi_p$), solute ($\Psi_s$), gravitational ($\Psi_g$) and matric potential ($\Psi_m$) factors (Singer and Munns 2006). Matric potential is caused by the soil matrix properties which work with the adsorptive forces of water due to hydrogen bonding (Singer and Munns 2006). This essentially allows the soil matrix to retain moisture by water adhering to humus and soil minerals. Therefore, in order for water to be removed from the soil matrix, external pressures must act which cause a change in water potential and overcome the matric potential.

The magnitude of the matric potential dominates the water movement in unsaturated soils (Singer and Munns 2006), with magnitude changing in accordance to moisture content and soil texture. Increases in soil moisture results in a decrease of matric potential, which leads to a greater ease of moisture removal. As water content decreases, larger amounts of potentials are required to drain the smaller pores due to water's adhesive forces. This relationship may be described by the soil moisture characteristic curve (Figure 2.6). When observing the fine textured (high clay content) horticultural soil (similar to Vertosols), it can be seen that soil matric potential increases rapidly with small decreases in volumetric water content, as opposed to the coarser, textured river sand. This shows that the heavy clay soils retain moisture extremely well and high potentials are required to overcome the large
negative potential and remove soil moisture. Clay particles are colloidal (<2 µm) meaning they have very high surface area for their volume, thus increasing the amount of surface area for adhesion within a bulk volume and resulting in smaller pore networks (Hubbard 2014). This explains why clay soils hold greater soil moisture than sandier soils as suction is applied. This relationship may be described by the capillary rise equation, presented as Equation 2.5. From this equation, it can be noted that both surface tension and adhesion (i.e. contact angle between surfaces) play an important role in the capillary rise and resulting pore suction.

![Soil moisture characteristic curve for various soil types](image)

**Figure 2.7** Soil moisture characteristic curve for various soil types (Campbell 1986)

\[
h = \frac{2 \cdot s \cdot \cos \omega}{\rho_{\text{water}} \cdot g \cdot \tau}
\]

Equation 2.5
where

\[ s = \text{surface tension of water} \text{ (commonly taken as 0.0728 Nm}^{-1} \text{ at 20°C)} \]

\[ \omega = \text{angle of adhesion between surface and water} \text{ (cos}\omega \approx 1) \]

\[ \rho_{\text{water}} = \text{density of water} [\text{Mg m}^{-3}] \]

\[ g = \text{gravitational constant} \text{ (taken as 9.81 ms}^{-2} \text{)} \]

\[ r = \text{pore size radius} \]

### 2.8.1 Gravitational affects

Gravitational potential leads to seepage through the soil matrix (drainage), which results in water being removed from the effective soil depth in relation to the plant root-zone, or depth of interest. Gravitational potential is the dominant factor of water movement in saturated soil (Singer and Munns 2006), as at saturation all soil pores are conducting and soil moisture potential is 0. It is known that fine textured soils (for example the Australian Vertosol) have slower rates of drainage (Thompson, Collett et al. 2013), due to their low hydraulic conductivity as opposed to coarser soils. In such soils, it is not viable to rely on seepage-induced soil moisture dry down over a relatively short time period leading up to harvest. Furthermore, deep drainage only occurs where gravitational potential overcomes matric potential. This means that high clay content soils will hold more moisture at low potential than coarse textured soils due to their increased surface area and subsequent adhesion, as explain by Equation 2.5.

### 2.8.2 Evaporation affects

Evaporation is the process whereby a liquid is converted into a vapour (Allen, Pereira et al. 1998). In order for evaporation to occur, three requirements must be met: 1) a source of energy must be present to induce water state change; 2) a transport mechanism for water vapour must occur; and 3) a source of water must be present (Hancock 2015). Solar radiation is the dominant source of energy that is responsible for the evaporation process (Allen, Pereira et al. 1998, Hancock 2015). With similarity to liquid-water within the soil matrix, water-vapour moves from regions of high water potential (high humidity) to regions
of low water potential, or low humidity (Singer and Munns 2006). This water potential gradient exists at the soil-atmosphere interface (evaporating surface). As the evaporation process continues, the surrounding air becomes increasingly saturated and therefore water potential is reduced. This results in a lessened evaporative driving force. This phenomenon may be described as the vapour pressure deficit (VPD), which refers to the air’s ability to act as a transport mechanism for the water vapour (Hancock 2015). This VPD then creates a negative potential whereby moisture from depth within the soil profile is drawn to the surface and the process continues.

Wind can greatly increase evaporation by replacing the saturated atmosphere adjacent to the evaporative surface with dry air, thus increasing the water potential gradient. Therefore, the evaporation process of a soil is largely dependent on air temperature, solar radiation, air humidity and wind speed (Allen, Pereira et al. 1998). Hancock (2015) reported that the aerodynamic components of evaporation (wind and humidity) were just as influential as the direct energy aspects (solar radiation) and should therefore be taken into account when estimating the evaporation potential. When considering a soil surface however, the evaporation process also depends on the degree of crop shading and amount of available water within the soil (Allen, Pereira et al. 1998).

Depending on the agronomic and climatic conditions, the actual rate of evaporation is governed either by the ‘evaporation potential’ or the ‘evaporation capacity’. Evaporation potential (EP) is influenced only by the climatological parameters listed earlier and refers to the evaporation that could occur under specific climatic conditions if water is freely available (i.e. free water surface) (Hancock 2015). Evaporation capacity (EC) however refers to the soil’s ability to supply water and meet the evaporative potential. EP and EC are rarely equal due to the cohesive and adhesive forces that exist between the water and soil particles. When the topsoil is close to saturation and the matric potential is low, evaporation is governed by the EP; however, as the soil begins to dry-out, the matric potential increases and E is governed by the EC (Allen, Pereira et al. 1998).

As the soil begins to dry out, its ability to conduct moisture near the surface is reduced due to the increased water potential - meaning only the smaller pore networks are responsible for conductivity (Allen, Pereira et al. 1998). This phenomena can be linked back to Equation 2.5 which shows that as pore sizes decrease, a greater suction head is required for water
movement. Therefore, the evaporative loss from a soil is not a linear relationship, and in order to estimate it accurately there needs to be an understanding of both the soil and environmental characteristics over time. Allen, Pereira et al. (1998) also concluded that in the absence of water supply at the soil surface, the rate of evaporation can rapidly decrease over a few days and can often completely cease. Therefore, over relatively short time periods, it may be concluded that the effects of evaporation are only largely significant in the topsoil. In this case, it is likely to be impractical to rely on evaporation alone to remove moisture from the subsoil in order to reduce the subsoil compaction risk. Furthermore, during cotton defoliation evaporation efforts are also impeded by ground cover resulting from fallen plant leaves (McKenzie 1998). With respect to cotton in Australia, reduced evaporative demand also results from the climatic conditions around the time of harvest (Autumn).

2.9 Transpiration Effects

Transpiration is the process whereby liquid water within the plant tissues is released through the leaf stomata and vaporised into the surrounding atmosphere (Starr 2015). Like evaporation, transpiration is similarly affected by the same climatic parameters, however there are a number of crop parameters that must also be considered (type of crop, stage of development, maturity etc.) (Allen, Pereira et al. 1998). During the transpiration process, the water exiting the plant leaves creates a negative potential within the plant. This results in the migration of water from the soil, through the plant and into the atmosphere. The ease of this migration from the soil to the leaves is also governed by the moisture content and hydraulic conductivity of the soil which effects the soil matric potential. As a soil becomes increasingly dry its matric potential becomes more negative, which increases the amount of force required to migrate the moisture from the soil into the plant. Transpiration may be responsible for removing moisture from deeper within the soil profile, which is desirable when desiring to reduce the compaction risk within the subsoil. A typical pattern of water extraction through the profile may be described in Figure 2.8 below. For a cotton crop whose maximum root length may extend to 100 cm (Min, Guo et al. 2014), this generic distribution suggests that 60% of the crop's water requirements are being extracted from below 25 cm.
2.9.1 Evapotranspiration

As evaporation and transpiration occur simultaneously and the physics that govern their nature are comparable, the two terms are usually combined and referred to as ‘evapotranspiration’ (ET). The proportion of evaporation and transpiration that makes up the total ET changes during the growing season is largely dependent on the crop’s ability to shade the soil (Pereira, Allen et al. 2015). Such dynamics are shown in Figure 2.7, where it is seen that as the season progresses, crop transpiration makes up the greatest proportion of ET. This is aligned with the leaf area index (LAI), which shows the leaf area per unit of soil surface. Whilst the transpiration proportion of ET decreases at harvest, it is evident that the greatest water loss from the soil is still due to transpiration. This highlights merit in considering delayed harvest to cause extended crop transpiration, as an attempt to dry down the soil profile at a wet harvest.
Figure 2.9 Contributions to evapotranspiration during the duration of the growing season (Allen, Pereira et al. 1998)

The proportions of ET also change over a much smaller time period (i.e. days following an irrigation or rainfall event), which is demonstrated in Figure 2.8. This depicts soil moisture drawdown in a soil profile over time after an irrigation event, whereby, initially the greatest proportion of soil moisture drawdown is occurring in the top 0-40cm. This is mainly due to evaporation as the moisture in the near-saturated topsoil is freely available and easily vaporised. However, as time progresses the greatest proportion of soil moisture drawdown occurs in the subsoil (30-80cm), and there is less of a drawdown near the surface. This suggests that surface layers have dried out enough to increase matric potential, thus reducing hydraulic conductivity. The evaporative potential at the surface is therefore compromised. The increasing subsoil drawdown however is likely due to the transpiration demands of the plant.
2.9.2 Assessment and Prediction of Evapotranspiration

Evapotranspiration is a difficult phenomenon to measure (KocAK and Baris 2009), due to the practicalities of capturing the water vapour without interfering in the ET process. For this reason, ET quantification is normally referred to as ‘ET estimates’ or ‘ET assessments’ (Hancock 2015). ET can be estimated using both direct and indirect methods. Direct methods include the evaporation pan lysimetry. These methods are limited, as pan evaporation only gives some indication of the evaporation potential and is not representative of crop evapotranspiration. Also, lysimetry is often extremely expensive and impractical. A numerical approach developed by Penman (1948) resulted in the production of the well-known Penman Montheith Equation, which is used to estimate evapotranspiration from climatic variables (Zotarelli, Dukes et al. 2009). This approach was updated by FAO (Allen, Pereira et al. 1998) to produce the FAO-56 Penman Montheith Equation, presented as Equation 2.6.
\[
ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34u_2)}
\]

Equation 2.6

Where:

\( ET_0 = \text{reference evapotranspiration \ [mm \ day^{-1}] } \)

\( R_n = \text{net radiation at the crop surface \ [MJ \ m^{-2} \ day^{-1}] } \)

\( G = \text{soil heat flux density \ [MJ \ m^{-2} \ day^{-1}] } \)

\( T = \text{mean daily air temperature at 2 m height \ [°C] } \)

\( u_2 = \text{wind speed at 2 m height \ [m \ s^{-1}] } \)

\( e_s = \text{saturation vapour pressure \ [kPa] } \)

\( e_a = \text{actual vapour pressure \ [kPa] } \)

\( e_s - e_a = \text{saturation vapour pressure deficit \ [kPa] } \)

\( \Delta = \text{slope vapour pressure curve \ [kPa °C^{-1}] } \)

\( \gamma = \text{psychrometric constant \ [kPa °C^{-1}] } \)

This can then be extended using Equation 2.7 to calculate the actual crop evaporation. This equation essentially converts the reference crop evaporation to actual crop evaporation via the use of a crop coefficient, \( K_c \), which is based off crop and location-specific information.
\[ ET_c = K_c \times ET_o \]

Equation 2.7

where

\[ ET_0 = \textit{reference crop evaporation} \]

\[ K_c = \textit{Crop Coefficient} \]

\[ ET_c = \textit{actual crop and soil evaporation} \]

This method provides the basis for modelling ET, as mathematical relationships and formulae can be developed.

2.10 Modelling Soil Moisture Dynamics

Soil-water interaction may be described by a number of existing numerical/computational models that have been formulated from first principle physical calculations, or based on assumptions around these. Given the amount of detailed climatic data collected nationally at a sub-regional scale, parameterisation of these models can lead to fairly accurate long-term trends. However, to increase accuracy there is a dependence on detailed soil parameters that define soil hydraulic conditions. This section will explore the capability of modelling to inform soil-moisture dynamics to initialise conditions for compaction risk assessment.

Modelling is particularly important when investigating soil moisture dynamics over a large period of time as understanding true dynamics at the field scale is extremely costly both economically and temporally. A number of models are commercially available within industry surrounding soil moisture dynamics in an agricultural system: HowLeaky? (McClymont 2007); APSIM (Agricultural Production Systems Simulator) (McCown, Hammer et al. 1996); and HYDRUS (Simunek, van Genuchten et al. 2005) are the most commonly utilised models in Australian agriculture.

HowLeaky? is a water balance simulation software package that uses the PERFECT (Littleboy, Freebairn et al. 1999) model. HowLeaky? was developed within the Department of Environment and Resource Management (DERM) and may be used to assess the impacts of soil conditions, land uses, management practices and climate types on water balance.
The PERFECT model used in HowLeaky? has been extensively validated for semi-arid to sub-tropical environments using data from more than 16 soil groups, 45 farming management operations and 7 locations (Abbs and Littleboy 1998, Ranatunga, Nation et al. 2008). However, the model has been identified to be quite limited due to the fact that it is only able to model based off average planting/harvesting dates, and calibration outcomes in data poor environments are limited (Melland, Vigiak et al. 2010). Furthermore, the model has not been calibrated or tested in temperate climates, which make up the majority of the cotton growing regions (Stone and Willis 1983). Therefore, the HowLeaky? model was deemed inappropriate for modelling the proposed management strategy.

APSIM is able to model the soil-water-crop interaction and was developed to simulate a number of biophysical process in farming systems (Keating, Carberry et al. 2003). The strength of this model is the detailed biophysical validation of the various crop models, meaning that the crop component of the model is extremely strong under most conditions. However, the cotton module of the model is less developed in comparison to grain crops, such as wheat (D Johnston 2015, Pers. Comm 16 September). APSIM models the soil-water interaction using the SoilWat (Probert, Dimes et al. 1998) module, which was developed from the previously existing CERES (Jones and Kiniry 1986) and PERFECT (Littleboy, Freebairn et al. 1999) models. Unlike HowLeaky?, APSIM can also incorporate crop specific models such as the cotton module, OZCOT (Hearn, A.B. et al. 1984), to predict crop performance, and in particular, soil-moisture demand. The SoilWat module incorporates a number of soil specific properties to predict the soil-water interaction, including the drained upper limit (DUL), the saturated water content (SAT), the lower limit (LL) and the saturated hydraulic conductivity (Huth, Bristow et al. 2012). However, the soil profile in APSIM is considered static, parameterised at initialisation and unchanged throughout subsequent simulations, which presents some issues in modelling changes in soil hydraulic properties over time.

In essence it is a physical model founded in the physics of fluid transport in porous media, which is an approach that solves the Richards equation (Liu, Yang et al. 2013). The strength of this model is the dynamics available in understanding water movement in a 3D domain (Kandelous and Šimůnek 2010). While the model allows climatic records and irrigation scheduling to be incorporated, the crop water use module of the model is very limited. It also does not have any parameters for cotton, although the user could specify the base
information for cotton water use if known or by coupling a crop growth module from another model (Han, Zhao et al. 2015). In comparison to APSIM, the crop water module of HYDRUS is elementary, resulting in potential underestimation of dynamics, and vice versa for the soil model in APSIM. The most power would be gained by coupling the models, but this is currently not available and both models use different coding languages.

Evaluating these models on their strengths and weaknesses, APSIM appears to currently be the stronger platform to evaluate crop specific soil moisture draw down. Considering the proposed management strategy is based on crop physiology, APSIM provides benefit over HYDRUS in predicting draw down. APSIM incorporates a widely used soil water balance module (SoilWat), and a cotton crop specific module (OZCOT) that have previously been well validate (Hearn 1994, Carberry and Bange 1998, Milroy, Bange et al. 2004, Richards, Bange et al. 2008). However, it is noted that coupling of HYDRUS and APSIM would be the most powerful approach, providing source coding could be integrated.

2.11 Modelling Soil Compaction

Predicting the soil water dynamics throughout a season is imperative for prediction of the soil water status at the time of harvest, but this alone does not supply understanding of compaction risk. Prediction of the subsequent machine-induced soil compaction at the initialised soil water status is thus pertinent in understanding compaction risk mitigation. Hence, modelling the compaction process provides a useful tool in estimating the likelihood of compaction prior to traffic (Bennett, Antille et al. 2015). Soil compaction models may be divided into two categories: 1) Analytical (pseudo-analytical); and 2) numerical (finite element models – FEM) (Defossez and Richard 2002, Abu-Hamdeh and Reeder 2003). Although the model types are comparable, they are distinguished mainly by the determination of the loading force propagation. A study undertaken by Bennett, Antille et al. (2015) identified that analytical models are more appropriate for soil compaction prediction as they have demonstrated high levels of practicality. This is opposed to numerical models, which require large sets of parameters to sustain their complexity.

The review of Bennett, Antille et al. (2015) has already provided adequate investigation into model applicability and merit, hence readers are directed to this review for expansion on the following discussion. In particular, the study highlighted the analytical model SoilFlex (Keller et al. 2007), as it provides the user with a greater amount of flexibility and
practicality, in comparison to other existing analytical models such as ‘TASC’ (Diserens and Steinmann 2002), ‘Compsoil’ (O’Sullivan, Henshall et al. 1999) and ‘SOCOMO’ (Johnson and Burt 1990).

SoilFlex is a two-dimensional model that is able to predict stress propagation domains, vertical soil displacement (rut depth) and changes in bulk density due to agricultural field traffic (Keller, Défossez et al. 2007). When simulating soil deformation the user is able to select one of three different approaches to stress-strain relationships, in order to calculate volumetric strain and change in bulk density (Keller, Défossez et al. 2007). These approaches all describe the compressive behaviour of agricultural soils and were developed by O’Sullivan and Roberston (1996), Larsson et al. (1980) and Bailey and Johnson (1989) respectively. Readers are directed to Keller et al. (2007) for a more intensive explanation of the underlying mathematics that govern each of the three approaches. Recent publications have used SoilFlex to understand the stress state propagation under the JD7760 (Bennett, Jensen et al. 2014, Braunack and Johnston 2014, Bennett, Woodhouse et al. 2015) and a current Cotton Research and Development Corporation Project (NEC1301) is validating this model for Australian Vertosols (Bennett, Antille et al. In Prep). Hence, for Australian circumstances the SoilFlex model has been evaluated as the most appropriate for subsequent soil compaction prediction and identification of soil compaction risk at harvest soil water status conditions.

2.12 Conclusion

The effects of soil compaction in conventional agriculture can be extremely detrimental, with the cotton industry being no exception. The importance of developing management strategies that reduce the compaction risk in less than ideal field moisture conditions is highlighted to be paramount to production and profitability longevity. It has been established that soil moisture is the greatest influencing factor in the compaction process and it is therefore pertinent to reduce soil moisture to lesson the compaction risk, where machine weight cannot be manipulated to have impact less than soil pre-compression stress.

It is evident that relying solely on evaporation to reduce soil moisture and compaction risk may achieve flotation but is unlikely to significantly affect subsoil, thus not reducing the risk of subsoil compaction. Although, plant evapotranspiration was found to contribute to soil
moisture removal from deeper in the profile. This may suggest that it is plausible to rely on crop evapotranspiration in less than ideal field moisture conditions to reduce compaction risk at harvest. For a wet harvest cotton scenario, defoliation might therefore be delayed in order to keep the crop active and continue the evapotranspiration effects. However, there is a paucity of literature investigating this as a legitimate strategy.

Furthermore, in developing a detailed understanding for the feasibility of this strategy, there are numerous factors that must be measured within the soil to understand the dynamics of the system. This review has highlighted that this is an expensive process in terms of monetary and time expanses. Hence, there is value in validating a modelling based approach to extrapolate the feasibility of this approach to the wider cotton industry. Based on the strengths and weaknesses of existing models, it would appear that the best approach considering current limitations would be to firstly use APSIM to initialise the soil moisture status conditions of the soil profile prior to harvest, followed by simulation of compaction at these conditions using SoilFlex.
3 Design and Methodology

This chapter outlines the experimental design and methodology components of the dissertation. It contains details on both the experimental design of the field investigations, as well as the experimental design for the modelling approach.

3.1 Field Trial

This section pertains to the design and methodology for the field investigation component of the dissertation. It must be noted that the initial experimental design for the trials changed somewhat due to adverse weather conditions during the trial.

3.1.1 Site Selection

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) and is displayed in Figure 3.1 below. The site was selected based on the following criteria: i) Conditions were typical of the majority of cotton growing regions; ii) The site was under furrow irrigation; and, iii) The site was within close proximity to Toowoomba, where the dissertation was being completed. The site satisfied each of these criteria.

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). It is therefore considered largely representative of the industry. 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. The site was located 40km West of Toowoomba, which allowed for reasonable access during timely field operations. Due to the limited resources, only one site was selected for field trial investigations. The results obtained from this site were used as a validation data set to assess the merit of the proposed management strategy over different cotton growing regions, using a modeling approach.
Figure 3.1 Location of Aubigny trial site, approximately 40km West of Toowoomba on the Darling Downs, QLD

The site was also selected in conjunction with other work that was being completed by Dr Alison McCarthy and Dr Dio Antille within the NCEA, involving the collection of site-specific weather data for the season.

According to the Bureau of Meteorology (2015), the site has a temperate climate where there is no ‘dry season’, although rainfall averages are higher for the summer months. The closest available weather station was situated in Oakey, 10km Northeast of the site. The monthly average statistics for Oakey are displayed in Table 3.1.
### Table 3.1 Oakey Climate Statistics

<table>
<thead>
<tr>
<th>Climate data</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8</td>
<td>9</td>
<td>7</td>
<td>8</td>
<td>2</td>
<td>0</td>
<td>5</td>
<td>4</td>
<td>9</td>
<td>7</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>Av. Rainfall (mm)</td>
<td>80.</td>
<td>81.</td>
<td>48.</td>
<td>31.</td>
<td>41.</td>
<td>29.</td>
<td>29.</td>
<td>29.</td>
<td>29.</td>
<td>30.</td>
<td>56.</td>
<td>76.</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>2</td>
<td>7</td>
<td>2</td>
<td>5</td>
<td>9</td>
<td>1</td>
<td>4</td>
<td>7</td>
<td>1</td>
<td>1</td>
<td>7</td>
</tr>
</tbody>
</table>

#### 3.1.2 Original 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. Therefore, all of the possible sets of treatments are shown in Table 3.2.

### Table 3.2 Experimental Treatments

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Defoliated</th>
<th>Not Defoliated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall event simulated</td>
<td>Plot 1</td>
<td>Plot 2</td>
</tr>
<tr>
<td>No rainfall event simulated</td>
<td>Plot 3</td>
<td>Plot 4</td>
</tr>
</tbody>
</table>

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 long enough in the direction of JD7760 travel to reduce the edge effects (i.e. 3m). A visual representation of each plot with the JD7760 configuration may be seen in Figure 3.2. The blocks were located 6 rows (one picker width) in from the edge of the field. This was chosen as a compromise between reducing the edge effects of the field and practicality issues surrounding the application of the simulated rainfall event. The statistical design of the project needed to be weighed against the physical impact of the project on the farmer’s field. It was important to limit damage to the farmer’s soil during the digging of soil pits post-experiment and to reduce interruption to in-field operations from small-scale irrigation equipment (project based not farm based equipment). Therefore, the blocking of replicates in a single machine frontage close to the edge of the field was negotiated with the farmer. A buffer of 3m was introduced between each plot to ensure the treatments of each experimental unit did not affect the treatments of the adjacent experimental unit. The layout of the experimental design is visually represented in Figure 3.3.
Figure 3.2 Layout of individual plot with cotton picker configuration. Dashed lines represent cotton rows and the solid lines represent the boundary of the plot. The solid red line represents the center differential furrow where the moisture sensors were installed.
Figure 3.3 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 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). They operate by measuring the dialectic constant of the soil using capacitance/frequency domain technology (Decagon, 2015). Installation consisted of digging a small soil pit to the desired depth and inserting the sensors into the undisturbed soil face, followed by careful refilling of the pit. 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.
The method used to simulate the rainfall event had to ensure that the applied water was evenly distributed throughout each plot and was applied directly to the soil. After some investigation it was identified that the best way to achieve this was via the use of drip irrigation lines, where the drip was applied directly to the surface. A total of 4 grids were manufactured, each with a total of 65 drippers. These were rated to apply a constant flow rate of 2 L/hr under a pressure head of 4m or greater. A diaphragm pump was used to achieve this. The plots were designed such that the water from each dripper could be evenly distributed throughout each plot and the entire soil volume could be wet-up. Following significant discussion, it was identified that the drippers on the outer edges were able to contribute soil moisture to a distance of 25 cm from the dripper. Therefore the grids were manufactured to be 2.5x6.5 m in size, meaning they were able to wet-up an effective area of 3x7 m. Before installation, the grids were tested at two separate locations on the Darling Downs, on similar and dissimilar soil types. After wet-up using the plots, soil cores were taken and it was observed that moisture was evenly distributed through the soil profile.

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 3.4 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.
3.1.3 Adjusted Experimental Design

The original experimental design was adjusted throughout the course of the trial due to unavoidable weather events, which interfered with the trial’s original methodology. On the 2&3/05/2015, 11-12 days before the cotton was harvested and 4 days before the simulated irrigation was scheduled, the site received a rainfall event of 145 mm. This effected the original experimental design as it abolished one factor of the rainfall treatment (i.e. the ‘no rainfall’ treatment). It was debated whether or not to apply more water on the ‘rainfall’ treatments. However, this was dismissed because of the low temperatures that followed and the consequential lack of crop evapotranspiration. Due to this, it was postulated that there would not be an observable soil moisture draw down difference if additional water was added. Therefore, it was decided to emit the ‘no rainfall’ treatment, 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.
Figure 3.5 Adjusted Experimental Design where blue shading represents the non-defoliated treatment, clear shading represents the defoliated treatments and line shading represents the buffer zones. Identified by code ‘XY’ where X = N for North Block, S for South Block, and Y represents the plot identification within the block.

As mentioned, the large rainfall event was also associated with a significant drop in daily average temperatures, which drastically reduced the evapotranspiration demand of the cotton crop. This reduction in temperature was quite unseasonal, as displayed in Figure 3.6, which was taken from SoilWater App (USQ 2015), using data from SILO Climate Data (The long paddock) (Queensland Government 2015). As seen, during the period between the second defoliation and harvest, average daily temperatures were significantly cooler than average. Therefore, this may suggest that the weather conditions were not representative of a ‘typical season’. This inferred that the direction of the dissertation should focus on the modelling aspects to assess the merit of the proposed management strategy over a larger number of seasons that were more ‘typical’. The data was always considered as a validation dataset for subsequent use, but the importance of this was enhanced.
Figure 3.6 Daily average temperatures over the period of defoliation where the dark blue line represents average conditions, the light blue lines represent all observations and the red line represents this season’s observed temperatures. SoilWater App (USQ 2015)

3.1.4 Methods of Measurement

The methods of measurement were developed according to the objectives of the project. As mentioned, soil moisture sensors were installed to measure the soil moisture drawdown at different depths in the various plots. In order to measure the extent to which the treatments affected the soil compaction process, a number of other measurements were taken. These are summarised in Table 3.3, for both before and after traffic. Due to the time demands of all the instruments, the ‘before’ measurements commenced 2 days prior to harvest (14/05/2015), and the ‘after’ measurements took place throughout the week following harvest.
<table>
<thead>
<tr>
<th><strong>Measurement</strong></th>
<th><strong>Before Details</strong></th>
<th><strong>After Details</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Samples</td>
<td>5 cores taken from each plot (2x Right inner wheel furrow, 2x Left inner wheel furrow, 1x Right outer wheel furrow). 10cm increments to 80cm (total of 40 samples per plot)</td>
<td>7 cores taken from each furrow of each plot, including both adjacent guess rows. 10cm increments to 80cm (total of 56 samples per plot)</td>
</tr>
<tr>
<td>Profiling</td>
<td>5 profiles taken from each plot (all traffic furrows and center differential furrow)</td>
<td>5 profiles taken from each plot (all traffic furrows and center differential furrow)</td>
</tr>
<tr>
<td>Shear Strength</td>
<td>5 repetitions taken in each traffic furrow and differential furrow of each plot (total of 25 reading from each plot)</td>
<td>5 repetitions taken in each furrow including both adjacent guess rows (total of 35 reading from each plot)</td>
</tr>
<tr>
<td>Penetration</td>
<td>Transect taken across each plot from Eastern guess row to Western guess row</td>
<td>Transect taken across each plot from Eastern guess row to Western guess row</td>
</tr>
<tr>
<td>Pit Face Shear Resistance</td>
<td>N/A</td>
<td>Measurements taken across each soil pit face from center diff row to Western guess row. Readings taken at 20cm increments in the horizontal direction and 10cm increments in depth (vertical direction) to 80cm (128 readings per pit)</td>
</tr>
<tr>
<td>Pit Face Photos</td>
<td>N/A</td>
<td>Photo taken of each furrow profile of each pit (total of 7 for each pit)</td>
</tr>
</tbody>
</table>
3.1.5 Soil Moisture Modelling Component

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).

3.1.6 Model Validation

The primary purpose of the field experiment was to obtain a soil moisture data set that could be used to validate APSIM for the use of modeling the proposed management strategy over time. 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. There are 7 possible types of observations in a given file, which are identified as a numeric ‘code’ in the output file. The codes are:

- 0 – An actual observation
- 1 – An actual observation from a composite station
- 2 – a value interpolated from daily observations
- 3 – A value interpolated from daily observations
- 6 – A Synthetic Pan value
- 7 – An interpolated long term average

This is particularly useful when weather stations in regions have only been active intermittently or they do not possess the full range of instruments. These infilling techniques are used for all forms of climate data (i.e. radiation, maximum temperature, minimum temperature, rainfall, pan evaporation, vapour pressure).
For the purpose of the validation simulation, the Pittsworth, QLD station was used as the primary weather station, as the Oakey climate file had data quality issues during the 2014/2015 season. The Pittsworth station was located 26.6km Southwest of the Aubigny trial site.

The ‘Black Vertosol-Mymbilla (Bongeen No001)’ soil file was chosen from APSIM’s APSoil database as it was thought to be representative of the soil at the trial site. After consultation with industry soil scientists (J Bennett, A Biggs 2015, Pers. Comm 20 August), it was decided that the soil represented in the Bongeen soil file was similar to that at the trial site. The purpose of these soil files is to enable the estimation of Plant Available Water Capacity (PAWC) of site-specific soils (APSIM, 2015) in order to more accurately model the soil-moisture dynamics. Data was available for 7 separate layers within the soil profile (0–15, 15–30, 30–60, 60–90, 90–120, 120–150, 150–180 cm) for the Bongeen soil file, and this was thought to be of good resolution.

The dates and nature of all farming operations for the trial field were replicated in the model to closely represent what had occurred during the season. These operations are summarised in Table 3.4.

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet-up Irrigation</td>
<td>28/10/14</td>
</tr>
<tr>
<td>Planting</td>
<td>4/11/14</td>
</tr>
<tr>
<td>Second Irrigation</td>
<td>18/12/14</td>
</tr>
<tr>
<td>First Defoliation</td>
<td>24/04/2015</td>
</tr>
<tr>
<td>Rainfall Event</td>
<td>2-3/05/2015</td>
</tr>
<tr>
<td>Second Defoliation</td>
<td>6/05/2015</td>
</tr>
<tr>
<td>Harvest</td>
<td>14/05/2015</td>
</tr>
</tbody>
</table>
These details were manually added into the APSIM model and the model was run with a warm-up period of 12 months.

### 3.1.7 Historic Modelling for Various Sites

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 model was established using the ‘sowing rule’ module within APSIM, which automatically selected a crop sowing date depending on climatic and soil moisture conditions. The stipulated planting window was of a 4-week duration between the 15th of October and the 15th of November. All other sowing criteria are displayed below in Figure 3.7.

![Figure 3.7 APSIM entered sowing criteria](image)

The model was established to simulate an irrigated cotton scenario, and therefore the ‘furrow irrigation’ module was applied. The irrigation criteria used in the simulation is
shown in Figure 3.8. The values utilised were the default values that were pre-loaded into the module.

(A)

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of soil layers used in calculating SW deficit</td>
<td>6</td>
</tr>
<tr>
<td>Fraction of ASW below which irrigation is applied (0-1.0)</td>
<td>0.8</td>
</tr>
<tr>
<td>The earliest date irrigation will be applied (dd-mmm)</td>
<td>1-oct</td>
</tr>
<tr>
<td>The latest date irrigation will be applied (dd-mmm)</td>
<td>1-mar</td>
</tr>
</tbody>
</table>

(B)

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automatic irrigation</td>
<td>on</td>
</tr>
<tr>
<td>Depth to which ASW is calculated, (mm)</td>
<td>600</td>
</tr>
<tr>
<td>Fraction of ASW below which irrigation is applied (0-1.0)</td>
<td>0.5</td>
</tr>
<tr>
<td>Efficiency of the irrigation, (0-1.0)</td>
<td>1</td>
</tr>
<tr>
<td>Allocation limits</td>
<td>off</td>
</tr>
<tr>
<td>Allocation in mm</td>
<td>0</td>
</tr>
<tr>
<td>Nitrate concentration (ppm N)</td>
<td>0.0</td>
</tr>
<tr>
<td>Ammonium concentration (ppm N)</td>
<td>0.0</td>
</tr>
<tr>
<td>Chloride concentration (ppm Cl)</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Figure 3.8 APSIM irrigation entered criteria; (A) furrow irrigation specific criteria, (B) general irrigation criteria.

When establishing the model parameters for end-of-season management decisions, it was found that APSIM did not provide a great deal of flexibility. Unfortunately, after consultation with industry professionals (D Johnston 2015, Pers. Comm, 18 September), it was found that the OZCOT module in APSIM was actually rather limited in respect to the flexibility of management events around the time of crop maturity and harvest. In particular, the timing of defoliation was only dependent on the percentage of open bolls and there was no ability
to manually delay defoliation to a pre-determined date. Increasing the percentage value of open bolls did delay defoliation, although the amount in which it was delayed was not consistent from year to year. Therefore, this method provided no practical way to simulate the strategy over time due to its inconsistencies.

APSIM did however have an ‘end crop’ manager script which could be used to terminate the crop on a specific date. This crop termination date was used to represent defoliation, as it had been identified that a defoliated crop is extremely dormant and therefore may be represented by a terminated crop. This was thought to be more practical as the simulation could be run with two separate crop termination dates (i.e. original harvest and delayed harvest), thus simulating the proposed management strategy. For consistency in the data evaluation process, these two dates were fixed over all years during the simulation.

The original crop termination date was set to be the 15th of April, which was typically 150–160 days after sowing. This was thought to be an appropriate date as traditionally, this was the ‘typical’ time of harvest (Oosterhuis 1990). Although selecting a fixed harvest day from year to year was not an ideal approach because each season is different, it provided a practical means for analysing and comparing data from year to year. The ‘harvesting rule’ module in APSIM was trialed, however this resulted in harvest dates in excess of 200 days after planting. This moved defoliation and harvest into June and July, which was not typical of a normal harvest. Therefore, as already discussed, the ‘end crop’ function in APSIM was used to represent the day of defoliation. The postponed defoliation was set 14 days after the original defoliation date. The simulation was run twice for each site, first using the original defoliation date and second with the delayed defoliation date.

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.
Initially, APSIM was used to simulate the Aubigny site. Data was available since 1900 in both the Pittsworth and Oakey data file. For the historic modelling however, the Oakey data file was chosen, as this was closest to the trial site.

Gooniwindi (QLD), Moree (NSW) and Warren (NSW) were also identified as predominant cotton growing regions and were areas where trial sites had been developed during the NEC1301 project (Bennett, Antille et al. In Prep), which this dissertation is contributing to. Therefore, it was deemed appropriate to model the proposed management strategy in these locations. The climate and soil files were chosen from SILO and APSIM’s APSoil on the merit of the most appropriate soil parameters. The chosen files are shown in Table 3.5.

<table>
<thead>
<tr>
<th>Region</th>
<th>APSoil File</th>
<th>Primary SILO Station</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goondiwindi QLD</td>
<td>Grey Vertosol (Goondiwindi No 219)</td>
<td>Goondiwindi Post Office (41038)</td>
</tr>
<tr>
<td>Moree NSW</td>
<td>Black Vertosol (Moree No 235)</td>
<td>Moree Airport</td>
</tr>
<tr>
<td>Warren NSW</td>
<td>Medium Clay (Warren No 705)</td>
<td>Warren Auscott</td>
</tr>
</tbody>
</table>

### 3.2 Soil Compaction Modelling Component

The moisture drawdown modelling in the previous section was used to produce a number of soil moisture contents at harvest at different locations. These moisture contents were then entered into SoilFlex (Keller, Défossez et al. 2007) to predict the associated soil compaction risk. The model required parameters for both loading conditions and soil conditions, in order to accurately simulate soil deformation. The loading parameters were calculated by Bennett, Woodhouse et al. (2015) for the JD7760, and were used as inputs in the developed SoilFlex model. These are summarised in Table 3.6. It must be noted that these are the parameters for one pass of a single front wheel.
### Table 3.6 SoilFlex Parameters for the JD7760

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheel Configuration</td>
<td>Dual</td>
</tr>
<tr>
<td>Gap between wheels</td>
<td>48 cm</td>
</tr>
<tr>
<td>Wheel load</td>
<td>5432 kg</td>
</tr>
<tr>
<td>Tyre inflation pressure</td>
<td>248 kPa</td>
</tr>
<tr>
<td>Tyre Width</td>
<td>53 cm</td>
</tr>
<tr>
<td>Recommended tyre inflation pressure</td>
<td>248 kPa</td>
</tr>
<tr>
<td>Diameter of the unloaded tyre</td>
<td>1.78 m</td>
</tr>
<tr>
<td>Wheel Slip</td>
<td>10%</td>
</tr>
</tbody>
</table>

There are three possible approaches for the calculation of soil deformation within SoilFlex. For the purpose of the investigation, the O'Sullivan, Henshall et al. (1999) model was used as it had been thoroughly referenced in the literature and was the most familiar deformation model out of the three options. The O'Sullivan, Henshall et al. (1999) required the following parameters:

- Soil Cohesion (kPa) – \( c = 60 \)
- Angle of Internal Friction – \( \phi = 30 \)
- Soil Texture = Clay Loam
- Gravimetric moisture content = variable depending on model run

These values were selected from guidance of industry professionals (J Bennett 2015, Pers. Comm 12 September)

After initializing the model, it was discovered that the O'Sullivan, Henshall et al. (1999) deformation approach in SoilFlex was only able to operate under gravimetric moisture contents between 8 – 12%. This was an identifiable limitation of the model as gravimetric
moisture contents required to be modelled were in excess of 28%. It was proposed that the best way to achieve reasonable outcome in the prediction of the compaction risk was to use the relative difference in moisture contents between the two treatments. These relative differences were inputted into SoilFlex at the upper range of workable limits (i.e. 22–25%). This upper limit was chosen as it was thought to be most representative of field moisture conditions that were quite high. For example, if the defoliated treatment had a gravimetric moisture content of 42% at harvest, and the undefoliated treatment had moisture content of 38% at harvest, the moisture contents used in soil flex were 25% and 21% respectively. The upper moisture level of 25% was kept as a constant for the largest pairwise soil moistures between treatments.

### 3.3 Statistical Analysis

A statistical analysis was completed for the soil bulk density samples; both from the soil cores and the bulk density rings, to determine if there were any significant differences in the results. All data points were assigned nominal values depending on what group or treatment they pertained to and were stacked accordingly. The software package SPSS (Statistical Package for Social Scientists) (IBM Corp 2013) was used to perform a myriad of statistical analyses due to previous experience using the software. This was achieved by completing a One-Way ANOVA between treatments at a 90% confidence interval.

A number of data cleaning methods were used to ensure the data sets were appropriate to perform an ANOVA. The requirements for the data in order to perform an ANOVA include:

- Linearality
- Homoscedasticity
- Normality
- Lack of outliers

Outliers were detected as data points that were 1.5 times greater than the inter-quartile range (IQR) beyond the first or third quartile, as suggested by (Hamilton 1990). Most of the outliers present in core bulk density samples were below 1.5xIQR and were quite unrealistic values (i.e. ρb = 0.6g/cm³). Therefore, these outliers were thought to be due to human sampling error during the coring exercise and were consequently removed from the
data set for analysis. All raw data sets displayed normally and linearly so there was no requirement for skew corrections.

Tukey’s Honest Significant Difference (HSD) test was used in conjunction with the ANOVA’s as a method to test multiple comparisons within the data. This was done to indemnify exactly which treatment means were significantly different from each other. The formula used to calculate the Tukey HSD is presented as Equation 8 below. This form of the Tukey HSD formula was used as not all samples were of the same size.

\[
HSD = \pm q(\alpha, v, a) \times \sqrt{\frac{1}{N} \times MSE \times \left( \frac{1}{n_i} + \frac{1}{n_{i+1}} \right) \ldots}
\]

Equation 8

Where:

\( q(\alpha, v, a) \) = Studentized range distribution for \( \alpha = \) ANOVA significance level, \( v = \) error degrees of freedom, \( a = \) number of treatments

\( MSE = \) Mean square error

\( n_i = \) the number of samples in the ith treatment.
4 Results

This section highlights the major observations that were made during the project for both the field trials and the modelling components of the dissertation.

4.1 Field Investigations

4.2 Soil moisture drawdown prior to traffic

From the soil moisture drawdown data presented in Figure 4.1, 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. 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.
At first glance, when observing the magnitude of the recorded soil moisture following the rainfall event, the values of volumetric moisture content appeared to be unrealistically high, suggesting that the sensors weren’t calibrated appropriately. When observing the raw soil sample data however, presented in Figure 4.2, the relative magnitudes of the moisture contents were comparable. This suggested that the soil’s saturation moisture content at the Aubigny site was quite high.

Figure 4.2 also 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.
Figure 4.2 Volumetric moisture content at depth between treatments before traffic. Where — represents the undefoliated treatments and — represents the defoliated treatments. Bars located at depth increments are Tukey’s HSD error bars at 95% confidence interval ($\alpha$=5%).

4.3 Changes in soil bulk density due to traffic

From Figure 4.3, 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.
When comparing the treatments before and after traffic, it was observed that both treatments resulted in significant compaction to a depth of 75 cm (Figure 4.4 and Figure 4.5). As a significant change in bulk density was observed at great depth, this highlights the extent of the machine impact within the soil profile.

**Figure 4.3** Bulk density at depth between treatments after traffic. Where — represents the undefoliated treatments and — represents the defoliated treatments. Bars located at depth increments are Tukey’s HSD error bars at 95% confidence interval ($\alpha=5\%$).
**Figure 4.4** Before and after traffic comparison in bulk density for defoliated treatment for the inner wheel traffic furrows. Where — represents the before traffic bulk density, — represents the after traffic bulk density. Bars located at depth increments are Tukey’s HSD error bars at 95% confidence interval (α=5%).

![Graph showing bulk density comparison](image)

**Figure 4.5** Before and after traffic comparison in bulk density for undefoliated treatment for the inner wheel traffic furrows. Where — represents the before traffic bulk density, — represents the after traffic bulk density. Bars located at depth increments are Tukey’s HSD error bars at 95% confidence interval (α=5%).

The resulting soil compaction after traffic was assessed between the furrows of each treatment according to their corresponding ‘traffic status’, which was subdivided into: 1) Untraficked (x3 rows), 2) Outer Wheel Traffic (x2 rows) and 3) Inner Wheel Traffic (x2 rows). The average resulting soil bulk density comparison for the defoliated and undefoliated treatments at depth is displayed in **Figure 4.6** and **Figure 4.7**, respectively. From these figures, it is evident that on average, the resulting bulk density under the inner wheel trafficked furrows were greater than that of the untrafficked furrows, however this result was not significant at the 95% confidence interval. Furthermore, the bulk densities
underneath the outer wheel furrows in the defoliated treatment were on average, greater than that under the untrafficked furrows, albeit not significant. This result however was not obtained in the defoliated treatments as no differentiation could be made between the bulk densities at depth in the outer wheel and untrafficked furrows.

**Figure 4.6** Comparison between traffic status furrows for defoliated treatment at depth. Where — represents the bulk densities under untrafficked furrows, — represents the bulk densities under outer wheel traffic furrows and — represents the bulk densities under inner wheel traffic furrows. Bars located to the right of figure are Tukey's HSD bars ($\alpha = 0.5$) for between treatment ANOVA.
**Figure 4.7** Comparison between traffic status furrows for undefoliated treatment at depth. Where — represents the bulk densities under untrafficked furrows, —— represents the bulk densities under outer wheel traffic furrows and —— represents the bulk densities under inner wheel traffic furrows. Bars located to the right of figure are Tukey’s HSD bars (α = 0.5) for between treatment ANOVA.

### 4.3.1 Changes in soil structure due to traffic

Soil pit face images for the defoliated and undefoliated treatments are presented in **Figure 4.8** and **Figure 4.9** 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 showed 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 4.9** (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.

Figure 4.8 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.
Figure 4.9 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.

4.3.2 Rut Depth resulting from traffic

The average rut depth results presented in Table 4.1 show a significant increase in rut depth after traffic in both treatments under the inner wheel traffic furrow, as would be expected. Furthermore 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. This significant increase in rut depth reflects the visual results obtained from the soil profile images, which display a massive soil structure caused by compression.
Figure 4.10 is presented to provide an example of how this data was obtained using a rut-profiler. All furrow data was collected similarly.

Table 4.1 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.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Before</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defoliated (cm)</td>
<td>12.48</td>
<td>19.44*</td>
</tr>
<tr>
<td>Undefoliated (cm)</td>
<td>12.29</td>
<td>17.88*b</td>
</tr>
</tbody>
</table>
**Figure 4.10** Images representing how rut depth data was obtained. Where (A) was taken from an untrafficked furrow after harvest and (B) was taken from a trafficked furrow after harvest. Bold lines on the backboard are drawn at 10 cm increments, with fine lines being spaced 1 cm apart.
4.3.3 Soil strength as influenced by traffic

Soils were assessed for soil strength on the basis of shear and penetration resistance. The shear strength contour plots presented in Figure 4.11 were obtained by selecting one representative profile plot for each treatment. Profile plots for each replicate of each treatment are presented in Appendix C. From the shear strength contour plots, it is evident that the shear resistance of the soil is increased directly under the traffic furrows, with general linear features of high shear strength beneath traffic furrows observed to extend from depth to the soil surface.Whilst traffic appeared to induce impact, there were not any significant differences between the treatments.
Figure 4.11 Soil profile shear strength contour plots for (A) 1 replicate of defoliated treatment, and (B) 1 replicate of undefoliated treatment. Machine wheel traffic configuration over the treatment plots is also produced on the top of figure.

All penetration resistance maps can be seen in Appendix B however; two penetration resistance contour plots are produced in Figure 4.12 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. Figure 4.12 (B) was chosen to show the influence of confounding traffic on the trial plots. 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.
Figure 4.12 Soil penetration resistance contour plot for 1 replicate of defoliated treatment (A) and 1 replicate of undefoliated treatment (B). (A) was selected to show least amount of confounding traffic whereas (B) was selected to identify the affect of confounding traffic. Machine wheel traffic configuration over the plot is also produced on the top of figure.

4.4 Soil Moisture Modelling

4.4.1 Model Validation

The observed versus predicted results are presented in Figure 4.13 to assess model validation for soil moisture changes in Australian Vertosols. From Figure 4.13, it is evident that soil moisture is more accurately predicted for the upper layers of soil. At the lower depths (30–60 cm), there is moderate correlation between the predicted data simulated by APSIM and observed values, however this correlation is not as strong as the shallower depths. It appears that at the 30–60 cm depths, APSIM has reduced sensitivity to changes in soil moisture as large changes in observed soil moisture result in small changes in predicted soil moisture.

Figure 4.13 Soil moisture content comparison plot between observed sensor data and predicted data simulated by APSIM across depths with added trendlines. • represents 0–15 cm depth (R²=0.891), • represents 15–30 cm depth (R²=0.687) and • represents 30–60 cm depth (R²=0.452)
4.4.2 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 a number of rainfall events had occurred just prior to the original harvest date (Figure 4.14 to Figure 4.17). 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 4.2). This reduced moisture content at harvest is due to the obvious departure in the soil moisture drawdown for the undefoliated plants at all locations and depths. 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 defoliated 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 effect 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 4.2), 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.

A strong relationship was observed when comparing the magnitude of the soil moisture drawdown across locations to the average climate statistics presented in Table 4.3. 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

Figure 4.14 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, ◊ is postponed defoliation, ● is original harvest, ◇ is original defoliation for (A) 0–15 cm, (B) 15–30 cm and (C) 30–60 cm depths.
Figure 4.15 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) 0–15 cm, (B) 15–30 cm and (C) 30–60 cm depths
Moree, NSW

Figure 4.16 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, ⋄ is postponed defoliation, • is original harvest, 🅰️ is original defoliation for (A) 0–15 cm, (B) 15–30 cm and (C) 30–60 cm depths.
Figure 4.17 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, ◊ is postponed defoliation, • is original harvest, ◼ is original defoliation for (A) 0–15 cm, (B) 15–30 cm and (C) 30–60 cm depths.
Table 4.2 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 strategy

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Moisture Content at Original Harvest (VMC %)</th>
<th>Moisture Content at Postponed Harvest (VMC %)</th>
<th>Difference (VMC %)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aubigny</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-15</td>
<td>45.66</td>
<td>44.04</td>
<td>1.62</td>
</tr>
<tr>
<td>15-30</td>
<td>47.03</td>
<td>45.72</td>
<td>1.31</td>
</tr>
<tr>
<td>30-60</td>
<td>45.8</td>
<td>44.53</td>
<td>1.27</td>
</tr>
<tr>
<td></td>
<td>Goondiwindi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-15</td>
<td>28.77</td>
<td>26.53</td>
<td>2.24</td>
</tr>
<tr>
<td>15-30</td>
<td>33.85</td>
<td>32.97</td>
<td>0.88</td>
</tr>
<tr>
<td>30-60</td>
<td>35.19</td>
<td>34.64</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>Moree</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-15</td>
<td>39.76</td>
<td>37.63</td>
<td>2.13</td>
</tr>
<tr>
<td>15-30</td>
<td>42.54</td>
<td>40.56</td>
<td>1.98</td>
</tr>
<tr>
<td>30-60</td>
<td>42.88</td>
<td>41.53</td>
<td>1.35</td>
</tr>
<tr>
<td></td>
<td>Warren</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-15</td>
<td>33.09</td>
<td>31.79</td>
<td>1.3</td>
</tr>
<tr>
<td>15-30</td>
<td>34.94</td>
<td>34.18</td>
<td>0.76</td>
</tr>
<tr>
<td>30-60</td>
<td>34.38</td>
<td>33.97</td>
<td>0.41</td>
</tr>
</tbody>
</table>
Table 4.3 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.

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

4.5 Soil Compaction Modelling

Due to the established limitations of the SoilFlex model, only the relatively differences in moisture content between the two harvest dates at all locations were able to be simulated. These differences are summarised in Table 4.4. As SoilFlex assumes a constant moisture content through the profile, the modelled 10, 30 and 60 cm moisture contents were averaged for each site. The predicted resulting bulk density after traffic is shown in Figure 4.18. As seen, reductions in moisture content result in a reduced severity of soil compaction after traffic, with the Moree location offering the greatest moisture drawdown due to the proposed strategy and therefore greatest reduction in the soil compaction risk.
Table 4.4 Average relative difference in volumetric water content drawdown at depth between original harvest data and delayed harvest date

<table>
<thead>
<tr>
<th>Site</th>
<th>Average relative difference in volumetric moisture content drawdown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aubigny</td>
<td>1.275</td>
</tr>
<tr>
<td>Goondiwindi</td>
<td>1.109</td>
</tr>
<tr>
<td>Moree</td>
<td>1.645</td>
</tr>
<tr>
<td>Warren</td>
<td>0.755</td>
</tr>
</tbody>
</table>

Figure 4.18 Predicted soil bulk density after traffic at depth due to relative changes in soil moisture content between the conventional and proposed management strategy. Where — is a reference density based on expected impact at time of traffic and all other moisture drawdowns are based on the relative deviation from this due to treatment effects from drawdown. Series are as follows: — Aubigny, — is Warren, — is Goondiwindi, and — is Moree
5 Discussion

5.1 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 affect on distribution of moisture removal throughout the profile, with a greater moisture removal toward in the top 0–45cm 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 affect 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. Although rut-depth did not prove to be significantly different between treatments, 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 (0–55cm) was comparable to depth range of the wetter soil profile (0–45cm) in the defoliated treatments. This 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 (~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 would likely 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.

5.1.1 Extent of traffic impact within the soil profile

Whilst compaction risk was reduced to a small extent due to the delaying of defoliation as a moisture drawdown and subsequent compaction management strategy, the extent of compaction impact within the soil profile was comparable. The JD7760 is a new innovation in the cotton industry that has been rapidly adopted with > 80% of the Australian cotton crop picked using this machine, and the capacity to pick >100% of the Australian crop with current machine numbers in Australia (Bennett et al. 2015). From the observed bulk densities before and after traffic, it is seen that there is a significant effect to 80 cm depth. The flow on effect of such deep compaction results in impeded water infiltration through the profile and increased soil strength which limits root growth depending on the extent of effect (Antille, Bennett et al. In Press). Furthermore, the extent of this impact is much greater than the extent of an achievable cultivation depth. In such a case the associated energy costs would exceed the potential benefit considering the machine would be expected to have this impact in each season it is used. As previously mentioned, the shrink-swell nature of Vertosol soils allows for some natural remediation, however this has been identified to only occur after repeated wet-dry cycles and is only significant in the surface layers (Sarmah, Pillai-McGarry et al. 1996). The inability to remediate compaction at depth therefore results in a compounding effect with multiple traffic passes in subsequent seasons, thus it is likely that a rising compaction layer will be observed (Bennett, Antille et al. 2015).

The cone penetration and shear strength results also indicate an increase in soil strength and therefore compaction at depth, which supports the bulk density data. An interesting observation of the penetration data revealed repeated regions of low soil strength directly under trafficked furrows at 70cm depth. Soil penetration resistance is known to be highly sensitive to changes in soil moisture (Lapen, Topp et al. 2004).
However, a zone of low soil strength under wheel traffic is counter intuitive as compaction results in consolidation of soil solid phase materials. The soil was trafficked at a very high moisture content, but had not reached the liquid limit, which is facilitated by the high moisture holding capacity of 2:1 clays where water enters the interlayer spacing of clay platelets (Probert, Fergus et al. 1987, Dudal and Eswaran 1988). In the case of these low soil strength regions occurring under traffic, it is suggested this is an artefact of JD7760 loading (~450–600 kPa) resulting in vertical drainage of soil pore moisture from the upper regions. The stress induced by the machine traffic was great enough to achieve increased soil strength as a clear artefact of machine traffic, so hydraulic drainage is conceivable. However, there is not enough evidence to directly conclude that this is the process causing these low penetration zones.

The magnitude of the stress imposed on the soil profile by the JD7760 resulted in clear increases in soil bulk density that were comparable for defoliated and undefoliated cotton, without any correlation between density and moisture within the 45–80 cm depth. The only reduction in compaction risk due to the proposed management method occurred in the 0–45 cm depth, thus suggesting that the proposed management strategy is only useful for lighter machines where subsoil compaction below the major rooting depth of cotton is unlikely to occur. However, given the extreme improvement of in-field efficiency afforded by the JD7760 (Bennett, Woodhouse et al. 2015), return to lighter machines is very unlikely without subsequent innovation of these to provide the same, or better, in-field efficiency. Hence, this is unlikely to be a useful strategy for heavy machines such as the JD7760, but might become a more useful strategy with further machine innovation (e.g. multiple, light, and small autonomous vehicles; Bates 2015).

5.2 Validation of APSIM to observed moisture drawdown

It must be noted that adverse weather conditions were experienced throughout the experimental field trial, which were untypical of a standard harvest. These conditions resulted in significantly reduced crop evapotranspiration rates; thus potentially masking the full significance of the proposed management strategy. Given that even in such conditions, a reduction in bulk density in the undefoliated treatments was detectable and highly correlated to soil moisture, further investigation under typical conditions is warranted. In order to achieve this, a modelling approach was thus developed to simulate the affects of the proposed management strategy over time, based on regional historic climatic data. This approach, whilst not validated in terms of compaction occurring, provides an indication of the range of achievable moisture drawdown under true, typical climatic conditions for the regions. APSIM is a highly validated model for crop growth under climatic conditions, and as such provides a means to mathematically interrogate the expected drawdown range given the climatic conditions under wet harvests where the proposed strategy would be employed. Using the observed data as a validation data set for APSIM, the observed and predicted results were compared for the Aubigny, QLD field trial. The validation provided a reasonable fit between the observed sensor data and predicted data simulated by APSIM as seen in Figure 4.14. Better correlations were observed in the upper soil layers ($R^2=0.82$ for 0-15cm, $R^2=0.69$ for 15-30cm, $R^2=0.53$ for
30-60cm), although these correlations suggest that APSIM will provide a moderate to strong confidence in prediction. This is sufficient to understand the range and extent of effect that the soil moisture drawdown strategy may have on soil compaction risk.

5.3 **Management strategy potential effect for wider cotton industry**

The results obtained from the modelling exercise were used to evaluate the affect of delayed defoliation on the soil moisture drawdown and thus compaction risk for the 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 model was established such that the proposed strategy was simulated in seasons where weather conditions had caused a large compaction risk at cotton harvest. 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.

Cotton is known to be quite a demanding plant in terms of its water requirements during the growing season (total water required: 700 – 1300mm; FAO 2015) and thus small reductions in soil moisture under an active plant would not be expected. This lack of total soil moisture drawdown under the cotton crop however may be described when evaluating crop water use towards the mature end of the growing season. It is known that the crop water use varies significantly during the season, due to the combined effect between climatic conditions and plant maturity. Changes in crop height, albedo, aerodynamic properties and leaf and stomata throughout the growing season all have an affect on crop evapotranspiration and therefore soil moisture drawdown (Allen, Pereira et al. 1998). Browne (1984) presented an idealized description of the variation in cotton water requirements throughout the growing season at Narrabri, NSW, as displayed in Figure 5.1 Idealized crop water use during the duration of the growing season at Narrabri, NSW. (Browne 1984). It can be seen that crop water requirements are significantly reduced towards the end of the growing season as harvest approaches. This limits the potential for rapid soil moisture removal from the profile. Although rapid moisture removal might not be achieved, it must be noted that the plant is still actively transpiring and removing moisture from the profile, albeit to a lower extent. Using the idealized moisture extraction of ~4 mm/day for the cotton plant immediately prior to harvest, it could be expected that a total of 56 mm of soil moisture is removed throughout the effective rooting depth over the 14 day delayed defoliation period. Based on the observed results at Aubigny 14 mm of moisture were used in the
observed 14 day period, which is substantially less than the expected 56 mm (0.56 MJ/ha). It is suggested that the idealized moisture requirement is from typical seasons where wet conditions are not influencing moisture uptake.

Figure 5.1 Idealized crop water use during the duration of the growing season at Narrabri, NSW. (Browne 1984)

The modelled soil deformation results obtained further demonstrated that small decreases in soil moisture have a large effect on the resulting bulk density. However, limitations were found within the SoilFlex model, but these were overcome by adjusting the modelling approach. The modelled reductions in soil moisture as a result of the proposed management strategy across all locations substantially reduced the resulting bulk density occurring from simulated JD7760r traffic. In the upper soil moisture regions of the model, a reduction of 2% gravimetric moisture content resulted in an approximate reduction of 4.5% in bulk density at all depths. This is substantial reduction in soil bulk density with only a small change in soil moisture (Keller and Arvidsson 2004, Bennett, Woodhouse et al. 2015, Antille, Bennett et al. In Press)
hence, achieving a small soil moisture drawdown would be expected to result in a meaningful compaction risk reduction.

5.4 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 JD770, 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 In Press). 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 affect 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 floatation 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 floatation using a delayed-defoliation strategy are not subsequently lost in yield quality downgrades, or lost yield from open bolls.
6 Conclusions

This study investigated a novel approach to soil compaction risk reduction, whereby defoliation of a cotton was delayed 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. Although the extent to which the crop was able to dry down the soil profile towards the mature states of the growing season was limited, the study found that changes in the resulting compaction was 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 these exist); yield parameters were not tested within the project scope. Furthermore, compaction from heavy machinery such as the JD7760 was shown to have compaction effect well beyond the feasible cultivation depth to a depth of 80 cm, irrespective of treatment strategy. Hence, with the predominant treatment effects of moisture drawdown and reduced compaction risk only operating within the 0–45 cm range, this strategy would not mitigate against long-term risks of heavy machinery.

The small differences in field moisture due to delaying defoliation provided significant impact in the resulting rut depths, suggesting that a greater degree of machine floatation can be achieved with only a small reduction in field moisture; although the effects of compaction are still evident in such conditions. Importantly, however, the energy required for traffic (i.e. reduced wheel slippage) and land reforming for subsequent seasons is reduced by achieving flotation. Hence, it is deduced that delaying defoliation is a management strategy that can provide a small offset in compaction risk, but supplies an important benefit of achieving flotation. Once again, growers will need to weigh the costs of this practice against the benefits.

Future work may include extending the field investigation to different locations within the cotton industry to further validate the developed APSIM model and subsequent use of SoilFlex for modelling soil mechanic dynamics. SoilFlex was shown to have limitation for Vertosol soils and will require calibration to this soil order if absolute data is required in place of relative differences.

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.
7 Bibliography


Google Earth (2013). Aerial image of trial site at Aubigny, QLD, 27°28'32.87"S ; 151°37'41.54"E, elevation 1.6km.


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8 Appendices

8.1 Appendix A

University of Southern Queensland
FACULTY OF HEALTH, ENGINEERING AND SCIENCES
ENG4111 and ENG4112 Research Project
Project Specification

For: Mr Stirling Robertson
Topic: Managing field moisture to reduce soil compaction risk at cotton harvest
Supervisors: Dr John Mclean Bennett
Project Aim: This project aims to investigate a novel approach whereby defoliation of the cotton crop is delayed in high-risk weather predictions to allow the crop to dry down soil profiles more rapidly thereby mitigating potential detrimental compaction effects of harvesting operations by decreasing soil plasticity.

Sponsorship: National Centre for Engineering in Agriculture (NCEA) project 1004960
Programme:

1. Research background information relating to compaction within the cotton system, soil-moisture-compaction relationships and the drawdown of soil-moisture from mature cotton plants
2. Establish field trials to simulate the proposed management strategy, (i.e. manually wetting up soil profiles to simulate a high-risk rainfall event)
3. Measure the soil-water drawdown over time and compare observed results with results obtained from soil-moisture computer models
4. Traffic soil and complete a number of investigations in order to quantify the resulting compaction
5. Model expected moisture draw down and use this to parameterise soil dynamics models for prediction of machine impact in soils with and without defoliation. Validate this against empirical data
6. Evaluate to what extent the proposed management strategy can reduce compaction risk
7. Submit an academic research dissertation on the research

AGREED _____________________ (student) _____________________ (supervisor)
Date: / /2015 Date: / /2015
Examiner/Co-examiner:________________________________________

8.2 Appendix B: Soil Penetration Resistance Maps

<table>
<thead>
<tr>
<th>REP</th>
<th>Defoliated Treatment</th>
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**REP**  Undefoliated Treatment

1

2
8.3 Appendix C: Soil profile shear resistance contour plots

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<th>REP</th>
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<td>Contour Plot for Shear Strength (kPa)</td>
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<tr>
<td>2</td>
<td>Contour Plot for Shear Strength (kPa)</td>
</tr>
<tr>
<td>3</td>
<td>Contour Plot for Shear Strength (kPa)</td>
</tr>
<tr>
<td>4</td>
<td>Contour Plot for Shear Strength (kPa)</td>
</tr>
</tbody>
</table>
Contour Plot for Shear Strength (kPa)

1. Undefoliated Treatment

2. Shear Strength (kPa)
   - $< 100.0$
   - $< 200.0$
   - $< 300.0$
   - $< 400.0$
   - $< 500.0$
   - $< 600.0$
   - $< 700.0$
   - $< 800.0$
   - $\geq 800.0$

3. Depth (m)

4. X Distance from Centre Diff (m)