Experimental Investigation and Modelling of the Impacts of Cotton Picker Traffic on Vertosol Soil Compaction and Potential Yield under Random and Controlled Traffic Farming Systems

A Thesis submitted by

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For the award of

Doctor of Philosophy

2020

Abstract

The John Deere 7760 (JD7760) cotton picker is used worldwide on mechanised cotton farms. More than 80% of Australian cotton farmers use it. A modified version, called CTF7760, was also adapted to controlled traffic farming (CTF) systems. The JD7760 has improved operational safety and efficiency, and requires less operating and labour costs. However, its weight (≈32 tonnes) is about twice that of previous models which raises concerns about soil compaction.

Vertosols are widely used for cotton production globally. It constitutes about 75% of soils under cotton production in Australia. However, Vertosols are highly susceptible to compaction even with one pass of machinery, especially under wet soil conditions. Soil compaction could translate into significant losses in crop yield and farm returns. The magnitude and distribution of soil compaction is dependent on factors such as wheel load, soil-tyre contact area, tyre inflation pressure and soil conditions. Controlled traffic farming, recently adopted by some Australian cotton farmers, is one of the effective solutions for reducing soil compaction. Nevertheless, the majority of Australian cotton farmers continue to use the conventional random traffic farming system (RTF).

Previous studies on soil compaction due to JD7760 traffic focused on cotton crop response across the overall field. None appears to have investigated compaction and cotton response at the single row level. Thus, the aim of this study was to investigate the influence of soil compaction due to JD7760 and CTF7760 traffic on a row by row basis. This study involved field trials in 2016 and 2017. These trials were also used to validate the soil compaction model (SoilFlex) and cotton yield model (OZCOT-APSIM).

Three farms with different traffic systems located at Koarlo (RTF), Undabri (RTF) and Yambacully (CTF) in Queensland, Australia were examined as study sites. Soil water content (Swc), dry bulk density (*Pb*) and soil penetration resistance (SPR) were measured before and after harvester traffic to a depth of 80 cm to assess the degree of soil compaction. These parameters were measured in cotton rows numbered Row 1, Row 2 and Row 3. At the RTF sites, Row 2 was located between the front dual-wheels of the JD7760 while Row 1 and Row 3 were located on the outer and inner sides of the wheels, respectively. At the CTF site, CTF7760 wheel traffic was between Row 2 and Row 3. Row 1 was separated from the wheel by Row 2 and a furrow due to harvester modification.

Vertosol response to rainfall and seasonal climatic variability was also monitored from October 2016 to May 2017 after harvest. Two novel approaches were introduced for row by row yield data collection from the JD7760: (1) harvesting of a single row at a time and (2) use of harvester CAN-BUS to extract yield data for each row. Harvester efficiencies based on yield losses were also determined.

It was found that increasing Swc due to rainfall in early October 2016 resulted in Vertosol swelling in the topsoil under both RTF and CTF. This led to a slight decrease in *Pb* and SPR and provided some compaction alleviation. High temperature in January 2017 resulted in Vertosol shrinkage which led to a significant increase in both *Pb* and SPR in the topsoil at all sites. The site under CTF exhibited lower sensitivity to seasonal variability with a lower rate of moisture loss (7%) in the topsoil for the period between January 2017 and May 2107, as compared to the RTF sites (18%). Significant compaction was observed after one pass of the JD7760 in the depth of 0–30 cm under both RTF and CTF. Compaction due to CTF7760 traffic in the cultivated area was however significantly lower than that of the JD7760.

Traffic over the furrows led to significant compaction which spread to neighbouring cotton rows and directly affected cotton yield. At the RTF sites, the 0–20 cm soil layer of Row 2 was the most affected by harvester traffic as it showed the highest *Pb* and SPR compared to Row 1 and Row 3. There was no impact on Row 1 after one pass of the CTF7760 harvester throughout the 0–80 cm depth. Traffic from the CTF7760 harvester covered 33% of the farm compared to 66% for the RTF sites. This means that CTF provided protection to about two-thirds of the farm in terms of soil structure preservation and reduced compaction effects compared to RTF.

Furthermore, it was found that Row 1 produced a higher yield than Row 2 and Row 3 with both the CAN-BUS and hand-picking under RTF and CTF. Row 2 at the RTF sites was the most sensitive to harvester traffic, leading to 21% and 14% lower cotton yields with machine and hand-picked methods, respectively, than at the CTF site.

Cotton yield under CTF was up to about 33% higher than under RTF. The CTF7760 harvester had a superior performance to the JD7760 harvester with 47%, 72% and 74% lower losses in Row 1, Row 2, and Row 3, respectively. The findings obtained with the soil compaction (SoilFlex) and yield (OZCOT-APSIM) models agreed well with field experimental results.

Overall, both field experiments and computer simulation models were employed to achieve the aim of this study. It was found that harvester traffic caused significant compaction in cotton rows and furrows located between, adjacent to, and in wheel tracks under both RTF and CTF in both the topsoil and subsoil, which consequently led to decline in cotton yield. However, this impact was less under CTF. The main original contributions of this study are that it has provided new knowledge and a deeper understanding of the impact of the JD7760 on both soil compaction and cotton yield at the single row level. This information is crucial, not only to Australian farmers, but for improvements in management practices in cotton and other crop farming systems globally. This study has also introduced two new approaches for measuring row by row cotton yield. The findings presented in this thesis represent an important scholarly contribution to the growing body of knowledge related to soil compaction and cotton yield.

Certification of Thesis

This thesis is entirely the work of **Mohammed Abed Mankhi Al-Shatib** except where otherwise is acknowledged. The work is original and has not previously been submitted for any other award, except where acknowledged.

Principal supervisor: Associate Professor Guangnan Chen

Associate supervisor: Associate Professor Troy Jensen

Associate supervisor: Professor John McLean Bennett

Student and supervisors signatures of endorsement are held at the University.

Acknowledgements

"In the name of Allah, the beneficent, the merciful"

I would like to initiate the acknowledgment with Allah (God) who has provided me with the strength and wisdom to finish my thesis.

Special thanks to the Iraqi Ministry of Higher Education and Scientific Research for providing me the scholarship to achieve this research. The financial support from the ministry is appreciated.

My deepest gratitude and specific thanks go out to my supervisors: Associate Professor Guangnan Chen, Associate Professor Troy Jensen, and Professor John McLean Bennett. We worked together as one team and they provided me the guidance, encouragement, and advices to complete my study objectives successfully in a reasonable time. Their efforts are highly appreciated.

Thanks must go to the farmers: Mr Glen Smith, Mr Nigel Corish and Mr Luke Moroney who allowed me to carry out the field experiments in their farms at Yelarbon and Goondiwindi, Queensland, Australia. I would also express my gratitude to thank Dr Broughton Boydell, the project engineer at John Deere Company, Australia who provided me the JOHN DEERE-DATALOGGER to extract the individual yield data from the John Deere 7760 cotton picker.

I also want to express my sincere gratitude to Dr Thomas Keller (Swedish University of Agricultural Sciences) who provided me a knowledge and guidance with using the SoilFlex model. My sincere appreciation goes to Mr David Johnston from CSIRO who supported and advised me a lot with using the OZCOT-APSIM model.

Thanks must also go to the University of Southern Queensland's (USQ) School of Civil Engineering and Surveying, Centre of Agricultural Engineering (CAE) and Centre for Sustainable Agricultural Systems (CSAS) for providing me with the facilities, equipment required, and funds to conduct the research.

I am particularly grateful to Mr Stirling Roberton of CSAS who supported me in the fieldwork and laboratory tirelessly. Thanks also go to Dr Enamel Kabir of USQ's Statistical Consulting Unit. I would like to express my thanks to Dr Henk Huijser and Mrs Sandra Cochrane for their trustworthy proofreading service. Additionally, thanks to my PhD student colleague Kojo Atta Aikins for this support.

Last but not least, special thanks to my mother, brother and sisters who also supported me in every possible way during my PhD journey.

I am most greatly indebted to all of you.

List of Publications

Unpublished paper: Drafted

1. Al-Shatib, M, Chen, G, Jensen, TA, & Bennett, J. McL. (2019). Examination of the effect of harvester traffic on compaction of Australian Vertosol soils and cotton performance row by row. (Paper drafted and ready to submit).
2. Al-Shatib, M, Chen, G, Bennett, J. McL, & Jensen, TA. (2019). Monitoring Australian Vertosol soils behaviour in response to the shrink-swell characteristic and cotton picker traffic. (Paper drafted and ready to submit).
3. Al-Shatib, M, Chen, G, Bennett, J. McL & Jensen, TA. (2019). Using the APSIM model to estimate the potential cotton yield under the impact of heavy harvester traffic row by row. (Paper drafted and ready to submit).

Table of Contents

List of Figures

List of Tables

List of Abbreviations

APSIM	The Agricultural Production Systems Simulator
AUD	Australian Dollar
BD	Bulk density
CAE	Centre of Agricultural Engineering, USQ
CAN-BUS	Controller Area Network
CTF	Controlled traffic farming
CSAS	Centre for Sustainable Agricultural Systems, USQ
CSIRO	Commonwealth Scientific and Industrial Research Organisation
FC	Field capacity
GMC	Gravimetric moisture content
JD7760	John Deere cotton picker 7760
kPa	Kilo-Pascals
KN	Kilo-Newton
Mg	Mega-grams
ML	Mega-litre
MPa	Mega-Pascals
QLD	Queensland State, Australia
NSW	New South Wales State, Australia
OBMB	On-board module builders
RTF	Random traffic farming
Pb	Dry bulk density
SMC	Soil moisture characteristic curve
Swc	Soil water content
SPR	Soil penetration resistance
USQ	University of Southern Queensland

Chapter 1. Introduction

1.1. Overview

This study investigated the soil compaction from a John Deere 7760 harvester and the impact of this compaction on cotton yield both across the field and at the single row level. This chapter presents a brief overview of the research topic. It provides background to the research problem and identifies the research questions. It also presents the main aim, hypothesis and research objectives. Finally, an outline of the thesis is presented to provide a brief description of the content of each chapter in the thesis.

1.2. Research background

Cotton (*Gossypium hirsutum L.*) is an important industrial crop of considerable economic value to many countries. The major cotton producers include China, the USA, India, Pakistan, and Brazil. Jointly they produce about 75% of global production (Yadav et al., 2018). In recent years, Australia has become one of the leading cotton producers and the third-largest exporter, with the highest average yield per hectare in the world (Eskandari et al., 2017; Eskandari et al., 2018).

Cotton performs well on Vertosols, earning the worldwide title “Black Cotton Soil” (Virmani et al., 1982; Forster et al., 2013). This reputation is due to cotton’s vertical root system which is not damaged by the cracking of the Vertosols (IUSS Working Group WRB, 2015). In Australia, cotton is mainly grown in New South Wales and Queensland on soil types such as Vertosol, Chromosol, Dermosol, and Sodosol (Hulugalle & Scott, 2008). Vertosols constitute around 75% of the soils under cotton production in Australia (McKenzie et al., 2003). Vertosols have high clay content and a strong shrink-swell capacity (Hulugalle & Scott, 2008). However, Vertosol is susceptible to compaction, especially under wet conditions (Chan et al., 2006). With just one pass of heavy machinery, a significant degree of compaction reaching deep into sub-surface layers can occur (Bennett et al., 2019).

Soil compaction is a major global challenge in mechanised crop production, and this is mainly due to machinery traffic. This challenge is exacerbated as machinery size and weight continue to increase in the quest to increase production (Hamza & Anderson, 2005; Glab, 2014). Traffic of larger and heavier machinery is the primary source of both surface and sub-surface compaction (Lipiec & Hatano, 2003; Zhang et al., 2006). Increasing compaction results in long-term soil structure damage and declining crop yield (McKenzie, 2010). More than 68 million hectares of the world's soils have been affected by compaction (Oldeman et al., 2017). Compaction could cost the Australian agriculture sector approximately AUD850 million annually (Walsh, 2002). One of the ways to prevent or minimise soil compaction in a highly mechanised farming system, is the adoption of a farming system that minimises machinery traffic.

The farming systems, in terms of machinery traffic, employed by cotton growers around the world can broadly be classified as either random traffic farming (RTF) or controlled traffic farming (CTF). RTF is the conventional system of traffic in which there are no specified paths for machinery traffic. This implies that soil compaction due to machinery traffic occurs haphazardly on the cultivated field. Trafficking under RTF can cover 85% and above of the field whenever a crop is produced (Kroulik et al., 2009). Under CTF, dedicated permanent lanes are used year in and year out, restricting machinery passage to specific uncultivated paths (Tullberg et al., 2007; Antille et al., 2016). The main motivation for the adoption of CTF is that it considerably minimises the area of soil compaction and ensures the maintenance of soil properties of the cultivated portions of the farm, thereby enhancing crop yield and reducing energy requirements (Chamen 2011; Kingwell & Fuchsbichler, 2011; McPhee et al., 2013; ACTFA, 2017). CTF is capable of reducing the influence of compaction by more than 50% relative to RTF (Bennett et al., 2016; Galambosova et al., 2017). Furthermore, repeated traffic on permanent lanes may not normally permit natural soil alleviation; therefore, deep tillage may be required between crop cycles, which could aggravate the problem (Antille et al., 2019).

Extensive field trial studies have revealed that soil compaction under RTF results in a significant change in soil properties (Nawaz et al., 2013). For instance, in silty clay loam soils, the random traffic of a sugarcane harvester caused significant compaction resulting in an increase of approximately 9% in the dry bulk density of surface soil (Braunack & Peatey, 1999). In contrast, the traffic of a sugarcane harvester under CTF with 1.5 m row spacing, caused less deterioration in the physical properties of sandy clay loam soil on both seedbeds and plant-rows (Esteban et al., 2019). On the other hand, repeated traffic on the same track, regardless of light or heavy equipment could result in subsoil compaction and soybean grain yield reductions (Botta et al., 2004).

CTF is currently adopted by the Australian cotton industry to restrict the impact of compaction on Vertosol soils, and increase yield (Tullberg, 2001). However, harvester traffic, regardless of RTF or CTF, remains the primary source of compaction leading to soil structure degradation and decline in yield (Bartimote et al., 2017; Bennett et al., 2017).

Around the world, farmers employ a variety of harvesters and pickers to harvest cotton. Australia and the USA are the main countries in the world where all cotton harvesting is fully mechanised (Muthamilselvan et al., 2007). One of the most popular cotton pickers in these countries is the John Deere 7760 cotton picker (JD7760). As present, this cotton picker is used by more than 80% of Australian cotton farms (Bennett et al., 2014; Roberton & Bennett, 2015). Its high adoption rate could be attributed to its improved operation safety, efficiency, and operating costs relative to previous models (Bennett et al., 2015). It also eliminates the need for module builders, boll buggies and tractors which help reduce labour cost (Martin & Valco, 2008; Willcutt et al., 2010; Bennett et al., 2017).

With all these improvements, however, this cotton picker weighs approximately 32 tonnes which makes it about two times as heavy as its previous model, the basket picker (Braunack & Johnston, 2014; Bennett et al., 2015). In an attempt to minimise compaction risk due to increased axle weight, its front axle has been fitted with dual-wheels and larger tyres (520/85R42 R1R2) (John Deere, 2016). Nevertheless, traffic of the inner and outer front dual-wheels have been identified as a major cause of compaction to depths of up to 80 cm in Vertosols (Bennett et al., 2015; Bennett et al., 2017). This leads to increased compaction in the wheel tracks, especially, in the topsoil (Bennett et al., 2015), which can also spread to adjacent rows (Braunack & Johnston, 2014).

A modified version of the JD7760 picker adapted for harvesting under CTF is called the CTF7760. The modifications include an increase in the frontage width from 6 to 9 m and the replacement of the front dual-wheels with single 620/70R42 wheels (Antille et al., 2016). Bennett et al. (2017) stated that the main difference between the use of the JD7760 and CTF7760 is that about 66% and 50% of cotton furrows are subjected to harvester wheel traffic under RTF and CTF, respectively. However, harvest traffic from the JD7760 picker, regardless of RTF or CTF, results in increased soil penetration resistance and bulk density in the wheel track at different soil depths (Bennett et al., 2016).

Harvest traffic is often a serious issue, particularly when soils are subjected to trafficking without annual ripping operations (Hamza & Anderson, 2005). Given that Vertosols readily experience significant compaction even due to a single pass, trafficking with the heavier JD7760 and CTF7760 worsens the compaction (Bennett et al., 2017). Daniells (1989) stated that the yield of cotton grown in Vertosol could be reduced by more than 33% when the soil is subjected to harvest traffic, particularly under wet conditions. Coelho et al. (2000) observed a significant decline in cotton yield due to compaction when dry bulk density increased to 1.60-1.70 g/cm^3. Also, compaction resulting from the random traffic of a harvester is found to be the main reason for the significant decrease (24%) in cotton yield reported by Braunack (2013).

A substantial amount of research (Bennett et al., 2013; Braunack, 2013; Braunack & Johnston, 2014; Antille et al., 2016; Bartimote et al., 2017; Bennett et al., 2017; Roberton & Bennett, 2017; Bennett et al., 2019) has identified the effect of compaction due to JD7760 traffic on soil structure and cotton yield. However, these results are usually represented as the overall results across the field. There appears to be a lack of studies presenting row by row impact of the JD7760 cotton picker traffic on soil compaction and cotton yield. Additionally, several studies have evaluated the efficiency of various cotton pickers and strippers based on yield loss. However, the efficiency of the JD7760 (standard configuration) and the CTF7760 (modified) cotton pickers have not been investigated.

Due to the wheel arrangement of the JD7760 and CTF7760 cotton pickers relative to cotton rows, the degree of compaction caused by wheel traffic will not be uniform for all rows. Braunack and Johnston (2014) stated that compaction caused by harvester wheel traffic could spread to adjacent rows. This makes it necessary to investigate the row by row variations in the impact of the JD7760 and CTF7760 traffic on soil compaction in Vertosol and on cotton yield. Understanding the row by row variation will enable cotton farmers to be more specific in their application of compaction treatment to different rows which can potentially translate to savings in finances and time.

1.3. Aim and hypothesis

The aim of this research was to investigate soil compaction due to the JD7760 cotton picker and its influence on individual cotton rows under RTF and CTF. The hypothesis of this research was formulated as:

Traffic of modern harvester (JD7760) increases soil compaction problems and has a negative impact on cotton yield at the single row level.

1.4. Research questions

To address the stated research problem, the main research question was formulated as:

What is the impact of the JD7760 cotton picker traffic on Vertosol soils compaction and cotton yield of individual rows under RTF and CTF?

Based on the statement above, five research sub-questions were subsequently formulated:

- How can the impact of the JD7760 traffic on soil compaction be measured?
- Is it possible to employ existing on-board cotton picker sensors to collect cotton yield data at a single row scale under different levels of soil compaction?
- What is the difference in harvest efficiency between the JD7760 standard configuration and the CTF7760?

- Which soil compaction models can be best used to simulate the impact of harvester traffic on Vertosol soils?

- How can row by row cotton yield under different levels of soil compaction under CTF and RTF be predicted?

1.5. Research objectives

The previous hypothesis was addressed through the following specific objectives:

- To obtain and compare the parameters of soil compaction due to JD7760 traffic at a single row scale in different fields under RTF and CTF

- To develop and evaluate different methods for estimating row by row cotton yield data

- To compare the harvest efficiencies (harvest losses) of JD7760 and CTF7760

- To select and utilise an appropriate soil stress model to simulate soil compaction due to JD7760 and CTF7760 traffic

- To utilise a crop model to predict the impact of JD7760 and CTF7760 traffic on row by row cotton yield.

The above objectives are linked with the research questions as follows: Objective 1 addressed Question 1, Objective 2 addressed Question 2, Objective 3 addressed Question 3, Objective 4 addressed Question 4 and Objective 5 addressed Question 5 (Figure 1.1). The contributions and significance of this study will be highlighted and further summarised in Chapter 10.

1.6. Thesis outline

This thesis consists of ten chapters. A brief overview of the chapters is presented below:

- Chapter 1 provides a general background to this research and identifies the aim, hypothesis, research questions and objectives of the study.

- Chapter 2 reviews the concept of soil compaction, compaction sources, the influence of machinery traffic on compaction, topsoil compaction versus subsoil compaction, Vertosol soils, controlled traffic farming, and managing and alleviating soil compaction. This chapter also provides an overview of the cotton crop, harvest methods, cotton row configuration, the impact of compaction on the crop performance, estimation of yield and harvest efficiency. In this chapter, soil compaction and agronomy models are reviewed, and a summary of the current literature is presented.

- Chapter 3 sets out the specific methodologies used to investigate the effects of soil compaction on cotton yield row by row due to trafficking by the JD 7760. This chapter presents the experimental arrangements for each objective. Site description, design of experiments, equipment, parameters, experimental procedures, and laboratory work are presented. Data collection and statistical analysis are also explained.

- Chapter 4 discusses the results of the influence of rainfall, seasonal variability, and harvester traffic on soil properties (soil water content, dry bulk density, and soil penetration resistance) overall field the three farm sites. This chapter presents the obtained data in the form of figures, tables, and contour maps.

- Chapter 5 discusses the results of the influence of harvester traffic on soil characteristics between the different individual rows of each site.

- Chapter 6 discusses the results of the effect of harvester traffic on soil characteristics at different soil depths in individual rows.

- Chapter 7 compares the results of the individual row yield data of each field in both machine and hand-picked methods. It also discusses the effect of traffic system and row spacing on the individual yield data between the study areas. Harvest losses are also investigated and compared in this chapter.

- Chapter 8 first provides a review of the available soil compaction stress models. The framework and the key characteristics of SoilFlex model are then described in great detail. The model outputs are also discussed in this chapter.

- Chapter 9 details existing crop performance models. In this chapter, OZCOT-APSIM software model is employed to predict the cotton yield within the individual rows of the study areas. The key findings and OZCOT-APSIM validation are discussed in this chapter.

- Chapter 10 summarises the conclusions and the new knowledge generated from this study. Further research is also recommended.

Figure 1.1 outlines the thesis structure and the relationship between these chapters.

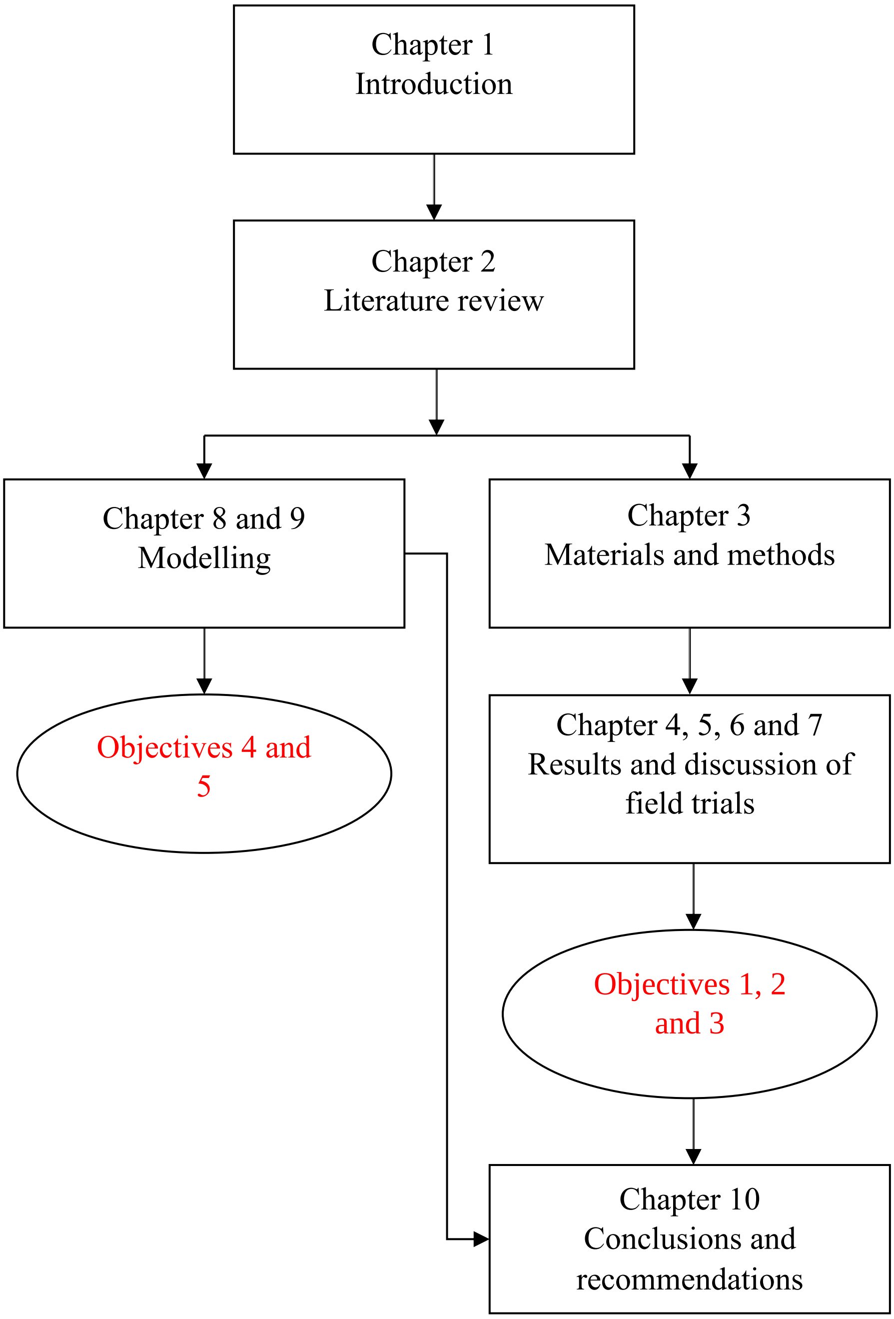


Figure 1.1: Block diagram of a thesis outline

Chapter 2. Literature review

2.1. Introduction

This chapter reviews the literature related to the concept of soil compaction, focusing on compaction causes, the effect of farm machinery on soil compaction, Vertosol soils, controlled traffic farming, and the impact of soil compaction on crop performance. Several strategies that are important for managing and alleviating soil compaction are considered. This chapter also provides an overview of the cotton crop, cotton pickers, estimation of yield and harvest efficiency. In addition, soil compaction and agronomy models are reviewed, and a summary of the literature is presented.

2.2. Concept of soil compaction

Soil compaction is a major constraint to agricultural production and is primarily caused by the wheel traffic of heavy equipment (Nawaz et al., 2013; Khodaei, 2015; de Lima et al., 2017). Compaction is defined as the compression of soil aggregates into a smaller volume, which decreases the bulk of pore space available for air and water because it alters the spatial arrangement, size and shape of clods and aggregates and consequently the pore spaces both inside and between these units (Seifu & Elias, 2019). In addition, changes in the soil structure and macroscopic due to compaction increase soil strength (Jury & Horton, 2004). After the passage of machinery, changes occur within the soil structure (Hillel, 1982). The arrangement of the primary particles collapse, whereby fine material is squeezed between larger and silt grains (Soane & van Ouwerkerk, 2013). Also, mechanical deformation, such as that occurring during tillage operations results in shear failure characterised through realignment of particles (Pestana et al., 2002; Chen & Zhang, 2019). Vertosols deformation may occur with no change in volume, resulting in minimal changes in bulk densities while soil physical properties are severely affected (Bakker & Davis, 1995).

Compaction is a global and serious problem that affects crop growth (Soane & van Ouwerkerk, 2013). More than 68 million hectares of the world’s arable land has been affected by compaction (Oldeman et al., 2017). Annually, soil compaction costs the Australian agricultural sector about AUD850 million (Walsh, 2002). Compaction issues have increased over past decades due to the increasing size of farms, equipment, and the time needed for sowing and harvesting operations (Tullberg, 2018). Compaction is associated with most field operations such as wheel traffic and tillage with various implements (Hamza & Anderson, 2005). Compaction caused by farm machinery traffic has adverse impacts on a number of soil physical properties (Chan et al., 2006). Protecting the soil by considering soil compaction issues has become a key concern and is well- recognised in many parts of the world (Farzaneh et al., 2012).

Excessive compaction produces undesirable impacts that may lead to a reduction in soil quality and crop yields (Zhang et al., 2006). Compaction reduces soil aggregates, which consequently causes a serious disturbance in soil porosity (Horn et al., 1995; Hamza & Anderson, 2005). This implies that compaction results in increasing soil strength, dry bulk density and a reduction in the porosity at the expense of the large voids (Nawaz et al., 2013; Ungureanu et al., 2019). Soil compaction can be indicated or assessed by a wide range of soil properties such as soil strength, dry bulk density, soil water content and porosity (Alakukku, 1996; Sivarajan et al., 2018).

The identification of factors affecting strength development is important for evaluating the impacts of compaction on soil characteristics and crop performance (Rodríguez et al., 2012). The influence of soil compaction on crop yields is the key issue behind much compaction research (Bennett et al., 2015). Few studies have been conducted to determine the influence of soil compaction on yield decline or the time taken for soil structure to recover (Braunack et al., 2012). In summary, soil compaction due to agricultural equipment is a global and serious problem for arable land, which can affect soil properties and plant growth. Thus, soil compaction should receive more close attention in global surveys of soil degradation (Soane & Van Ouwerkerk, 1995).

2.3. Fundamentals of compaction and causes

The weight of machinery has dramatically increased in the past several decades due to an increase in food demand (D’Or & Destain, 2016). Compaction is regarded as a global concern facing the agricultural sector, particularly when the soil is subjected to trafficking without annual ploughing practices (Glab, 2014). Wheeled traffic is the primary reason behind the occurrence of compaction, leading to redistributed soil pores, changing soil properties and structural deterioration (Soane & Van Ouwerkerk, 1994; McKenzie, 2010; Shen et al., 2016). For example, intensive compaction due to machinery traffic can increase the dry bulk density of soils by approximately 32% and decrease soil porosity up to 17% (Frey et al., 2009).

The investigation of compaction from agricultural machinery began in the 1950's (Schafer et al., 1992). Many studies were undertaken to determine the impact of compaction on soil physical properties, and its subsequent effect on crop production (Destain et al., 2014). In general, soil compaction studies are divided into three areas: (1) equipment manufactured to compress soil or machines used purposely to do so; (2) incidental compaction due to machines used for other purposes; and (3) management practices for controlling undesired compaction (Taylor & Gill, 1984).

The key causes of compaction are external factors which can be summarised as: (1) topical or comprehensive compaction that is spread from the topsoil to the subsoil due to machinery; (2) physical compaction induced by frequent traffic; and (3) subsoil compaction caused by extreme surface loadings (Spoor, 2006). Moreover, machinery traffic exerts three key compacting forces on soils: (1) vertical stress due to axle loads; (2) shear stress induced by wheels slippage; and (3) the vibration of machines (Kozlowski, 1999).

Soil compaction due to farm machinery traffic is almost always accompanied by shear deformation. Soil deformation depends on several factors, such as initial bulk density, particle size distribution, soil organic matter and moisture, ground slope, type of harvesting, number of skidding cycles, and the caution and expertise of machine operators (Mouzai & Bouhadef, 2011). Wheels, Tyres and rollers occur relatively high stresses which, since the affected soil can move away rather easily, may induce large deformations (Keller, 2004). Several studies reported that compaction and shearing due to machinery traffic affect many soil properties and processes and lead to soil physical degradation (Pagliai et al., 2003). Shearing can affect the quality of soil more negatively than compaction, particularly in the surface soil (Horn, 2003). Agricultural field traffic unavoidably exerts vertical and horizontal stress components as well as shear forces to the soil (Spoor & Godwin, 1979).

In brief, it has been demonstrated in this review that field traffic is a key source of soil compaction and deformation. Figure 2.1 summaries the causes of compaction and their influences on soil characteristics, with direct impacts on soil chemistry, plant growth, and biodiversity of the soil, and indirect impacts on exchanges of matter with external compartments (Nawaz et al., 2013).

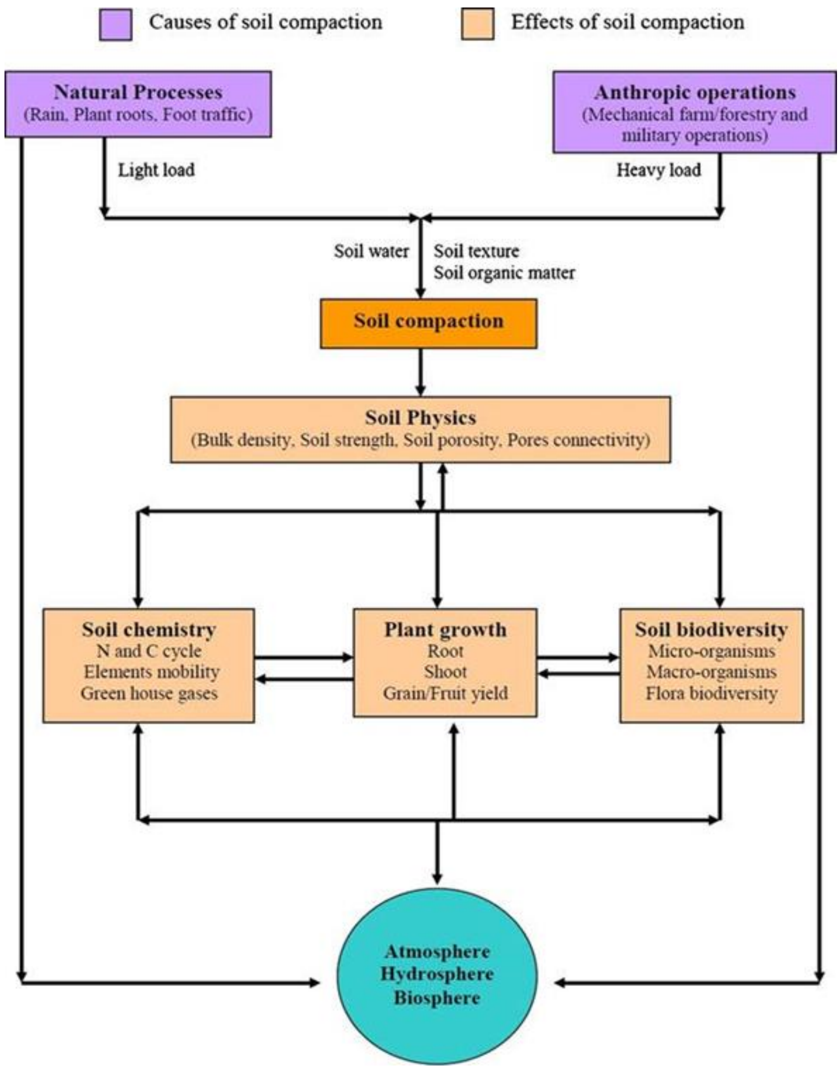


Figure 2.1: Causes and effects of soil compaction on soil properties, plant growth, and biodiversity of soils

Source: Adopted by the researcher from (Nawaz et al., 2013).

2.4. Topsoil compaction versus subsoil compaction

Agricultural field traffic is the primary source of topsoil and subsoil compaction (Horn et al., 1995). Light equipment traffic results in one form of compaction in topsoil and usually does not exceed a depth of 10 cm (Zhang et al., 2006; Alaoui et al., 2018). Topsoil compaction can be characterised by decreased infiltration rate, increased ponding on the surface and a decline in plant growth (Raper & Bergtold, 2007). A major portion of topsoil compaction is due to the first pass of machinery (Alakukku et al., 2003; Hamza & Anderson, 2005). Topsoil compaction cannot be considered a key issue because soil has the ability to reconstruct due to human activities and environmental factors (Gysi et al., 1999). Normal tillage and natural processes can be sufficient to alleviate the influence of topsoil compaction (Hamza & Anderson, 2005).

Excessive equipment traffic is the main cause of subsoil compaction which can be observed below a depth of 40 cm (Hakansson et al., 1994; Brus & Van Den Akker, 2018). Subsoil compaction normally occurs due to the cumulative traffic impact of heavy machinery (Gysi et al., 2000; Raper & Bergtold, 2007). It is considered to be permanent because pore functions are not able to be renewed after the structural deterioration of soil (Hoefer & Hartge, 2010). Additionally, subsoil compaction is a hidden risk, which threatens important soil ecosystem services, including crop yields and soil functions that, in turn, affect the environment. Thus, subsoil compaction requires more attention, particularly in clay soil conditions (Lamandé & Schjønning, 2018). Subsoil compaction is generally alleviated through deep ripping (Hamza & Anderson, 2003). However, deep ripping is expensive if required annually (Raper & Bergtold, 2007). To conclude this section, it can be stated that farm traffic can cause severe topsoil and subsoil compaction, including changing soil properties and plant growth decrease.

2.5. Vertosol soils

Vertosol soils or dark cracking clays are a collection of soils with heavy texture, dark colours, and high clay content (Eswaran et al., 1988). Vertosols exist in Australia, the USA, India, China, Sudan, Chad and Ethiopia (Virmani et al., 1982; Ahmad, 1983; Zaffar & Sheng-Gao, 2015). In Australia, Vertosol soils are often found in Queensland, New South Wales, coastal districts of the Northern Territory, and Tasmania, which combined, cover about 70.5 million hectares (Virmani et al., 1982). This soil has a high percentage of clay content, around 40–80 g/100 g, and is normally quite dark in colour due to the presence of commingling calcium and high quantities of magnesium (Hulugalle & Scott, 2008; Kettler et al., 2009). The texture of Vertosol is mostly lighter in the topsoil, and the clay content increases with increasing depth towards the subsoil (Daniells et al., 1996).

The major types of Vertosol are black, brown and grey (McKenzie et al., 2003). These soils are widely used for dryland and irrigated cotton (Jutzi, 1988; Cattle & Field, 2014; Isbell, 2016; Knox & Griffiths, 2017). One advantage of Vertosol is its inherent ability to self-repair because of high clay content and clay type that governs volume change (McKenzie & McBratney, 2001). However, water holding capacity and drainage are issues (Ghosh et al., 2010). Furthermore, a unique characteristic of Vertosol is its shrink-swell property which is related to its cephalic characteristics and smectitic content (Potter & Chichester, 1993; Patil et al., 2011).

The shrink-swell property of Vertosol is highly dependent on its soil water content (Kamara & Haque, 1988). Dry conditions result in shrinkage, while the wet conditions result in swelling (Hakansson & Lipiec, 2000). Therefore, Vertosol soils can self-repair after multiple wet-dry cycles (Ahmad, 1983; Coulombe et al., 1996; Pillai & McGarry, 1999). Nevertheless, a major issue with Vertosol soil is its ability to readily respond to compaction, especially when wet (Chan et al., 2006). Significant compaction can occur in Vertosols after one pass of heavy machinery, and this impact can reach into sub-surface layers (Bennett et al., 2019). Compaction elimination in Vertosols may cost the Australian cotton industry around AUD $1.3 billion annually (Watson et al., 2000).

Overall, this section has provided a brief summary of the literature relating to Vertosol in terms of its' classification, behaviour and problems. It is one of the most common soil in several countries. Vertosols contain high clay texture with strong high shrink-swell capacities. It might be able to improve its structure after multiple dry-wet cycles. However, trafficking under wet conditions could cause soil structural damage rapidly.

2.6. Effect of machinery traffic on soil physical properties

There is a wide range of soil parameters that can describe soil quality. Soil function parameters (e.g. physical and cultural environment, filtering and transformation of compounds, source of raw materials, storage, habitats for living creatures and gene pools, production of food and biomass, carbon pool, and archive of geological and archaeological heritage) are closely related to soil quality, which was defined by an American Soil Science Society (Karlen et al., 1997)

There are three main categories of soil properties: chemical, physical and biological (Pouyat et al., 2010). Compaction due to farm machinery is an important form of physical soil deterioration (Batey, 2009). Several methods were used in civil and agricultural engineering research to ascertain the degree of soil compaction, both in the laboratory and in situ. In agricultural soils, various criteria, indices and approaches such as soil strength, cone index, dry bulk density, soil water content, porosity, pore size distribution, infiltration, plant growth, root density, and plant yields have been employed in different studies to identify soil compaction (Kulli et al., 2003; McGarry 2003; Keller et al., 2013; Lestariningsih & Hairiah 2013; Keller et al., 2015; Sivarajan et al., 2018; Seifu & Elias, 2019). Among these methods, the static cone penetrometer has overmuch assented between researchers in the worldwide and accepted as a standard method for soil compaction measurements (Perumpral, 1987). Standard Proctor Compaction test, Rubber-balloon test, Sand Cone test, Nuclear test and Penetrometer test are the major methods used by civil engineers to assess compaction status (Table 2.1) and rarely used by soil scientists (Park, 2010; Edwin et al., 2015).

Table 2.1: The methods used for measuring soil compaction by civil engineers

Method	Location of test	Principle of test	Comments
Standard Proctor Compaction test	Laboratory	• Determine soil compaction properties, especially the relationship between water content and density of soils	• Widely used in civil and agricultural engineering research
Rubber-balloon test	On-site	• Measure the density and moisture content of compacted soil	• More expensive and the risk of error is high Widely used by civil engineers
Sand Cone test	On-site	• Determine the density of compacted soils	• Inexpensive and fairly accurate
Nuclear test	On-site	• Measure the density and moisture content of the compacted soil	• Quick and fairly accurate Used by civil engineers
Penetrometer test (static and dynamic)	On-site and Laboratory	• Measure soil strength	• Widely used in civil and agricultural engineering

Compaction due to agricultural field traffic directly influences on soil physical properties than other soil functions (Lal, 1997; Vogel et al., 2019). Measuring physical properties provides information related to the soil's ability to withstand physical forces associated with wheeling traffic, rapid water entry into the soil that contribute to aggregate breakdown, compaction, soil dispersion, and erosion (Horn et al., 1995). Compaction results in an increase in bulk density owing to soil particles, reduction in water permeability owing to a reduction in pore spaces and increase resistance penetration of water, nutrient, roots and soil strength (Hamza & Anderson, 2003). Several studies (Hakansson & Lipiec, 2000; Radford et al., 2000; Braunack & Johnston, 2014; McPhee et al., 2015; Bennett et al., 2017; Bennett et al., 2019) used soil water content, dry bulk density and soil penetration resistance to determine the impact of machinery traffic on soil compaction. Thus, these parameters are highlighted in this study. Table 2.2 summarises the studies that employed soil and agronomic parameters as indices for soil compaction.

Table 2.2a: Soil and agronomy parameters used as an indicator for soil compaction

Author's	Country	Soil type	Soil parameter	Agronomy parameter
Meek et al. (1992)	Australia	Sandy loam	Soil water content and Dry bulk density	-
Daniel & Wu (1993)	USA	Clay	Soil water content and hydraulic conductivity	-
Al-Adawi & Reeder (1996)	USA	Silty clay loam	Soil penetration resistance, dry bulk density and total porosity	Corn and soybean yields
(Alakukku 1996)	Finland	Clay	Total porosity and pore size distribution	-
Jansson & Johansson (1998)	Sweden	Silty loam	Dry bulk density, penetration resistance, intrinsic air permeability, saturated hydraulic conductivity, porosity and pore-size distribution	-
Abu-Hamdeh (2003)	USA	Clay loam	Dry bulk density	Plant height and root density
Hamza & Anderson (2003)	Australia	Sandy clay loam	Dry bulk density, soil penetration resistance, soil water content, porosity	Wheat yield, chickpea yield
Hulugalle et al. (2007)	Australia	Clay	Total porosity and dry bulk density, soil water content	Cotton yield
Botta et al. (2009)	Argentina	Clay	Soil penetration resistance	-
Braunack et al. (2012)	Australia	Clay	Soil penetration resistance	Barley growth
Van Quang & Jansson (2012)	Vietnam	Silty clay	Soil penetration resistance, dry bulk density, water content	-
Moraes et al. (2013)	Brazil	Silty clay	Soil penetration resistance, dry bulk density	-
Braunack & Johnston (2014)	Australia	Clay	Soil penetration resistance	-
Destain et al. (2014)	Belgium	Silt loam	Cone index	-

Table 2.2b: Soil and agronomy parameters used as an indicator for soil compaction (continued)

McPhee et al. (2015)	Australia	Clay loam	Soil penetration resistance, dry bulk density, porosity, soil water content	Yield
Schjønning et al. (2016)	New Zealand	Sandy loam	Soil penetration resistance	Yield
Roberton & Bennett (2017)	Australia	Clay	Soil water content	-
Bennett et al. (2017)	Australia	Clay	Soil water content, dry bulk density, soil penetration resistance	Cotton yield
Bartimote et al. (2017)	Australia	Clay	Soil water content, dry bulk density	Cotton yield
Sivarajan et al. (2018)	USA	Sandy loam	Soil penetration resistance	Corn and soybean growth
Bennett et al. (2019)	Australia	Clay	Soil water content and dry bulk density	-

2.6.1. The dry bulk density of the soil

The dry bulk density *(Pb)* of a soil reflects the soil's capability to function for structural support, water movement and soil aeration (Dexter & Czyż, 2000; Lampurlanés & Cantero-Martinez, 2003). Dry bulk density is defined as the mass of dry soil per unit volume of the soil (Hossain et al., 2015). The dry bulk density of soil is an important indicator for assessing soil health and compaction status (Nawaz et al., 2013; Hugar & Soraganvi, 2014; Vero et al., 2014). It is inversely related to soil porosity, which gives an idea of the pore space left in the soil for air and water movement (Lampurlanés & Cantero-Martinez, 2003). The volume of a typical soil is approximately 50% solids and 50% pore space (25% water and 25% air) (USAD, 2017).

Dry bulk density of soil is usually determined by direct methods (Cores, Clod and Excavation) and indirect methods (Radiation and Regression) (Al-Shammary et al., 2018). Direct methods are more practical and widely used by civil engineers and agricultural soil scientists (Ma et al., 2013). Indirect measurements can have many limitations, such as proneness to large errors when sampling different locations and is time consuming (Xu et al., 2016). Core sampling is the most common method employed by scientists to measure *Pb* in agricultural soils because it is simple, quick and inexpensive (Casanova et al., 2016; Al-Shammary et al., 2018). This method requires a volumetric cylinder or solid ring to be pressed or hammered into the soil to take a core sample (McKenzie et al., 2002). Figure 2.2 summaries the procedures for measuring the dry bulk density of soil using direct methods (Core, Clod, and Excavation) (Al-Shammary et al., 2018).

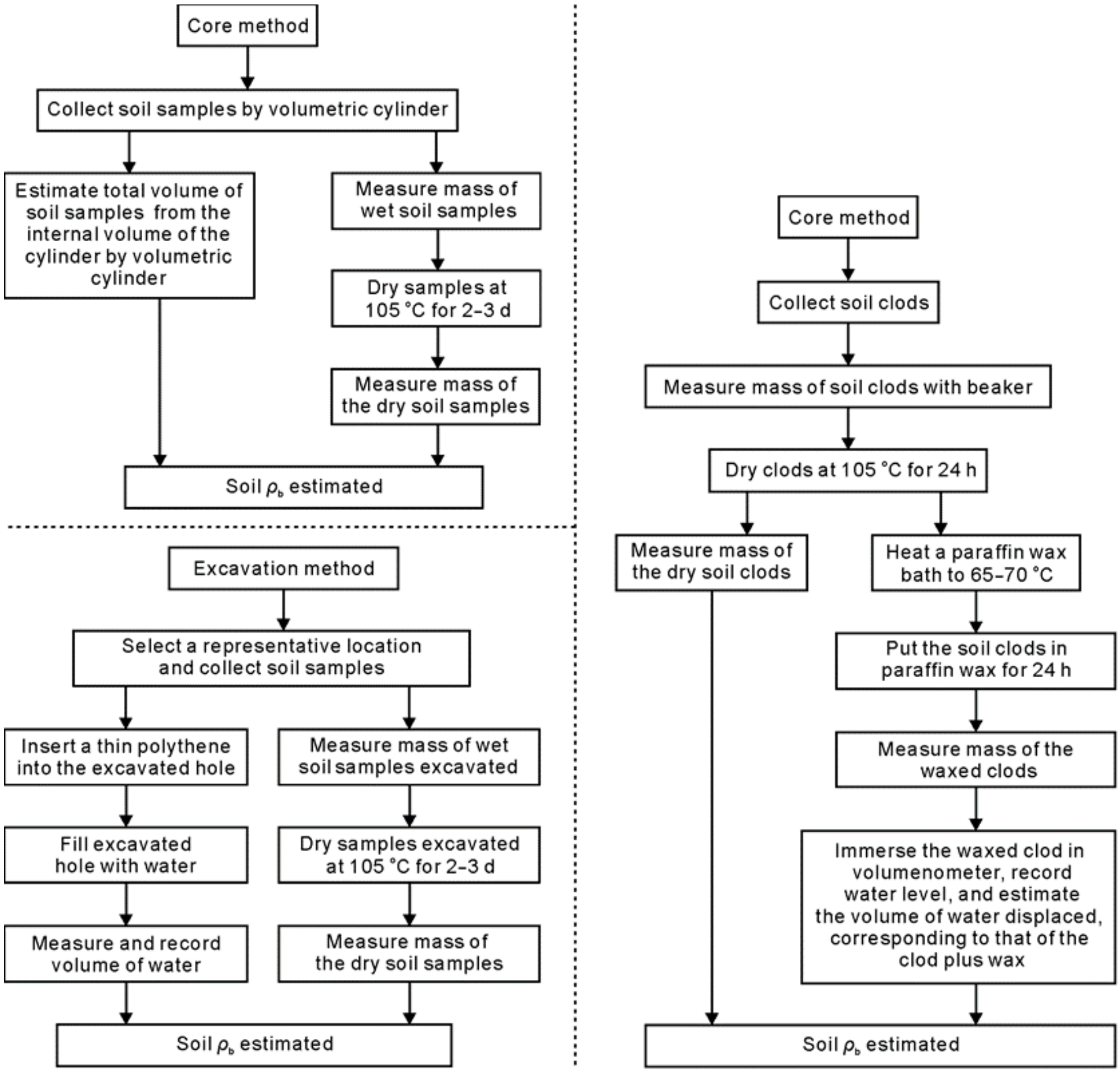


Figure 2.2: Direct methods (Core, Clod, and Excavation) used for measurement of *Pb* Source: Adopted by the researcher from (Al-Shammary et al., 2018).

The *Pb* values of agricultural soils often range between 0.9 g/cm^3 and 1.8 g/cm^3 (Erbach, 1987). There is an optimum dry bulk density at which soil pore size distribution results in the retention of the right amount of air and water needed for plant growth (Lutz, 1952). The dry bulk density of the soil in one way might reflect soil physical functioning, the type and arrangement of soil aggregates along with the distribution of pores (Osunbitan et al., 2005; Munkholm et al., 2016). Changes in *Pb* affect porosity and water movement due to changes in the pore size distribution (Kosugi, 1999; Bhattacharyya et al., 2006). With increased *Pb* (due to compaction), soil aggregates are packed more closely and thus, the pores between them are smaller than at lower bulk densities (Garey, 1954; Zhang et al., 1993).

Compaction is the key reason for increasing soil bulk densities. When compaction occurs, soil particles are rearranged, leading to changes in pore size distribution and pore connectivity (Nagy et al., 2018). Compaction can reduce the number and size of large pores and increase the mechanical resistance of the soil by pressing soil particles more closely together (Xiao et al., 2018). Increasing compaction of soil means increasing *Pb* which in turn affects porosity, pore size distribution, infiltration, root penetration, plant nutrient availability, and soil microorganism activity, which impact key soil processes and productivity (Horn & Smucker, 2005; Carminati et al., 2008; Lipiec et al., 2012). Furthermore, increasing bulk density due to excessive compaction results in increased mechanical impedance, creating unfavourable growing conditions for roots as supplies of air, water, and nutrients are reduced (Daniells et al., 1996; Houlbrooke et al., 1997; Jansson & Johansson, 1998). Table 2.3 demonstrates the key relationship between dry bulk density and plant growth (USAD, 2017).

Table 2.3: The main relationship between *Pb* and root growth based on soil texture

Soil Texture	Ideal bulk densities for plant growth (g/cm^3)	Bulk densities that affect root growth (g/cm^3)	Bulk densities that restrict root growth (g/cm^3)
Sands, loamy sands	< 1.60	1.69	> 1.80
Sandy loams, loams	< 1.40	1.63	> 1.80
Sandy clay loams, clay loams	< 1.40	1.60	> 1.75
Silts, silt loams	< 1.40	1.60	> 1.75
Silt loams, silty clay loams	< 1.40	1.55	> 1.65
Sandy clays, silty clays, clay loams	< 1.10	1.49	> 1.58
Clays (> 45% clay)	< 1.10	1.39	> 1.47

Several studies described the process of soil densification during traffic on the overall field and its consequences on crop growth (McPhee et al., 2015; de Lima et al., 2017; Sivarajan et al., 2018; Bennett et al., 2019; Esteban et al., 2019). For example, traffic by light tractors leads to increased *Pb* of loam soil by approximately 15% in the surface layer (Al-Ghazal, 2002). Soil compaction due to equipment traffic results in a significant increase in *Pb* of clay loam soil beneath the wheel tracks; by 9% in the sub-surface layers (Farhadi et al., 2013). Compaction caused by the passage of heavy machinery increases the dry bulk density of clay soils to 1.26 g/cm^3 at a depth of 10–25 cm (Nawaz et al., 2013). The use of heavy machinery under wet conditions is the key source of increasing *Pb* of sandy loam soil to about 1.72 g/cm^3 in the topsoil (Meek et al., 1992). Compaction due to the heavy wheel traffic of tractors increases *Pb* of clay soil rapidly, by approximately 15% at a 15–25 cm depth (Chan et al., 2006). The *Pb* values of clay loam soil increases by 13% in the surface soil after four passes of the tractor wheel (John Deere 3350) (Ahmadi & Ghaur, 2015).

The long-term impacts of soil compaction by harvester traffic induces an increased *Pb* of sandy loam soils to 1.74 g/cm^3 at the depth of 20–25 cm (Twum & Nii-Annang, 2015). Compaction due to one pass of harvester results in an increased *Pb* of silty clay loam by 14% in the topsoil, while frequent traffic causes a significant increase in dry bulk density in both surface and sub-surface layers (Hamza & Anderson, 2005; Moraes et al., 2013). Repeated traffic using different types of farm machinery is the key reason for the increasing *Pb* of sandy clay loam soils; by approximately 9% in the surface layer (Fasinmirin & Joseph, 2012).

Furthermore, compaction due to one pass of the JD770 cotton picker increases the dry bulk density of Vertosol from 1.54 to 1.62 g/cm^3 at the depth of 20–30 cm (Woodhouse et al., 2013). The average *Pb* of Vertosol rapidly increases after single traffic, of a John Deere 7760 harvester, by approximately 11% throughout the 0–30 cm depth (Bennett et al., 2015). Trafficking of the JD7760 under controlled traffic farming causes lower compaction by 6% in the surface layer when compared to random traffic farming systems (CFI, 2016). However, a significant increase in the *Pb* of Vertosol has been observed after a single pass by the JD7760, irrespective of the traffic system applied (Bennett et al., 2017).

Overall, this section has provided a brief summary of the literature relating to the process of compaction in terms of changing *pb* due to mechanised traffic on the overall field under different soil types, depths and traffic conditions. It was found that the dry bulk density is an appropriate index for assessing soil compaction due to harvesters traffic.

2.6.2. Soil penetration resistance

The main physical properties that control the penetration resistance (SPR) of soils are the degree of soil compaction, soil water content and particle size distribution (Bennie, 1988; Ampoorter et al., 2010; Medina et al., 2012; Van Quang & Jansson, 2012). Penetration resistance results from cohesive forces between soil particles and their frictional resistance (Landsberg et al., 2003). The SPR test is widely used as an indicator to evaluate soil structure and compaction status (Moraes et al., 2014a). Soil penetration resistance has a strong correlation with *Pb* when the measurements are taken at the same soil water content (Bennie, 1988). However, dry bulk density has not the major impact on SPR in the short-term (Van Quang & Jansson, 2012).

Several techniques were used to measure soil strength in situ including cutting blades, rectangular cutting plate, ring cutting plate and cone penetrometer (Ajdadi & Gilandeh, 2017). The penetrometer method is widely used by researchers to quantify the soil quality and to identify the layers with an increased degree of compaction (Chennarapu et al., 2018). Many types of cone penetrometers such as Static, Dynamic, Quasi-static and Dynamic, Inertial, Electric, Laboratory, and Dutch have been employed by civil engineers and soil scientists to assess compaction status (Perumpral, 1987; Figueiredo et al., 2011; Van Quang & Jansson, 2012; Lunne et al., 2014). Penetrometers are based on two principles of penetration: (1) static penetrometer or penetrograph: in operation, the whole set is pressed against the soil; and (2) dynamic or impact penetrometer: in operation, the rod penetrates the soil according to the impact of a weight falling from a constant height, in freefall (Stolf et al., 1998; Moraes et al., 2014b).

The static penetrometer is widely used by agricultural researchers to indicate soil compaction at field scale (Bengough et al., 2000). It is a quick and suitable method to provide valuable information and is easy to repeat in situ (Ayers & Perumpral, 1981). However, this technique is not recommended under very wet conditions (McKenzie & McBratney, 2001). A static penetrometer consists of a shaft with a 'pointed or blunt tip' on one end that is inserted into the soil to measure soil resistance (Arriaga et al., 2014). Two cone base dimensions are recommended by (ASAE, 1986): (1) 129 mm^2, 12.83 mm diameter (0.2 in^2. , 0.505 in. diameter) with 9.53 mm (0.375 in.) diameter shaft for hard soils; and (2) 323 mm^2, 20.27 mm diameter (0.2 in^2. , 0.798 in. diameter) with 15.88 mm (0.625 in.) diameter shaft for soft soils.

Static cone penetrometers were employed extensively in field trials to measure SPR and to assess soil compaction due to agricultural machinery traffic (Hulme et al., 1991; McKenzie & McBratney, 2001; Braunack & Johnston, 2014; Bennett et al., 2017). It has been revealed that soil penetration resistance values increase exponentially as Swc decreases and *Pb* increases (Moraes et al., 2012). For example, SPR ranged between 3.7–4.2 MPa when Swc was approximately 16% (Jobbagy et al., 2014). SPR also reached up to 3 MPa when the compactness degree was of 85% (Hakansson & Lipiec, 2000).

The excessive use of machinery in agriculture tends to increase SPRto up to 5 MPa, which results limits the expansion of a crop root's system and the absorption of water and nutrients (Rosolem et al., 2002; Lampurlanés & Cantero-Martinez, 2003). High resistance to penetration can be observed, after the single traffic of equipment, in the surface layer (Van Quang & Jansson, 2012). Frequent traffic causes significant compaction, which leads to increased soil penetration resistance in sandy loam soils to 2–3 MPa at the depth of 0–20 cm (Reintam et al., 2009). Table 2.4 shows the critical boundary of SPR for different soil types (Gebauer et al., 2012).

Table 2.4: Critical values of penetration resistance of soil types

Soil type	Soil penetration resistance (MPa)
Sandy loam and sand	more than 4
Sandy clay	3.7 – 4
Silt	3.5 – 3.7
Silty clay	3.2 – 3.5
Clay	less than 3.2

The primary traffic from a harvester caused significant compaction, which increased soil penetration resistance of about 0.5 MPa in the 15–25 cm depth (Landsberg et al., 2003). Significant compaction was observed underneath the wheel track of a combine harvester resulting in an increased SPR from 2.5 to 3 MPa throughout the 0–60 cm depth (Svoboda et al., 2016). Traffic from a sugar beet harvester induced significant compaction in silty clay loam soils, which increased soil penetration resistance up to 3 MPa at the depth of 30 cm (Schafer-Landefeld et al., 2004). Repeated traffic by a grain harvester was the major reason for the increased resistance in clay soils in both surface and sub-surface layers (Moraes et al., 2013). Furthermore, traffic from a sugarcane harvester resulted in increasing penetration resistance of silty clay soils to 3 MPa at the depth of 25 cm (Braunack & Peatey, 1999).

Traffic from the JD7760 cotton picker produced significant compaction, which led to increased resistance of Vertosol to penetration underneath the dual-wheel, which expanded to reach neighbouring cotton rows (Braunack et al., 2012; Braunack & Johnston, 2014). Significant compaction caused by the JD7760 traffic led to an increase in Vertosol resistance to about 2–3 MPa at the depth of 100 cm compared to before the traffic occurred (Bennett et al., 2016).

In conclusion, this section has provided a brief summary of the literature relating to the effect compaction due to wheeled traffic on soil penetration resistance. It has been identified that harvesters traffic regardless of the number of passes is a key reason for increasing soil penetration resistance in both surface and sub-surface layers for the different soil types. Therefore, SPR is a useful indicator for assessing soil compaction under different traffic systems.

2.7. Effect of soil water content on soil compaction

Soil water content (Swc) is a soil characteristic that plays a critical role in a large variety of biophysical processes such as seed germination, plant growth, and plant nutrition (Mosaddeghi et al., 2000; Keller, 2004). It is expressed on a volumetric or gravimetric basis. The definition of volumetric water content (θv) is the volume of water per unit volume of soil (Jury & Horton 2004). Gravimetric water content (θg) is defined as the mass of water per unit mass of dry soil (Hillel, 1982).

Swc is a function of changing soil physical characteristics (Hillel, 1982). It is a factor that significantly influences compaction (Malizia & Shakoor, 2018). Small changes in the water content of soil result in a rapid increase in the potential for compaction (Roberton & Bennett, 2017). Compaction can be minimised or delayed when farm practices are carried out at the appropriate soil water content level (Hamza & Anderson, 2005). The standard Proctor Test is often performed by geotechnical engineers to determine the relationship between Swc and dry bulk density which can be achieved at maximum compaction (Das & Sobhan, 2013).

The Proctor Test demonstrates that soil compaction depends on Swc, soil type and the compactive effort applied (Sridharan & Sivapullaiah, 2005). The compactive effort is related to the amount of mechanical energy that is applied to the soil mass (Das & Sobhan, 2013). Figure 2.2 presents an example of a typical compaction curve for a medium textured soil from a standard Proctor Test. Increased compactive effort results in greater dry unit weights because the shape of the no air voids line must occur at lower optimum moisture contents. This means that under higher compactive efforts, a lesser amount of moisture is required to compact the same soil to its maximum (but lower) density. Hence the compaction under the same load and machine is different in different soils and moisture contents (Bowles, 1979).

Starting from the dry side in Figure 2.3, dry bulk density can be seen to increase with increasing soil water content until it reaches the peak called maximal density at Swc value called optimum moisture, above which dry bulk density decreases (Hillel, 1982). This phenomenon could be explained by the fact that dry soil resists compaction due to its stiffness and the bonds between particles. As Swc is increasing, the water acts as a lubricant between soil particles, leading to reduced cohesive forces between particles, permitting them to slip over one another easily (Al-Shayea, 2001; Craig, 2004; Das & Sobhan, 2013). At saturation, no amount of kneading results in increased in dry bulk density of the soil (Hillel, 1982).

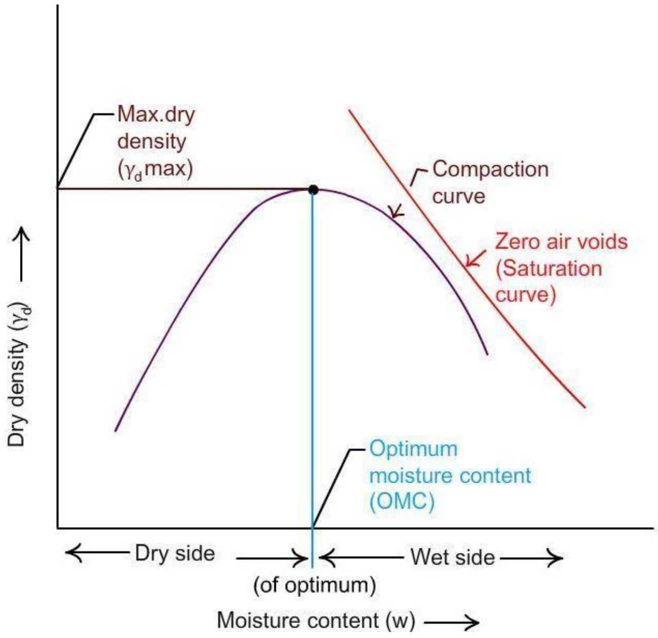


Figure 2.3: Dry bulk density-water content curve for a medium textured soil for a given compactive effort

Source: Adopted by the researcher from (Das & Sobhan 2013).

In the case of Australian soils, for example, Vertosol has a high capacity for water storage due to a high proportion of clay mineral (Virmani et al., 1982; Bennett et al., 2019). More than 93% of Vertosol compaction can occur when Swc is about 24% (Bennett et al., 2016; Roberton & Bennett, 2017). Thus, machinery traffic on the soil with higher water content (≥30%) has even more adverse influences on the soil properties (Raper, 2005; McPhee et al., 2015). Trafficking under wet conditions (>60% field capacity) causes both topsoil and subsoil compaction (Allen & Musick, 1997). Traffic from the JD7760 cotton picker produces significant compaction in the surface soil when Swc is at 21.4% (Bennett et al., 2017). Overall, it is critical to know the appropriate level of Swc at which trafficking and farming operations cause minimal compaction. This helps determine the correct timing for those operations to avoid the risk of soil compaction however, farmers believe that cultivation and harvesting are more important than avoiding soil compaction (Bennett et al., 2015).

2.8. Relationship between machinery traffic and compaction

With the need for machinery, completely avoiding soil compaction may be extremely difficult, if not impossible (Schafer et al., 1991). The problems of both topsoil and subsoil compaction are closely related to ground contact pressure and axle load and tracks (Botta et al., 2002; Keller et al., 2007). Compaction due to wheeled traffic results in changing soil volume through the applied loads to increase soil densities and decrease porosity, i.e. compress soil aggregates (Wolkowski & Lowery, 2008). Compaction mainly occurs when farm machinery passes over the soil surface causing a decline in volume pore available for water and air as the mineral components are compressed closer together (Raper, 2005). In other words, soil compaction occurs when machinery traffic damages soil structure (Chamen et al., 2015).

Soil compaction by mechanised traffic is characterised by a reduction in total porosity in the area underneath the wheel track at the surface soil (Hamza & Anderson, 2005). The degree of soil compaction due to equipment traffic depends on the following: (1) soil strength, which is influenced by soil characteristics such as soil texture and organic matter content; (2) structure of the tilled layer at wheeling and its water status; and (3) loading which depends on the axle weight, tyre size, machinery velocity, and tyre-soil interaction (Horn et al., 1994; Horn et al., 1995; Hamza & Anderson, 2005).

Trafficking resulting from normal farming operations is a key source of soil structure damage, and the occurrence of topsoil and subsoil compaction (Voorhees et al., 1978; Botta et al., 2002; Ghadiri et al., 2015). Traffic from large machinery with dual wheels induces a significant level of compaction (Wolkowski & Lowery, 2008). Heavier machinery traffic changes soil structure with each passage, which leads to increased *Pb* and reduces its production capacity (Naseri et al., 2007; Ampoorter et al., 2012). Traffic from a combine harvester in wet conditions produces significant compaction, which results in poor Vertosol structure at the 40 cm depth (Radford et al., 2000;

Schafer-Landefeld et al., 2004). The repeated traffic of a sugarcane harvester produced considerable compaction resulting in soil structure damage and reduced yield (Braunack et al., 2006). The influence of farm machinery traffic on soil properties (soil water content, dry bulk density and SPR) has been highlighted in Section 2.6. In brief, more studies are required for soil compaction resulting from mechanised operations performed under different field conditions.

2.9. Effect of the John Deere 7760 cotton picker traffic on soil compaction

Since its introduction in 2008, the new round module builder JD7760 has been widely adopted by the Australian cotton industry (Bennett et al., 2013; Van der Sluijs et al., 2015), with an adoption rate over 80% (Bennett et al., 2014; Roberton & Bennett, 2015). This picker is fitted with six spindles to harvest six cotton rows individually (Woodhouse et al., 2013). The machine has the ability to mechanically build, wrap, eject and drop regular and consistent modules without stopping (Bennett et al., 2015). However, its weight has increased to around 32 tonnes, i.e. twice the weight of John Deere's previous picker called the basket picker (Braunack et al., 2012; Gebauer et al., 2012). Figure 2.4 shows the new generation of the John Deere 7760 cotton picker.

Figure 2.4: The John Deere 7760 cotton picker, noting that the harvester on the right has a front dual-wheel

Source: Adopted by the researcher from a field trial.

Given that over 80% of Australian cotton farms are now being harvested with the John Deere 7760, its weight raises a major soil compaction concern the Australian cotton industry (Bennett et al., 2014; Roberton & Bennett, 2015). Several factors can directly affect the range and level of compaction, including machine size, number of passes, harvest velocity, and wheel slippage (Kolka et al., 2012).

Many studies highlighted the effect of compaction by wheel traffic on soil, while fewer studies addressed its influence on crop yields (Neale, 2009). Both growers and the industry are seeking to maximise profits in their farming systems by employing larger and wider machines (CFI, 2016). The John Deere company has offered many advantages of using the JD7760 such as safer operation, high efficiency, and the lowest operating costs (Bennett et al., 2015). Unfortunately, a heavier harvester causes significant compaction which can reach the depth of 100 cm (Kozlowski 1999; Arvidsson et al., 2001; Berisso et al., 2012).

Compaction by the JD7760 can increase soil strength rapidly and it can reach adjacent cotton rows (Braunack et al., 2012). Significant compaction was observed after a single pass of the JD7760 at the 0–80 cm soil depth (Bennett et al., 2015). However, the adoption of controlled traffic farming may reduce soil compaction risks (McKenzie, 1998; Braunack et al., 2006). Overall, the Australian cotton industry might need more information to overcome soil compaction hazard associated with the JD7760 (Bennett et al., 2014). Figure 2.5 shows the general framework of the effect of the JD7760 in relation to different aspects, as suggested by Bennett et al. (2015).

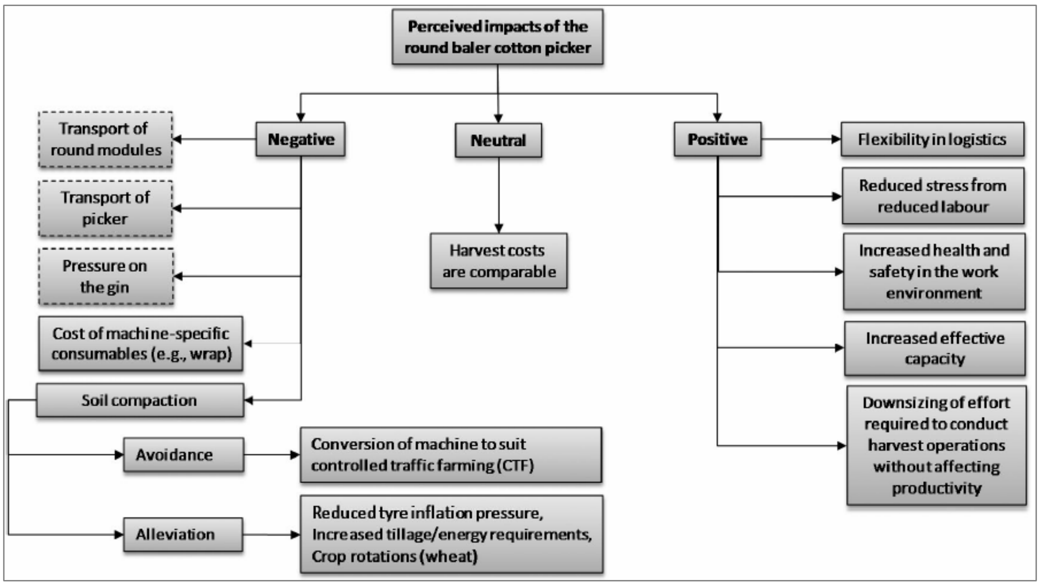


Figure 2.5: A general framework of the effect of the JD7760 cotton picker in different aspects

Source: Adopted by the researcher from (Bennett et al., 2015).

2.10. The influence of tyre size and inflation pressure on compaction

Several external factors affect soil compaction, including the contact pressure generated at the tyre-soil interface, the inflation pressure of tyres, tyre size and axle load (Botta et al., 2009; Rodríguez et al., 2012; Idowu & Angadi, 2013; Bennett et al., 2016). The hazard of soil compaction normally depends on the stress exerted on the soil (Hamza and Anderson, 2005; Arvidsson, 2014). Despite the soil mechanical strength, loading and soil-tyre interaction contribute substantially to soil compaction (Chehaibi et al., 2012). The size and distribution of stress in the soil-tyre interface is controlled by the tyre inflation pressure or by the wheel load which is still a source of dispute (Schjønning & Lamandé, 2010). The number of passes and the tyre-soil contact pressure in particular are the major factors contributing to soil compaction (Keller, 2004). To reduce compaction effects, it is preferable to utilise the equipment on tyres with large contact areas, with ground pressure as low as possible (Chehaibi et al., 2012).

Tyre inflation pressure usually has a large impact on increasing topsoil compaction and very little effect on the sub-surface layer, while wheel loads may have the dominant effect on increasing subsoil compaction (Botta et al., 2002; Arvidsson & Keller, 2007). Investigations show that trafficking with high tyre inflation pressure leads to increased vertical stress propagation, soil deformation, and soil compaction (Keller et al., 2007; Holthusen et al., 2018). Increasing tyre inflation pressure increases the risks of compaction in the surface soil (Keller & Arvidsson, 2004). Increasing tyre inflation pressure and the dynamic vertical load of tyre causes major compaction to a depth of 50 cm (Abu-Hamdeh et al., 2000). In contrast, soil compaction may be less when using low tyre inflation pressure (Chehaibi et al., 2012; Afzali et al., 2014).

The use of low tyre inflation pressure (150 kPa) with wheel loads >8 Mg may reduce compaction of clay soils at the surface layers (Danfors, 1994). Reducing tyre inflation pressure to 50% of the recommended pressure offers several benefits for soil compaction alleviation compared to tyres operated at the recommended level (Bennett et al., 2015; Bennett et al., 2016). Advantages of adopting the low inflation pressure of farm machines include reducing tyre-soil interface, decreased external rolling resistance, increased tyre performance and the alleviation of soil compaction (Van et al., 2008).

Tyre size and arrangement have a direct influence on the size of the contact area (Rodríguez et al., 2012). Recently, tyre size has increased (due to increased axle weight) to keep soil surface unit pressure comparatively constant and alleviate compaction effects (Lamandé & Schjønning, 2011). Using larger and wider tyres with low inflation pressure can reduce the risk of wheel sinkage and compaction (McKenzie et al., 2003). The use of a wider tyre may reduce soil compaction hazards under wet conditions (McNabb et al., 2001). Adopting wider tyres with reduced inflation pressure from 25 to 125 kPa decrease soil displacement, rut depth and compaction (Ansorge & Godwin, 2007). Furthermore, employing a larger overall diameter may be more beneficial than a wider tyre in terms of reducing the problems of compaction (Ansorge & Godwin, 2007).

The use of dual-wheels with low tyre inflation pressure may reduce soil stress in the top 15 cm (Arvidsson, 2014). The John Deere company has equipped the front wheel of the JD7760 cotton picker with a dual-wheel and larger tyres (520/85R42 R1R2) to limit the compaction risk due to the increased axle weight of the picker (John Deere, 2016). Nevertheless, traffic of the inner and outer dual-wheel of the JD7760 is a major cause of compaction in the topsoil and the subsoil (Bennett et al., 2017; Bennett et al., 2019). The subsequent section will highlight the impact of axle weight on compaction.

In summary, it has been shown in this review that tire size and inflation pressure are related to the development of compaction in the topsoil and the subsoil. Trafficking with high tire inflation pressure can increase the risk of topsoil compaction. The use of a large and wider tire with low inflation pressure may be able to alleviate soil compaction under different field conditions.

2.11. The impact of machinery axle loads on compaction

As mentioned in the previous sections, the trend towards the use of heavy machinery means that topsoil compaction and subsoil compaction continue to increase. More than 30 Mg of loads are used per axle in several countries (Al-Adawi & Reeder, 1996). In Australia, the main reason behind compaction occurrence is that growers adopt larger machinery in order to obtain high efficiency and productivity (Pankhurst et al., 2003). An axle load of 6–10 Mg is a primary cause of compaction, leading to soil degradation and yield reduction (Schafer et al., 1992; Radford et al., 2001). Farm machinery traffic with an axle load of >10 Mg induces significant compaction which can reach the sub-surface soil (Hakansson et al., 1994; Wolkowski & Lowery, 2008).

Significant compaction was observed after a single pass of a heavy axle load at the depth of 60 cm (Schjønning & Rasmussen, 1994). Repeated traffic by an axle load of 10 Mg can increase the compaction hazard and may reach the subsoil (Etana & Hakansson, 1994; Al-Adawi & Reeder, 1996). Trafficking by heavy axle loads in wet conditions is the major reason for subsoil compaction (Alakukku et al., 2003; Chamen et al., 2003). Furthermore, traffic by heavy axle load (10 Mg) with high tyre inflation pressure can create a high risk for deep subsoil compaction (Arvidsson et al., 2001).

Previous studies (Voorhees et al., 1986; Abu-Hamdeh & Al-Widyan, 2000; Hamza & Anderson, 2005) indicated that traffic from a heavy axle load of >18 Mg results in a rapid change in the soil properties. Impacts of soil compaction due to wheeled traffic are often determined by measuring *Pb* and penetration resistance of the soils (Alakukku, 1996). The effect of machinery traffic on soil properties was highlighted in Section 2.6.

Furthermore, traffic from heaviest harvesters with a maximum load of 35 Mg can result in soil deterioration and compaction (Arvidsson et al., 2001). Both front and rear axle traffic of a combine harvester is a major source of surface soil compaction (Svoboda et al., 2016). From the calculated stress of homogeneous soil under different axle loads (Figure 2.6), it can be seen that soil stress beneath the loaded wheel decreases with increasing profile depth, whilst increasing with increased tyre-soil contact area (Alakukku, 1999). This may be explained by vertical stresses in the topsoil depending directly on ground contact pressure, while the stresses in the deep layers largely depend on the axle loads (Hillel, 1998; Alakukku, 1999).

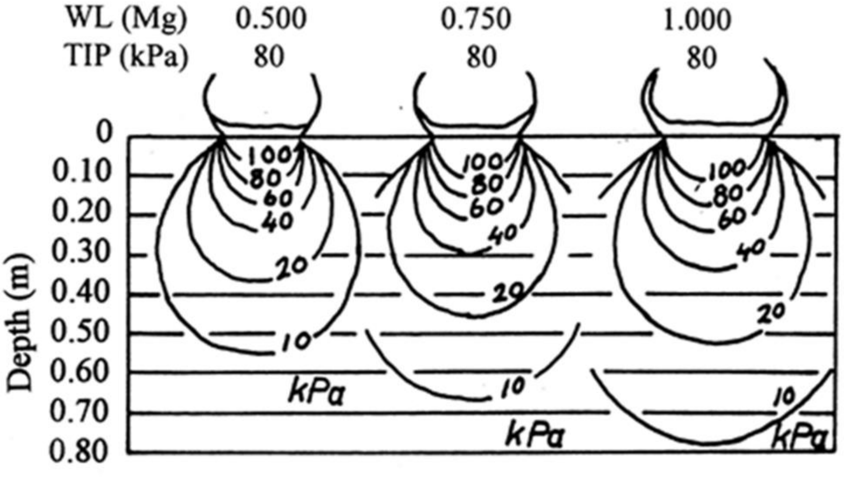


Figure 2.6: Calculated vertical stress as a function of wheel load (WL 0.5, 0.75 and 1.0 Mg) with constant tyre inflation pressure (TIP 80 kPa) of homogeneous silty soil

Source: Adopted by the researcher from (Alakukku, 1999).

Once again, traffic from the JD7760 cotton picker can produce significant compaction in both topsoil and subsoil, which is considered to be the main concern for farmers in terms of eliminating deep subsoil compaction and energy requirements (Bennett et al., 2019). During harvest time, the front axle of the JD7760 continues to be stable around 21.5 Mg when the first round bale is formed. Thereafter, however, the load begins to decrease to 20 Mg when the bale is transferred to the rear platform. The normal load of the rear axle is about 10.6 Mg but increases to 12.8 Mg due to the first bale, thus the rear axle loads have dramatically changed from 14.5 to 16.5 Mg when the second bale is produced (Figure 2.7) (Bennett et al., 2015). Overall, axle load is the key factor behind the soil compaction occurrence. The degree of soil deformation or compaction induced, varies from soil to soil depending on the soil conditions, type of machine and the frequency of passes (Naderi-Boldaji et al., 2018).

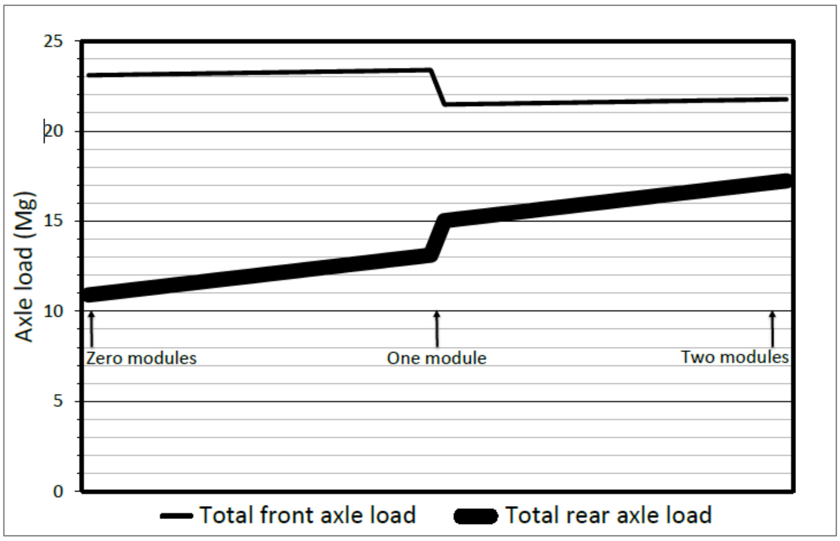


Figure 2.7: Dynamic axle loads for front and rear axles of the JD 7760. The x-axis represents the period that is required to produce one round bale

Source: Adopted by the researcher from (Bennett et al., 2015).

2.12. Controlled traffic farming

Controlled traffic farming (CTF) is a strategy built on adopting permanent lanes for agricultural machinery traffic to mitigate the influence of soil compaction (Tullberg et al., 2007). CTF is one of the most effective approaches to dealing with the risks of soil compaction by means of restricting the passage of machinery in the field (Bennett et al., 2016). The key advantage of CTF is the preservation of soil quality, thereby enhancing crop performance and reducing energy requirements (Kingwell & Fuchsbichler, 2011; McPhee et al., 2013). Nevertheless, frequent wheeling with lighter equipment can result in compaction equal to or greater than with fewer passes with heavier equipment (Jorajuria et al., 1997).

Employing CTF is a vital strategy to increase crop yields and profit margins, and reduce soil compaction risk (Antille et al., 2015c). However, many of the reported benefits of CTF for the cotton crop are less clear, particularly within farming systems, because of fewer studies conducted (Antille et al., 2016). The framework of CTF is that all machinery should have, or be modified to have, the same track width in order to restrict the wheels traffic in the permanent lanes (Antille et al., 2015b). In Australia, the controlled traffic approach has played an important role in providing a solution for more than 0.5 Mega hectares (Tullberg, 2001). Adopting CTF could reduce compaction by more than 50% compared to random traffic farming (RTF) (Galambosova et al., 2017). However, the key challenges to an entire industry switching to controlled systems are a lack of matching machinery tracks, working widths, and tyres (Tullberg, 2010).

Switching to CTF systems could yield improvements to soil quality attributes through the confinement of machinery traffic to tramlines on the farm (Godwin et al., 2015). For example, modifying wheel paths of a sugarcane harvester to a 2 m wheel track width to match CTF, resulted in improved inter-row soil properties (Souza et al., 2012). Nevertheless, this modification may not always show significant alleviation in soil compaction (Braunack & McGarry, 2006).

To limit compaction, Australia’s cotton industry has modified the current JD7760 cotton picker use under the CTF system (Antille et al., 2016). The main modification to this harvester is an increase of frontage width to 9 m as shown in Figure 2.8. In addition, the front axle of the harvester has been modified by replacing one tyre of the dual-wheel with a single tyre (620/ 70R42, inflation pressure 0.34 MPa). This modification allows the harvester to use the same tramlines when picking the six cotton rows that were shown with 1.5 m row spacing (Antille et al., 2016; Bennett et al., 2017). Figure 2.9 illustrates a comparison between RTF and CTF systems in terms of the wheel track of the harvester and cotton row spacing.

Figure 2.8: The JD7760 modified (9 m frontage with 1.5 m row spacing)

Source: Adopted by the researcher from a field trial.

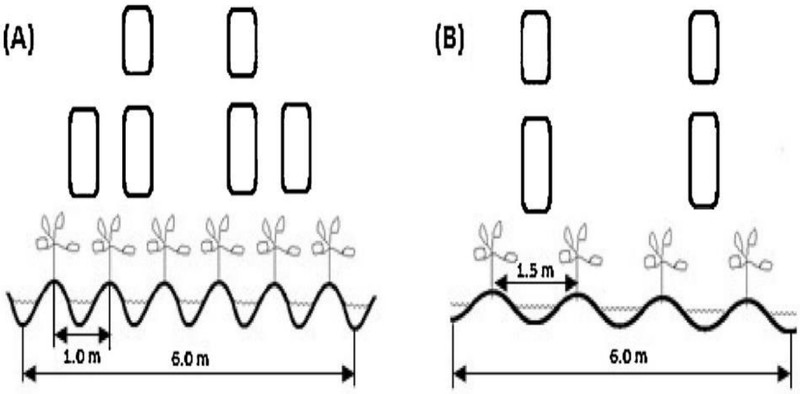


Figure 2.9: The JD7760 configurations: (A) 1.0 m row spacing RTF and (B) 1.5 m row spacing CTF

Source: Adopted by the researcher from (Bennett et al., 2017).

As mentioned above, to adopt CTF, permanent paths are required to restrict machinery passage and avoid compaction risk (Tullberg et al., 2007; Souza et al., 2015; Bennett et al., 2017). Compaction induced by the CTF 7760 harvester traffic might be lower than the JD7760 standard at the surface soil (Bennett et al., 2019). The main difference between RTF and the CTF in cotton farming is that about 66% of cotton furrows are subjected to wheel traffic under the standard JD7760, while 50% of furrows are subjected to traffic under CTF7760 (Bennett et al., 2017). However, adopting controlled traffic farming in cotton farms is complicated and costly due to the configurations of machinery wheels or the number of rows that are cultivated or picked (Braunack & Johnston, 2014).

In summary, it has been demonstrated in this section that adopting CTF might be a useful strategy in regards to reducing the risk of compaction. The implementation of CTF reduces the overall coverage and intensity of spatial compaction by restricting the motion of all farm machinery to a permanently trafficked region within the field, called tramlines. Traffic from the JD7760 regardless of controlled or random system may incur significant compaction of both topsoil and subsoil due to the weight of the axle.

2.13. Influence of compaction on soil environment and crop performance

In general, agricultural field traffic is one of the main causes of soil compaction which has damaging consequences for agriculture and the environment (Horn et al., 1995; Keller & Hakansson, 2010). Soil compaction affects the function of the pores to store and transport water and gases which is essential for plants (Ishaq et al., 2001). The impacts of soil compaction are often persistent, particularly in the subsoil, and they are intensified with repeated passes (Antille et al., 2018, Stoessel et al., 2018). Compaction also affects erosion, flooding, organic matter, salinization, nitrogen and carbon cycling, and crop growth (Nawaz et al., 2013). Furthermore, compaction-induced changes results in soil degradation, pollution of the atmosphere and of ground and surface waters, and they may also increase the consumption of finite natural resources, such as fuel and mineral fertiliser (O'Sullivan et al., 1995). Figure 2.1 illustrates the major interactions between soil physicochemical characteristics and root function and structure observed under conditions of soil compaction (Correa et al., 2019).

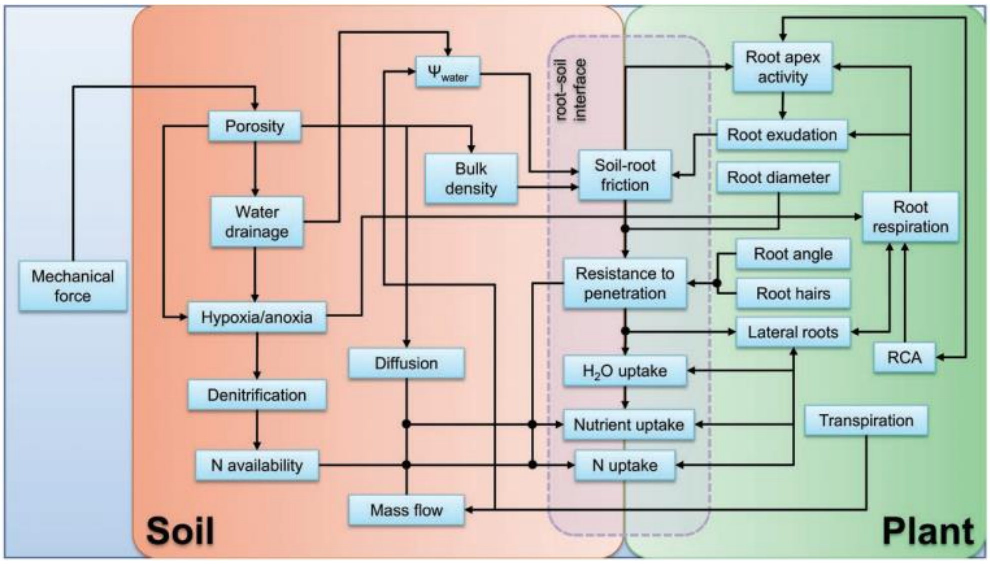


Figure 2.10: Block diagram of the major interactions between soil physicochemical characteristics and root function and structure observed under circumstances of soil compaction. Ψ_{water}, water potential; RCA, root cortical aerenchyma.

Source: Adopted by the researcher from (Correa et al., 2019).

Plant growth and relative yield can provide a reasonable index for compaction status (Grzesiak, 2009). Reduction in plant growth and productivity is highly connected to the development of soil compaction (Azzi et al., 2017). For example, yields may be fall, by approximately 26.8% after two years of compaction (Abu-Hamdeh, 2003). In fact, wheat yields may decline significantly when *Pb* is 1.6 g/cm^3 and soil resistance to penetration is up to 2.5 MPa (Hakansson & Lipiec, 2000; Vrindts et al., 2005). However, soil compaction is not the only factor that affects plant growth (Braunack & Peatey, 1999).

Several studies showed that compaction can reduce the yield of different crops up to approximately 60%, by reducing crop emergence, root growth and nutrient uptake (Marshall et al., 2016; DeJong-Hughes, 2017). Compaction due to machinery traffic causes physiological disorders of in-plant performance (Gebauer et al., 2012). Frequent traffic by machinery with 16 Mg axle load may result in poor soil structure, hamper nutrient uptake, and cause root damage and yield decline, by 9% annually (Alakukku & Elonen, 1995; Botta et al., 2016).

Traffic from a sugarcane harvester can cause major compaction leading to reduced yields by approximately 24% (Braunack & Peatey, 1999), while compaction due to combine harvester decreases grain yield by 18% (Liu et al., 2017). The harmful effects of wheeled traffic may result in cereal yields decreasing by 22% (Lipiec et al., 2003). Wheat yield can decrease due to compaction when *Pb* and soil penetration resistance values increase by 15% and 47% respectively on average (Junior et al., 2014). In brief, from the above review of the literature, it is apparent that yield decline is a function of soil compaction. Compaction due to equipment traffic results in increasing dry bulk density, soil strength, and hampers root development and penetration into the soil, which decreases water and nutrient uptake by plants and can translate into reduced crop yield and profitability (Al-Adawi & Reeder 1996).

2.14. Managing and alleviating soil compaction

Generally speaking, compaction can be found in the topsoil and subsoil. Compaction problems exist in a wide range of soils and cases (Alakukku et al., 2003; Batey & McKenzie, 2006). Mitigation of compaction mainly aims to ameliorate soil structure damage by decreasing soil strength and density, increasing water infiltration and air spaces of the soil, and promoting root penetration (Raper & Mac Kirby, 2006). This raises the question of how soil compaction can be detected, and then alleviated or avoided.

As highlighted in previous sections, wheeled traffic resulting from normal agricultural operations is the primary source of soil structure deterioration, topsoil compaction and subsoil compaction (Voorhees et al., 1978; Botta et al., 2002; Ghadiri et al., 2015). Compacted layers often range between 30– 60 cm below the surface, particularly when the soil is subjected to frequent machinery traffic without annual ripping operations (Randrup, 1997; Randrup & Dralle, 1997). Soils with high clay contents are more susceptible to compaction (Gong et al., 2018). Thus, managing agricultural activities and environmental variations can play a role in improving soil structure and minimising compaction risk (Bronick & Lal, 2005).

Alleviation strategies vary significantly in effectiveness depending on the range and depth of compaction, soil type and climate (Chamen et al., 2015). Many techniques have been adopted to reduce both topsoil compaction and subsoil compaction including: (1) reducing the repetition of tillage operations by adopting no-till systems; (2) avoiding mechanical operation at high Swc; (3) adopting controlled or tramline systems; and (4) improving topsoil by adding organic matter (Raper, 2005; Nawaz et al., 2013).

Previous studies showed that normal tillage operations can largely eliminate topsoil compaction (Hamza & Anderson, 2005). Nevertheless, one practice may not be sufficient to completely reduce compaction of the surface soil (Hakansson & Voorhees, 1997). Therefore, the risk of topsoil compaction could be minimised by adopting the following: (1) reducing tyre inflation pressure to less than allowable pressures or using dual tyres; (2) matching tyres with the right axle weight; and (3) adopting conservation tillage (Hillel, 1982; Botta et al., 2002).

The mitigation of subsoil compaction is often left to natural processes such as soil wetting followed by drying, soil freezing followed by thawing and biological activities (Hakansson et al., 1987; De Boer et al., 2018). Soil recovery may be also affected by soil type, texture, compaction conditions (Antille et al., 2019). De Armond et al. (2019) reported that alleviation subsoil compaction of heavy clay soil due to natural processes had occurred after 24 and 30 years. Nevertheless, because the intensity and frequency of these processes are reduced in the deep layers, subsoil compaction may persist for a very long time (Alakukku, 1996; Schjønning et al., 2013).

Adopting deep ripping implements such as subsoilers is widely used to relieve subsoil compaction (Singh et al., 2019). However, this is a costly operation, and is not always an effective or long lasting solution (Raper & Bergtold 2007). Raper (2005) summarised the following major strategies which may help to loosen subsoil compaction due to machinery traffic:

- Avoiding traffic under wet conditions, i.e. (>60%) of field capacity
- Reducing wheel loads by decreasing the size of the equipment
- Employing dual wheels or using wider and radial tyres with optimum inflation pressure, which helps to increase the footprint of machinery

- Adopting CTF systems
- Adopting precision agriculture.

In Australia, alleviation of the compaction of clay soils such as Vertosols can be complex because Vertosols have the ability to respond to the effect of compaction easily, particularly under wet conditions (Chan et al., 2006), and they may also be self-repairing after frequent wet-dry cycles (Pillai & McGarry, 1999). This matter generated much concern among farmers, especially when they use larger and heavier equipment such as the JD7760 (Bennett et al., 2015). Three techniques could help to manage the risk of Vertosol compaction: (1) reduced axle weight; (2) adopting CTF; and (3) managing soil water circumstances through the timing of field operations (Roberton & Bennett, 2017). However, a number of passes on the same tramlines of light machinery can do as much or even greater damage than heavier machinery with fewer passes (Hamza & Anderson, 2005).

In summary, it has been demonstrated in this review that many strategies are available to manage and alleviate topsoil compaction and subsoil compaction. For example, field practices should not conducted when soil water is at or near field capacity. Controlled traffic farming might be a useful technique to avoid the risk of compaction. Monitoring compaction should be a part of routine soil management (Batey, 2009).

2.15. Yield of cotton

2.15.1. Introduction

In Australia, cotton crop is grown on 200,000–300,000 hectares and the majority of production is in New South Wales and Queensland (DAF, 2015). *Gossypium hirsutum L.* and *Gossypium barbadense* are the two major species grown, with *Gossypium hirsutum L.* forming approximately 90% of the total production (Redfern, 2015). More than 80% of Australian cotton farms are irrigated (Williams et al., 2018). Crops require about three months of growing time between September and November, whilst defoliation and harvesting occur from March to May (Antille, 2018).

Australia is the third-largest cotton producer in the world (Chen & Baillie, 2009). Australian cotton production is known to have the world's lowest cost (de Garis, 2013). The average cotton yield has now risen more than 2 tonnes per hectare due to the adoption of modern technology during the growth and harvest stages (Zhao & Tisdell, 2009). For instance, according to the Australian Bureau of Statistics (ABS, 2014), gross production in Queensland is estimated to be about 140,001 hectares, whilst the average domestic product is around 370,000 tonnes. In addition, the cotton industry employs a large number of Australians and contributes more than AUD1 billion to the Queensland economy annually (Cotton Australia, 2013). The map in Figure 2.11 illustrates the major cotton growing regions of Australia.

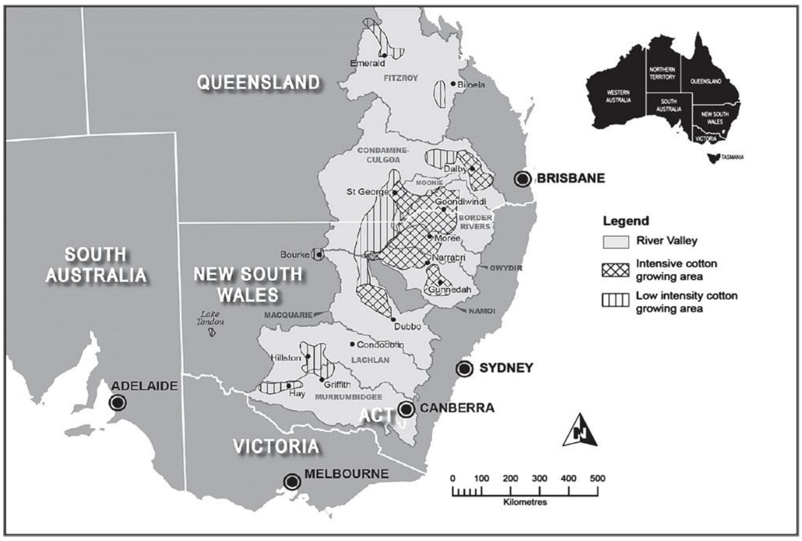


Figure 2.11: The main cotton growing areas in Australia

Source: Adopted by the researcher from (Silburn et al., 2014).

2.15.2. Overview of cotton pickers

Around 30% of the world’s cotton yield is currently picked with a variety of harvesters or pickers (Chaudhry, 1997; Bennett et al., 2015). Farmers and contractors are routinely using different types of cotton pickers, including the older basket systems that are unloaded into boll buggies, half module systems, and round module pickers (Bennett et al., 2014). The first picker was designed to harvest only one cotton row at a time, and was considered capable of replacing up to forty hand labourers (Gedam, 2014). A decade ago, Case IH revealed a new six-row harvester that builds half-size modules of cotton and drops the bale on the farm in less than a minute (Laws, 2006). However, this Case IH is expensive to operate because it requires the use of boll buggies, module builders, and two or three tractors for pulling (Laws, 2007).

Recently, the new round module builder JD7760 was released by the John Deere Company (John Deere, 2017). This picker has the ability to mechanically build, wrap, eject and drop regular and consistent modules without stopping (Wattonville, 2008). In addition, it can provide an opportunity for farmers to reduce picking costs per hectare, using preferable lint, thus contributing to the reduction of gross production costs per bale of cotton (Van der Sluijs et al., 2015). The JD7760 has the capability to harvest about 95-98% of the cottonseed with high efficiency (Batey, 2009; Willcutt et al., 2010). However, it is costly, requiring significant investment to switch from conventional pickers (Chico-Santamarta et al., 2013).

2.15.3. Effect of the soil compaction on cotton performance

The influence of compaction on crop growth and yield is a global concern. The increasing use of heavy farm machinery is the major source of declining yields (Daniells et al., 1996; Idowu & Angadi, 2013; Wolkowski, 2017). Adverse impacts of compaction on cotton production can be observed in the short and long-term (Van den Akker et al., 1998). Furthermore, yields can actually slightly increase under moderate compaction (Lipiec & Hatano, 2003; Igon & Ayotamuno, 2016).

More than one-third of actual yield loss occurs when soil structure is subjected to significant compaction (Daniells, 1989). Changes in soil physical properties can lead to long-term yield suppression of 7% (Ishaq et al., 2003). Compacted layers result in the reduction of cotton yields by approximately 30% (Bennett et al., 2013). The reduction in soil quality can also cause a 30% reduction in cotton yield (Hulme et al., 1991). Previous research revealed that cotton yield might decline significantly when the dry bulk density of the soil is between 1.60 g/cm^3 and 1.70 g/cm^3 (Coelho et al., 2000). Cotton yield can decrease, by approximately 15% after the first year of compaction occurrence (McKenzie et al., 2003; Braunack et al., 2012). Compaction, due to harvest traffic, is the main reason for a 23% decline in cotton growth and yield (Lowry et al., 1970; Neale, 2008). Traffic from the JD7760 harvester can reduce cotton yield by 15%–30% and this could cost the Australian cotton industry about AUD150 to AUD350 per hectare (CFI, 2016). Overall, adverse influences of soil compaction on cotton performance can occur in both the short and long-term which affects the total growing land profit and the net income.

2.15.4. Cotton row configuration

In Australia, the configuration of cotton rows plays a significant role in promoting production and can directly affect crop growth (Whish et al., 2005). To maintain soil quality and improve cotton yields, farmers employ several approaches for cotton growing, e.g. solid, single skip, double skip, wide row, and alternative skip (Quigley et al., 2015). For example, wide row spacing and skipped rows play a major role in the performance of dryland production, which could be employed as a management technique to reduce production hazards in dry periods (Routley et al., 2003; Whish et al., 2005). Solid row spacing can increase yield in irrigated situations by increasing crop leaf area and associated light interception (Routley et al., 2003; Brodrick et al., 2010). The 1.0 m (solid) and 1.5 m (wide) row spacing are the major strategies used for cotton growing in irrigated and dryland farms (Bartimote et al., 2017).

The 1.0 m row spacing is the conventional method widely employed by farmers under irrigated conditions (Bennett et al., 2017). CTF with 1.5 m row spacing is currently used by the Australian cotton industry to avoid the risk of compaction and improve cotton production (Tullberg et al., 2007; Tullberg, 2010). Adopting 1.5 m row spacing under CTF, may restrict soil compaction to only 15%–20% of the total area (Antille et al., 2016; Bartimote et al., 2017). In addition, 1.5 m row spacing might achieve higher cotton yields than 1.0 m row spacing; by 30% after several years of adoption (Quigley et al., 2015). Figure 2.12 shows the two main strategies that are used for cotton growing in Australia. In summary, by CTF the strategy, soil compaction may be lower, and this could translate positively on the cotton yield when compared to the conventional methods.

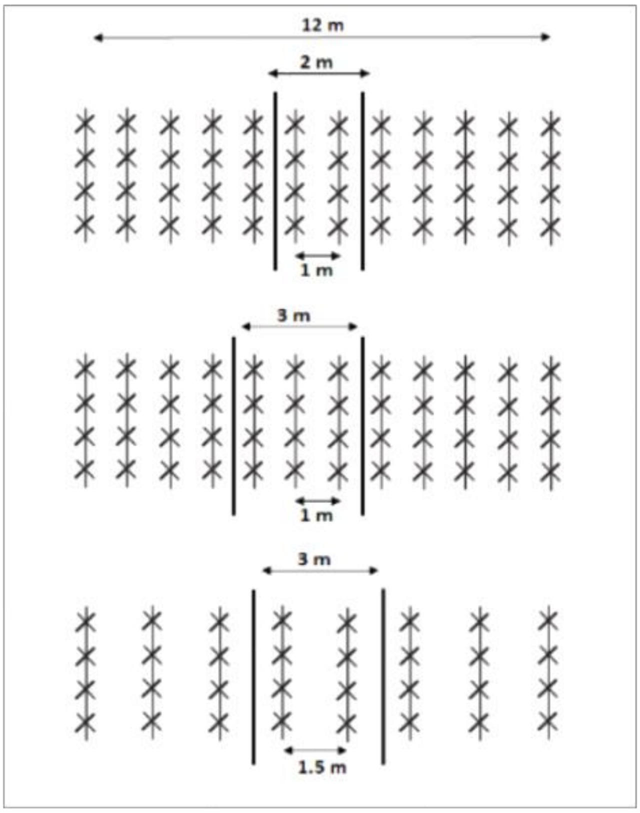


Figure 2.12: Cotton row configurations of 1.0 m and 1.5 m row spacing
Source: Adopted by the researcher from (Bange et al., 2005).

2.15.5. Methods to estimate cotton yield

Australian cotton production has increased rapidly during the last two decades at an average of 10% bales/hectare annually (Constable & Bange, 2006). The reliability of yield estimations is based on harvest method, efficiency and the turnout of the gin (Goodman & Monks, 2003). Modern technologies have the ability to make a precise and effective estimation of the yield (Zhang et al., 2002).

Precision agriculture is a recent technique that employs modern technology to improve crop production (Srbinovska et al., 2015). The major factors of precision agriculture include yield monitoring, remote sensing, Global Positioning System (GPS) and Geographical Information Systems (GIS) (Nemenyi et al., 2003). Yield monitors and GPS receivers are able to gather geographic data that is analysed by GIS software to highlight yield variations at farm scale (Andrade-Sanchez & Heun, 2013).

With the abovementioned modern machinery and technology, Harvest Doc, Green Star, and Harvest Identification are the key features of the JD7760 cotton picker (John Deere, 2010a). The power of these tools lies in their ability to perform yield monitoring, mapping, tracking and documenting functions immediately, which helps to make better-informed management decisions (John Deere, 2010a). Harvest Doc is used as the foundation and can record valuable information such as farm details, total harvested area, harvest hours, average yield, load weight, boundaries, soil type, and climate (John Deere, 2013). In addition, yield maps are generated by collecting the data from Mass Flow Sensors that are placed on harvest equipment (John Deere, 2004; Vellidis et al., 2012).

CAN-BUS (Controller Area Network) is a serial network technology designed by Robert Bosch GmbH in 1983, and has since spread to the public via the Society of Automotive Engineers (Davis et al., 2007). The key advantage of CAN-BUS is that it can instantly provide useful information during peak operations (Darr, 2012). Such a BUS is compulsory for effective use of electronics in agriculture. It guarantees unimpeded information and data transmission between agricultural systems from different manufacturers such as harvesters, tractors and farm computers (Speckmann & Jahns, 1999). Furthermore, hand-picked is another approach used by several countries (Chaudhry, 1997). This method is inexpensive and provides a high-quality lint yield (Nerkar et al., 2017), but it is the slowest and most tedious. Overall, many methods are available for farmers estimate of cotton yield. Features of modern technology (JD7760) are useful and accurate techniques that can be utilised to collect yield data in the field directly.

2.15.6. Harvest performance and yield losses

Several other factors can also affect relative cotton yield. For example, both delayed harvesting after cotton defoliation and harvester conditions can be the main reasons behind for increased harvest losses, which may result in yield reduction by approximately 20% (Khalilian et al., 1999; Sawan, 2017).

While cotton pickers have the ability to harvest 95–98% of the seed cotton, there is an issue related to picking efficiency in the form of harvest loss, which can reach up to

20% (Willcutt et al., 2010). The functional performance of the spindles of the cotton yield is mainly dependent on the availability of open cotton bolls (Muthamilselvan et al., 2007). By comparison, the JD9996 picker has less efficiency, in terms of cotton left unpicked, than the JD7460 stripper (Faulkner et al., 2011). It was also observed that cotton loss to the ground may fluctuate between 1.4% and 5%, while stalk losses vary between 1.7%–7.8% (Erdal, 2014). On the other hand, productivity rate and harvest loss by cotton pickers are higher than strippers with regards to the yield quality and losses (Faulkner et al., 2011).

A comparison between picker and stripper harvesters revealed that lint turnout was higher under the pickers by approximately 5%, which can reduce ginning cost per hectare when considering the quality of yield (Wanjura et al., 2013). Field-work has been carried out by Sessiz and Esgici (2015) who examined different models of cotton harvesters to verify the impact of these models and operators' abilities in terms of harvest loss and yield. Their findings are summarised in Table 2.5. Furthermore, harvester efficiency can be estimated by yield losses, overall yield quality, fuel consumption, and operators' conditions (De Baerdemaeker & Saeys, 2013). However, harvesting immature plants with bolls not opening due to an early frost, can also affect harvester efficiency (Willcutt et al., 2010). To date, it can be seen that several studies highlighted the efficiency between cotton pickers and strippers based on yield loss, while the efficiency between the JD7760 standard configuration and the CTF modified have not been investigated.

Table 2.5: A comparison between different cotton pickers in terms of cotton yield and yield loss

Cotton variety	Machine Model				
Properties	1998	2007	2011	2012	2012
	JD9970	JD9970	JD9970	JD9970	JD7760
Cotton lint yield, kg da^{-1}	486.42	443.57	458.5	346.2	487.85
Mean loss, kg da-1	60.18	25.71	38.51	25	33.14
Loss rate, %	12.3	5.8	8.4	7.22	6.79

2.16. Modelling

2.16.1. Soil compaction model

Soil compaction models represent a vital approach to improving soil characteristics and increasing yield (Schafer et al., 1991). According to Defossez and Richard (2002), the framework of soil compaction models is divided into two parts. The first part is to determine the propagation of loading stress due to machinery, while the second is to identify the relationship between modelling stress and strain behaviour (Appendix 2.1). However, cross-farm variability in soil properties and conditions are the main limitations leading to uncertainties in a model’s outputs (Gysi, 2000).

Many mechanical soil compaction models are being used to predict compaction that occurs beneath wheel tracks. These models predict soil compaction following three major steps including: (1) prediction of contact area and the distribution of load; (2) modelling of propagation of stress at the soil surface; and (3) use of an appropriate equation to characterise the relationship between stress and volume alteration in the soil profile (O'Sullivan et al., 1999). Agronomic models (STICS) and the compactor model (COMPSOIL) were coupled by Defossez et al. (2014) to calculate soil stresses as a function of equipment characteristics and the change in Swc at the surface layer. However, the combined models require more investigation because they are quite sensitive to the input parameters of soil properties (Defossez et al., 2014).

Soil shrinkage curves (ShC) is a model that is utilised to assess soil compaction by the distinction between plasma-porosity and macroporosity compaction, and to calculate for spatial variability in soil characteristics at field scale (Boivin et al., 2006). This model offers many advantages in that it is simple, accurate, and easy to operate. However, it has some limitations in wet soil conditions (Boivin et al., 2006). The hysteretic spring contact model (HSCM) and linear cohesion/adhesion model were integrated to model the cohesive behaviour of soil at different levels of compaction and its interaction with a sweep tillage tool (Ucgul et al., 2015). This model could predict both draft and vertical forces at different velocities, depths, water content, and soil compaction. The SoilFlex-LLW model has been used to predict change in the least limiting water range due to compaction by farm machinery (Keller et al., 2015).

FRIDA is a compaction model, which is employed to simulate wheel footprint using a super-ellipse stress allocation through a combined exponential and power-law. All of these compaction models may need to be validated with different machinery and soil conditions (Schjønning et al., 2008).

SoilFlex is an analytical model that was developed by Keller et al. (2007) to simulate soil compaction due to farm machinery traffic. This model is flexible and allows for a realistic simulation of contact area and stress distribution in the contact area from easily available tyre parameters (Keller et al., 2007). A two-dimensional model is integrated into SoilFlex. It aims to compute soil stress, changes in dry bulk density and vertical displacement of the soil due to wheel traffic (Keller et al., 2007). SoilFlex includes three main factors: (1) description of stress in the topsoil; (2) analytical computation of the stress distribution over the soils; and (3) calculation of soil deformation as a function of stress (Keller et al., 2007). The input and output parameters of SoilFlex are shown in Appendix (2.2).

The key feature of SoilFlex is its ability to employ tyre size (520/85R42 & 20.8–38) with tyre inflation pressure of 270 kPa as an input parameter for the JD7760 picker (Braunack & Johnston, 2014). In addition, SoilFlex has an advantageous feature which simulates the traffic of several types of machines with dual or tandem wheels (Keller et al., 2007). SoilFlex is considered a recent analytical model which can easily be used to describe upper boundary circumstances (tyre load) (Nawaz et al., 2013). However, this model has not been employed for a wide range of soils and thus requires more investigations to simulate compaction of Australian soils (Bennett et al., 2013). Further details about SoilFlex will be provided in Chapter 8. Table 2.6 summarises the existing soil compaction models that have been used by previous studies. Overall, many models employed to predict and manage of soil compaction. With SoilFlex, it is possible for researchers and agricultural advisers to simulate the traffic of machinery combinations that are utilised in field practices which is a considerable aspect that has been not addressed in previous models (Keller et al., 2007). However, the majority of compaction models are restricted in their implementation and required more investigations because they are based on several indicators, and each parameter may create complexities for the heterogeneous structures of soils.

Table 2.6a: Summary of an existing soil compaction models

Model	Key references	Origin	Principle of model	Key advantages	Limitations
Support Vector Machines (SVM)	Perez Gonzalez (2013); Karamizadeh et al., (2014)	Venezuela	• Application of Polynomial, Gaussian and exponential radial basis function kernels	• Offering a simple and reliable way of modeling the behaviour of soils • Enhancing the capacity in soil mechanics laboratories	• Lack of transparency of results • Not suitable for large data sets
Fuzzy logic approach	Carman (2008); Kaufmann (2008)	Turkey	• Mamdani approach fuzzy modelling principles	• Prediction the changes in penetration resistance, bulk density and final pressure of soil due to wheel traffic	• Tedious to develop fuzzy rules • Not giving generalisable results
SOCOMO	Van den Akker (1999)	Netherlands	• Based on Boussinesq theory that depicts the propagation of stresses in a homogeneous, linear elastic, isotropic and semi-infinite solid mass	• Providing useful data for adjusting wheel machines (number, tyre inflation pressure and width) • Calculating soil stress under wheel loads	• SOCOMO is based on a linear elastic behaviour of soil without volume change

Table 2.6b: Summary of an existing soil compaction models (continued)

Model	Key references	Origin	Principle of model	Key advantages	Limitations
Finite element method (FEM)	Defossez & Richard (2002)	France	• Based on the Boussinesq equation for stress propagation and describing stress distribution within the soil by two or three mechanical constants	• Allowing processing 3D problems by using the principal stresses σ1, σ2, σ3	• 3D compaction problem usually treated as a 2D problem by supposing axisymmetry or plane deformation
Three-dimensional finite element	Cueto et al. (2013)	Cuba	• Mamdani approach fuzzy modelling principles	• Prediction the effect of inflation pressures, ground pressure and tyre load on the stresses on the contact and the soil profile • Useful for teaching and research	• It designed for small tyre size
SoilFlex	Keller et al. (2007)	Sweden	• Based on analytical equations for stress propagation in soil	• Allowing for a realistic prediction of the contact area and soil stress distribution in the contact area from easily available tyre parameters	• Assuming soil profile as isotropic

2.16.2. Crop performance model

Since the 1960s, many crop yield models have been employed to predict the theoretical yield of crops (Krueger 2011). Yield models are broadly divided into two groups: simulation models and statistical models (Dahikar & Rode, 2014). These models are being improved and tested with experimental data. They have significant methodological gaps which are reflected in the differences between experimental values and grower yields (Carberry et al., 2009).

GOSSYM is a dynamic simulation model that can simulate both crop performance for an irrigated area and nitrogen fertilisation practices (Gertsis & Whisler, 1997). Agro-climatic yield is another model that was developed by Bazgeer et al. (2014). It utilises regression models and historical data to predict cotton yield for rain-fed farming. The Cotton2K model can predict the mode of growth and yield under various climatic conditions for irrigated cotton (Lascano et al., 2013). Furthermore, Artificial Neural Network (ANN) models are an excellent methodology for precisely setting cotton yield. They depend on the non-linear connection between the influence of factors and yield (Zhang et al., 2008).

The Agricultural Production Systems Simulator (APSIM) is a software model developed by the Agricultural Production Systems Research Unit in Australia (Keating et al., 2003). APSIM involves several types of plants, soil characteristics, fertilisers, and irrigation. The framework of the APSIM model includes:

- A group of biophysical modules, which simulate biological and physical procedures in agriculture systems

- A collection of management modules which permit the operator to determine the aim of management rules, which in turn describe the scenarios that are simulated that then dominate the behaviour of the simulation

- Different modules to simplify information input and output to and from the simulation
- A simulation factor that enforces the simulation procedures, and controls all messages that are passed between the independent modules (Keating et al., 2003).

According to McCown et al. (1996), APSIM can provide better predictive modelling because of its approaches:

- Representation of the best of particular aspects of cropping systems in order to enable significant phenomena for superior simulation
- Better processes in various models enabled and simply recombined to supply an excellent configuration for a specific function.

In Australia, only the OZCOT model, which is a part of the APSIM model, is used to simulate cotton yield (Thorp et al., 2014). The model can predict theoretical yield by employing historical climate data and field observations (Hearn, 1994). The potential yield is often estimated based on average growth, radiation efficiency, and simulation of the OZCOT model (Constable & Bange, 2015). Through OZCOT, it is possible to simulate different factors that could directly affect relative yields, such as climate, irrigation, and fertility. The OZCOT 'top-down' strategy might achieve a simple and robust simulation for growth and production (Hearn, 1994). The key parameters of OZCOT are soil characteristics, plant indexes, and climate variables (McCarthy, 2010). OZCOT will be discussed further in Chapter 9. Table 2.7 illustrates existing cotton simulation models that have been used by various research studies (Thorp et al., 2014).

Table 2.7: Summary of an existing cotton simulation models

Model	Origin	Time Step	Key References	Decision Support Tools
GOSSYM	Greece and Spain	Daily	Baker et al. (1983) Reddy et al. (2002b)	COMAX
Cotton 2K	USA	Hourly	Marami (2004)	None
COTCO2	USA	Hourly	Wall et al. (1994)	None
OZCOT	Australia	Daily	Hearn and Da Roza (1985) Hearn (1994)	APSIM CottBASE HydroLOGIC VARIwise Whopper Cropper
CSM-CROPGRO-Cotton	USA	Daily	Hoogenboom al. (1992 Jones et al. (2003)	DSSAT

Overall, this section has provided a brief summary of the literature relating to existing crop simulation models. APSIM is a set of models that employs by researchers and agricultural specialists to predict the performance of different crops. APSIM includes management models and interconnected biophysical to simulate systems comprising soil, crop, tree, and pasture processes and has the flexibility to integrate non-biological farm resources such as agricultural equipment and water storage (Holzworth et al., 2018). However, agronomy models require more efforts in order to improve and assess in developing or modifying their capability of responding to environmental conditions and simulate growth and yield of cotton (Thorp et al., 2014).

2.17. Conclusion

This chapter reviewed the relevant literature on the threat posed by compaction on soil structure and crop yield. The review discussed the main concept of soil compaction. It showed that there is an adverse impact of soil compaction from wheeled traffic on plant growth, which can be observed in the short- and long-term. The review also revealed that traffic from the JD7760 cotton picker causes significant compaction, which can negatively affect cotton yields.

The review showed that many soil and agronomy properties can be employed as indicators of soil compaction status. This chapter has also attempted to provide a clear explanation of the literature relating to soil compaction and agronomic simulation models. It has shown that a number of simulation models have been developed which can contribute to the discovery of optimal farming systems under different conditions.

The following significant research gaps have been identified through this review:

- A lack of studies into the impact of soil compaction due to JD7760 cotton picker traffic on row by row yield of cotton both in Australia and globally
- None of the studies reviewed seem to have employed the features of modern technology (JD7760) to estimate cotton yield at a single row scale
- No studies have evaluated and/or compared the efficiencies of the JD7760 standard configuration and the CTF7760 modified harvester

- Existing simulation models require more investigation to improve or assess their ability to respond to agricultural conditions (soil and agricultural activities) to provide accurate predictions of harvester traffic effects on compaction in various environmental conditions and to accurately simulate cotton production at farm scale.

Chapter 3. Materials and experiment methods

3.1. Introduction

This chapter outlines the specific methodologies used to investigate the effect of soil compaction due to the John Deere 7760 cotton picker traffic on individual cotton rows and furrows. In addition, the response of Vertosol soil to seasonal variability was monitored. This chapter particularly highlights the approaches used to address each of the objectives of this study. Site description, field selection, trial design, measured parameters, equipment used, field experiments and laboratory work are described in details. Data collection and statistical analysis are also explained.

3.2. Farm locations, plot layout and study parameters

In this research, random traffic farming (RTF) and controlled traffic farming (CTF) were investigated to develop an understanding of the impact of JD7760 cotton picker traffic on soil characteristics and cotton yield. Random traffic was defined as any traffic system not conforming to true controlled traffic farming, while true controlled traffic is achieved where all machinery wheel tracks are equivalent and there is only a single wheel on either side of the axle, and multiple passes of the field occur over the same permanent track. The frequency of permanent tracks is a function of the smallest machine operation frontage, which is 6.0 to 9.0 m for a cotton picker in the cotton system.

Field trials were carried out in Vertosol soils at three cotton farms located at Koarlo, Undabri and Yambacully in 2016 and 2017. Koarlo is located in Yelarbon while Undabri and Yambacully are located in Goondiwindi. They are 280 km and 350 km south-west of the Queensland state capital Brisbane, Australia respectively (Figure 3.1). RTF was practiced at the Koarlo and Undabri sites, while CTF was adopted at the Yambacully site for two years.

Cotton (*Gossypium hirsutum L.)* is widely grown in the region due to the suitability of the soils, access to water, and the climate. In Australia, cotton is typically planted in the period between September and November, and harvested in the period between March to May (Antille, 2018). Grey Vertosol is the predominant soil type in these districts (Bennett et al., 2016) but, as these are alluvial soils, soil sequences are common. The farm fields were selected to be representative of Vertosols as much as was reasonably possible.

Figure 3.1: Locations of Yelarbon and Goondiwindi, QLD

3.2.1. Site description

3.2.1.1. Koarlo site

Two different fields were chosen at Koarlo in Yelarbon, QLD, (28°36'43.30"S, 150°30'47.93"E, 235 m above sea level). They are located about 28 km from the Goondiwindi town centre (Figure 3.2). The first field was studied in 2016, and the second field in 2017. Cotton was planted with row spacing of 1.0 m at both fields and was irrigated using a furrow system (Figure 3.3). Both fields were planted on 1 October 2016 and 2017. The region has a semi-arid climate according to the Australian Bureau of Meteorology (Queensland Government, 2018). Table 3.1 demonstrates the mean monthly maximum temperature for the Koarlo site during 2015-2016 and 2016-2017. The total amount of water used during the growth stage was about 8.1 ML in 2016 and 7.5 ML in 2017. The total amount of rainfall during the period from September 2015 to May 2016 was 460.9 mm, while from September 2016 to May 2017 total rainfall was 473.8 mm (Table 3.2). Both fields were picked using the JD7760 in standard configuration.

Figure 3.2: Koarlo site at Yelarbon

Figure 3.3: Furrow irrigation system of Koarlo (1.0 m row spacing)

Table 3.1: The mean monthly maximum temperatures for Koarlo during 2015-2016 and 2016-2017

Temperature (°C)	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Ave.
2015- 2016	24.5	31	34	33	38	35	33	30	30	31.5
2016- 2017	22	26	32	36	42	37	31	26	24	30.5

Table 3.2: The amount of rainfall for Koarlo during 2015-2016 and 2016-2017

Rainfall (mm)	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Total
2015- 2016	36.3	27.2	100.9	144.5	33.0	7.0	28.5	28.5	55.0	460.9
2016- 2017	47.3	112.0	10.7	52.4	70.3	33.7	100.6	26.9	19.9	473.8

3.2.1.2. Undabri site

The Undabri field is located in Goondiwindi, QLD (28°23'26.78"S, 150° 9'40.54"E, 204 m above sea level), and is 15 km from the Goondiwindi town centre (Figure 3.4). A centre pivot system was used to irrigate this site (Figure 3.5). Cotton was planted on 5 October 2016 with row spacing of 1.0 m and harvested with a JD7760.

The climate of this district is a semi-arid (Queensland Government, 2018). Table 3.3 shows the mean monthly maximum temperature for Undabri during 2016-2017. The total amount of water applied during the growth stage was 4.5 ML, while the total amount of rainfall during the period between September 2016 and May 2017 was 480.4 mm (Table 3.4). Unlike the other two sites, the farmer indicated that this site was subjected to severe historical compaction before the start of this study. This was expected to have an impact on the soil of this particular site.

Figure 3.4: Undabri site in Goondiwindi

Figure 3.5: Irrigation system of Undabri site (centre pivot system)

Table 3.3: The mean monthly maximum temperatures for Undabri during 2016-2017

Temperature (°C)	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Ave.
2015- 2016	24.5	31	34	33	38	35	33	30	30	31.5
2016- 2017	22	26	32	36	42	37	31	26	24	30.5

Table 3.4: The amount of rainfall for Undabri during 2016-2017

Rainfall (mm)	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Total
2016- 2017	56.9	122	11.5	68.2	91.6	38.6	34.6	28.7	28.3	480.4

3.2.1.3. Yambacully site

This site is also located in Goondiwindi (28°27'2.40"S, 150° 9'35.27"E 206 m above sea level), and is 13 km from the Goondiwindi town centre (Figure 3.6). Controlled traffic farming with 1.5 m row spacing and overland flow (furrow) irrigation system were used at this site (Figure 3.7). This area also has a semi-arid climate, according to the Australian Bureau of Meteorology (Queensland Government, 2018). Table 3.5 shows the mean monthly maximum temperature for the Yambacully site during 2016-2017. The total amount of water used during the growth stage was 10.5 ML, while the total amount of rainfall received during the period between September 2016 and May 2017 was 456.7 mm (Table 3.6). Cotton was planted on 5 October 2016 and harvested with the CTF JD7760 modified harvester.

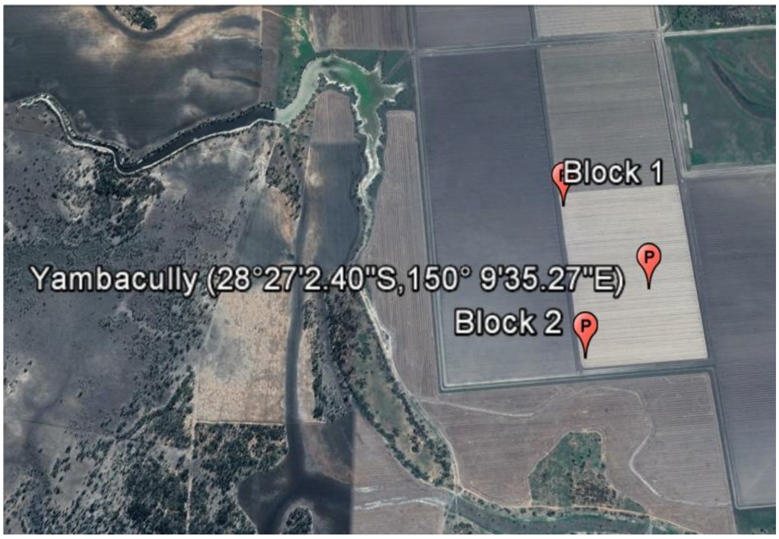


Figure 3.6: Yambacully field at Goondiwindi

Figure 3.7: Furrow irrigation system of Yambacully field (1.5 m row spacing)

Table 3.5: The mean monthly maximum temperatures for Yambacully during 2016-2017

Temperature (°C)	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Ave.
2015- 2016	24.5	31	34	33	38	35	33	30	30	31.5
2016- 2017	22	26	32	36	42	37	31	26	24	30.5

Table 3.6: The amount of rainfall for Yambacully during 2016-2017

Rainfall (mm)	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Total
2016- 2017	39.4	122	8.1	55.5	102.8	30.3	44.6	24.7	29.3	456.7

3.2.2. Field history and agronomy

Koarlo, Undabri and Yambacully were chosen on the basis of traffic history so that a range of histories can be assessed. These sites had been used for agricultural production for over 30 years with no history of controlled traffic. Both Koarlo and Undabri were subjected to the JD7760 standard configuration traffic (RTF) since 2012, while controlled traffic farming was practised in Yambacully since 2015 and subjected to the CTF7760 modified harvester traffic. In this study, the measeurments in October 2016 reflected the pre-history of earlier traffic across the field.

Soil tillage before planting did not occur at all sites. Both Koarlo and Yambacully were subject to a triple-disc-hiller pass on 12 m frontage, and the 1.0 m system had a 6 m frontage lister, while the 1.5 m had a 9 m frontage lister pass prior to all other field preparation activities. No-till was used in Undabri. The variety of cotton (*Gossypium hirsutum L. S71BR)* was planted at all sites. Field preparation between cotton crops included mulching, root-cutting, listing, fertiliser spreading and inter-row cultivation. Mulching and root cutting occurred on a 6 m frontage for the 1.0 m system (Koarlo). Both Koarlo and Undabri have adopted cotton-wheat-cotton rotation, while cotton-fallow-cotton rotation was practised in the Yambacully site.

3.2.3. Experimental design

The experiment was designed to provide a snapshot of the extent of influence of external factors on soil properties and cotton yield. The baseline experimental design was organised in a factorial design. This design allows for in identifying the impact of many factors as well as their interactions. The experiments were undertaken in October 2016, January 2017, and May 2017 (before and after harvest) to:

- Monitor Vertosols behaviour (shrink-swell), due to the impact of rainfall, seasonal variability and the JD7760 traffic on the overall field

- Investigate the impact of harvest traffic by JD7760 on soil water content (Swc), dry bulk density (*Pb*), soil penetration resistance (SPR) and cotton yield row by row.

In this study, two blocks were chosen in each field. Each block had six sampling transects. The transects were randomly assigned in each block to reduce the chance of biased results. The block was designed so that they captured the full frontage. The length of each block was 324 m, while the width was 6 m for RTF and 9 m for CTF (Figures 3.8 and 3.9). The transect dimensions were 1.5 m in length and 6 m in width to correspond to the JD7760 standard frontage, while the width was 9 m to match the CTF traffic system. The distance between each transect was 50 m. The sites' effect was considered as a fixed factor, because all the soil studied in these sites were Vertosols, having many similar properties. Furthermore, all experimental blocks served as control sites from October 2016 to May 2017 (before traffic) when there was no harvester traffic. This was to enable a more accurate assessment of traffic-induced compaction relative to potential changes in soil properties due to seasonal variability, the shrink-swell behaviour of Vertosol soils, and biological activities. Experimental arrangements are discussed further in Section 3.3.1.2.

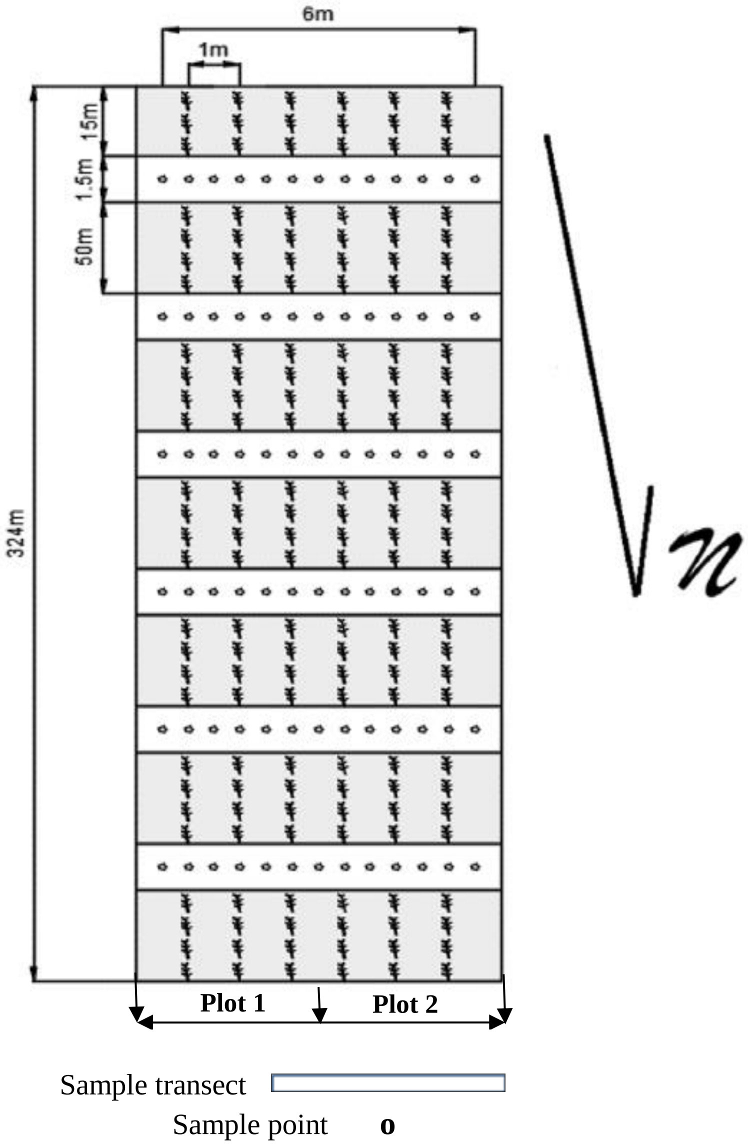


Figure 3.8: Experiment design sketch of Koarlo and Undabri (1.0 m row spacing)

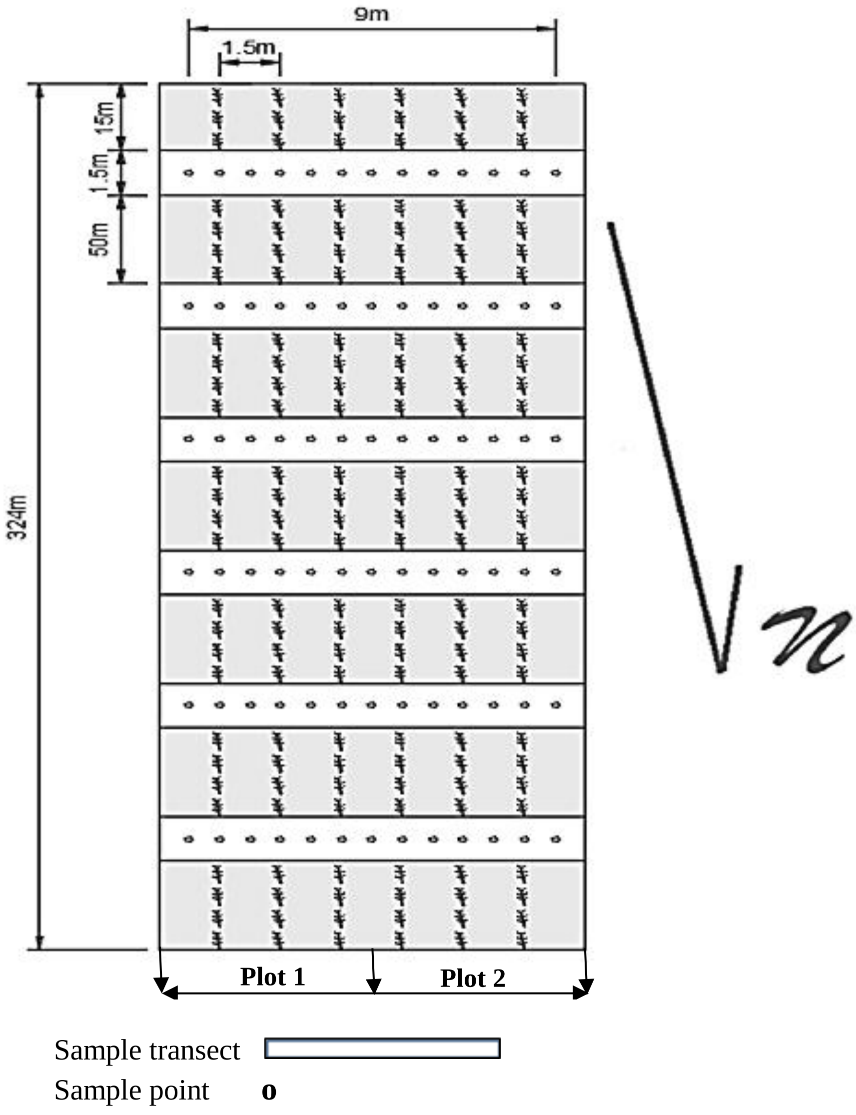


Figure 3.9: Experiment design sketch of Yambacully site (1.5 m row spacing)

3.2.4. Research parameters

The soil properties were measured based on the current standards and methods of published articles. The following parameters were used to investigate the effect of soil compaction on cotton yield due to JD7760 traffic in the field:

- Soil water content (Swc): Soil water is a critical factor which strongly affects soil characteristics and crop growth. Soil water was directly measured using a gravimetric approach.

- Dry bulk density of the soil (*Pb*): This is the oven-dry weight of soil per unit of volume, which was measured in grams per cubic centimetre. An increase in *Pb* represents a reduction in soil porosity responsible for transmission of water and nutrients, as well as pathways for root growth. Dry bulk density was determined by direct sampling and segmenting of soil cores.

- Soil penetration resistance (SPR): Cone index, measured with a cone penetrometer, provides a measure of soil resistance, which can be converted to soil strength. Changes in soil strength occur naturally with drying (i.e. soils are stronger when dried, without any external influence on the soil structural characteristics), or when soil bulk density changes. Cone index can also be used to infer the likelihood of root penetration for a given soil density.

- Machine-picked yield data: This is yield data obtained by the cotton pickers to provide a rapid measure of yield throughout the fields. Hand-picked yield data was obtained by manually picking cotton which was used to calibrate the machine-picked yield, as the machine picked yield utilised a number of sensors with calibration limitations.

- Harvest lost: The amount and quality of lint per hectare can be an indicator of harvest efficiency. Basically, delayed harvesting, after cotton defoliation and harvester conditions, represents a main source of harvest losses which may reach up to 20%. The estimation of yield losses is the key factor in identifying what additional adjustments are required for machine harvest. Hand-picking of machine-harvested plants was used to determine yield loss.

3.3. Field experiment methods and equipment

3.3.1. Soil sampling

3.3.1.1. Soil sampling instruments

A portable petrol post driver (Christie's Engineering CHPD 78 Post Driver, 4 strokes), volumetric cylinder (thin-walled metal tube 1500 mm length and 52.5 mm diameter), and foot lever were used to collect soil samples. A plastic table, ruler (100 mm) and spatula were also employed. To preserve the water in the soil cores, sealed foil bags (213 mm length and 165 mm width) were used for storing samples. To avoid loss, samples were transported in sealable containers. A large oven (approximately 400 samples capacity) was used to dry soil samples at 105˚C for at least 72 hours to calculate *Pb* and Swc (Bennett et al., 2017). A sensitive electronic scale (Max 2200 g) was also used to weigh soil samples before and after drying in the oven. Figure 3.10 shows the sampling instruments that were used in this study.

Figure 3.10: Sampling instruments

3.3.1.2. Field work

Soil cores were collected from Koarlo, Undabri, and Yambacully in October 2016, January 2017 and May 2017 (before and after harvest). The incidence of sampling was based on the procedure outlined in McKenzie et al. (2002) method (502,03). Collection was done by pressing the cylinder with a jackhammer and driving it vertically into the soil to the depth required. Then, the cylinder was carefully removed by the lever to maintain a known volume of soil as it existed in situ. As the core sampling procedure used a hammering action to push the cylinder to the desired depth, the extracted core length was measured and compared against the hole depth to ensure that compaction had not occurred during sampling; this approach did not cause compaction of samples (McKenzie et al., 2002; Bennett et al., 2017). Each cylinder provided an 800 mm long sample which was cut into 100 mm sub-samples. Overall the field trials provided a total of 13728 samples during the study period as follows:

- May 2016: The field trial only occurred in Koarlo in May 2016. It commenced mid-May and finished after two weeks. Rainfall occurred before the May 2016 experiment but was not observed during this trial. Two blocks were used to collect soil samples at this property. Each of the blocks had six replications.

  The blocks were designed to examine six typical rows of cotton with row spacing of 1.0 m. Sampling transects were located across the full frontage of the JD7760 standard configuration. The field was divided into two blocks randomly. Each block had six transects. The dimensions of each transect were 1.5 m in length and 6 m in width, to correspond to the harvester frontage. The distance between each transect was 50 m (see Figure 3.7). To ensure that accurate measurements were obtained, both plants and cotton hills were removed from all transects.

  The soil cores were taken from the position of each cotton row and furrow of each transect to a depth of soil of 80 cm (see Figure 3.7). This procedure was conducted before and after harvester traffic and provided a total of 312 tubes. Next, the tubes were divided into 10 cm sub-samples, producing a total of 2496 samples. Sealed bags were used to store and carry samples to the laboratory to prepare for further measurement.

- October 2016: During this period, sampling was undertaken at Koarlo, Undabri, and Yambacully starting on 21 October 2016, and completed one week later. Two blocks were chosen in each field. Three transects were assigned randomly in each block to reduce the chance of biased results. The transect dimensions were 1.5 m in length and 6 m in width for Koarlo and Undabri. By contrast, the width and length were 1.5 m length and 9 m respectively in Yambacully to match the CTF traffic system (see Figure 3.8).

  As usual, soil cores were also gathered from sample points in each station to correspond to the positions of cotton rows and furrows. The sampling method used similar procedures as in the previous experiment. This experiment obtained a total of 1872 samples. The samples were transported to the laboratory for further measurements.

- January 2017: Soil cores were taken at the above three sites on 16 January 2017 and continued for five days. Sampling occurred in the same soil blocks that were organised in each field as mentioned above. There was considerable rainfall between January and May 2017, after January 2017 experiments were conducted. The core sampling method was the same as those discussed above. This experiment provided 1872 samples.

- May 2017: Sampling began in May 2017 and was extended for one month. As mentioned, CTF was adopted at Yambacully, while RTF was applied at both Koarlo and Undabri. At the CTF site, two blocks were arranged to correspond to six rows of cotton as per row spacing of 1.5 m. Each block had six soil transects. The dimension of each transect was 1.5 m in length and 9 m in width to match the CTF7760 modified harvester frontage (see Figure 3.9). Soil sampling locations at the RTF sites were designed similar to the trial that occurred in May 2016.

The crop and cotton hills were removed from each transect for both systems. Rainfall was not recorded during the experiments. For reliability, soil cores were collected from the previous trials' blocks in each site . The soil cores were collected before and after the harvester traffic, which provided a significant number of samples (7488). Laboratory work was carried out to obtain further measurements. Table 3.7 summarises the sampling incidents. Appendix 3.1 shows soil cores collected during the study period.

Table 3.7 Summary details of soil sampling during the study period

Trial period	Field	Details
May 2016	Koarlo	1 field 2 blocks 6 transects in each block 13 sample points in each transect (including rows and traffic furrows and centre differential position) 8 soil depths within 1 sample point Sampling occurred before and after traffi Total of 2496 samples per field
October 2016	Koarlo, Yambacully, and Undabri	3 fields 2 blocks per field 3 transects in each block 13 sample points in each transect 8 soil depths within 1 sample point Traffic none Samples per field (624) Total cores (1872) samples
January 2017	Koarlo, Yambacully, and Undabri	3 fields 2 blocks per field 3 transects in each block 13 Sample points in each transect 8 soil depths within 1 sample point Traffic none Samples per field (624) Total cores (1872) samples
May 2017	Koarlo, Yambacully, and Undabri	3 field 2 blocks per field 6 transects in each block 13 sample points in each transect (including rows and traffic furrows and centre differential position. 8 soil depths within 1 sample point Sampling occurred before and after traffic 2496 samples per field Total of 7488 sample

3.3.1.3. Laboratory measurements

Soil water content and Pb were determined at laboratories at the University of Southern Queensland's (USQ). The laboratory measurements were based on the method outlind in International Organisation for Standardisation, 11272, ISO (2017). The soil samples were weighed directly after completing field experiments to estimate the field wet weight of each sample. To determine the proper dry weight of the samples, they next were placed in an oven for at least 72 hours at 105 °C (Figures 3.11 and 3.12). The mass of the dry soil samples was weighed and then both gravimetric soil water content (θg) and dry bulk density (Pb) were calculated using Equations (1) and (2) (Hossain et al., 2015). Equation 3 was used to calculate volumetric soil water content (θv). For each location to a depth of 80 cm, soil texture was determined using the hydrometer method (Gee & Bauder 1986). The soil texture was dominated by clay content as shown in Table 3.8. Clay content for the soils at the study sites normally ranges between 40%– 80% (Kettler et al., 2009).

$$\theta \mathrm{g} = \frac{\text{Weight Water (g)}}{\text{Weight Dry Soil (g)}} \times 100 \text{ ……………………. (1)}$$

$$Pb = \frac{\text{Weight Dry Soil (g)}}{\text{Soil Volume (cm}^3\text{)}} \text{ ………...……..………….. (2)}$$

$$\theta v = \theta g \times Pb \text{ ………...……………..………….. (3)}$$

Figure 3.11: Soil samples placed inside the oven 105°C for 72 hours

Figure 3.12: Weighing soil samples

Table 3.8: Soil texture details of field trials

Property	Soil depth (cm)	Soil texture			%
		Sand %	Silt %	Clay %	
Koarlo	0–10	33.75	20.0	46.25	100
	10–20	32.5	16.25	51.25	100
	20–30	27.5	20.0	52.5	100
	30–40	30.0	16.25	53.75	100
	40–50	31.25	15.0	53.75	100
	50–60	30.0	13.75	56.25	100
	60–70	28.75	15.0	56.25	100
	70–80	26.25	13.75	60.0	100
Yambacully	0–10	11.25	16.25	72.5	100
	10–20	12.5	13.75	73.75	100
	20–30	11.25	15.0	73.75	100
	30–40	8.75	17.5	73.75	100
	40–50	10.0	15.0	75.0	100
	50–60	10.0	15.0	75.0	100
	60–70	11.25	16.25	72.5	100
	70–80	8.75	17.25	73.75	100
Undabri	0–10	21.25	15.0	63.75	100
	10–20	22.5	13.75	63.75	100
	20–30	17.5	16.25	66.25	100
	30–40	17.5	20.0	62.5	100
	40–50	13.75	16.25	70.0	100
	50–60	16.25	13.75	70.0	100
	60–70	16.25	15.0	68.75	100
	70–80	16.25	17.5	66.25	100

3.3.2. Measuring soil penetration resistance

In this research, a static cone penetrometer CP40II (Rimik) and load cell rated 100 kg were used to measure soil penetration resistance (Figure 3.13). A small cone size (130 mm^2, 12.83 mm diameter) with shaft (9.53 mm diameter) was selected as it suits hard soils (ASAE 1986). This cone penetrometer is able to measure soil strength up to 5.6 MPa and can reach soil depth of 750 mm with intervals of 10, 15, 20 and 25 mm (Rimik, 2017). In addition, GPS was used to reference the points measured in each location.

The penetrometer was mounted to the constant drive device to ensure that the cone driven into the soil at a constant penetration rate (42.5 mm/s) (Rimik 2017). Data were collected from Koarlo, Undabri and Yambacully during October 2016, January 2017, May 2017 (before and after harvester traffic). At all study sites, SPR measurements were taken when the soil cores were collected (Ayers & Perumpral, 1981). This was done by selecting 6 m distance across cotton rows and furrows in each transect of 1.0 m row spacing, while 9 m was determined for 1.5 m row spacing. Insertions were made at every 250 mm in each transect (Braunack & Johnston, 2014; Bennett et al., 2017).

Penetration data was recorded at every 10 mm depth down to a depth of 700 mm. For accuracy, both the crop and cotton hills were removed to guide the penetrometer equipment in a straight path. Penetration measurements resulted in 2232 insertions during the study period. Soil penetration resistance data have been presented as contour maps using the OriginLab 8.5 software (OriginLab Corporation, 2018). This software creates contour maps automatically from xyz data in a worksheet without the need for an intermediate matrix (OriginLab Corporation, 2018). Table 3.9 shows the specifications of the Rimik CP40II cone penetrometer that was used in this study. Appendix 3.2 demonstrates SPR measurement in situ.

Figure 3.13: Motorised penetrometer CP40II (Rimik)

Table 3.9: Specifications of Rimik CP40II penetrometer

Penetrometer type	Static cone penetrometer
Weight	3.9 kg
Case dimensions	470 * 358 * 175 (mm)
Maximum Small Cone Index	5600 kPa, 75 kg
Resolution	0.03 kg
Maximum Insertion Depth (mm)	750 mm
Interval Spacing	10, 15, 20, 25 mm
Memory Capacity (no of insertions)	2047
Operating temperature (degrees C)	-10 to 75
Screen resolution (characters)	160 * 128
Load cell	100 Kg
Small Cone size (dia.mm, area mm^2)	12.83, 130
Shaft size (dia.mm)	9.53
Penetration speed	42.5 mm/s

3.3.3. Measurements of cotton yield

3.3.3.1. Cotton pickers used

Three cotton pickers (JD7760) were employed to harvest the study areas. Two standard pickers (6 m frontage with front dual-wheels) were used to harvest at Koarlo and Undabri (Figure 3.14). The CTF7760 modified harvester was employed at Yambacully (Figure 3.15). A major modification was made to the frontage of the CTF7760 to reach a 9 m width. In addition, the front axle was changed by removing one tyre of the dual-wheels to become a single tyre 620/70R42 (Figure 3.16). The general specifications of the standard machine are shown in Appendix 3.3 (Wattonville, 2008).

Figure 3.14: The standard John Deere 7760 cotton picker

Figure 3.15: The modified John Deere 7760 cotton picker

Figure 3.16: A modified the JD7760 cotton picker fitted with single tyres (620/70R42)

The JD7760 Harvest Identification (Harvest Doc, Yield Monitor, GPS, Mass Flow Sensors and CAN-BUS) was also employed to measure cotton yield in the field scale (Figures 3.17 and 3.18). To achieve the objective of this study, JOHN DEERE-DATALOGGER was used to extract yield data from the harvester row by row (Figures 3.19 and 3.20). Moreover, a personal computer and USB were utilised to storage the data. A Petrol Hedge Trimmer, tape measure, sealed bags and large electronic scales were also used in this study.

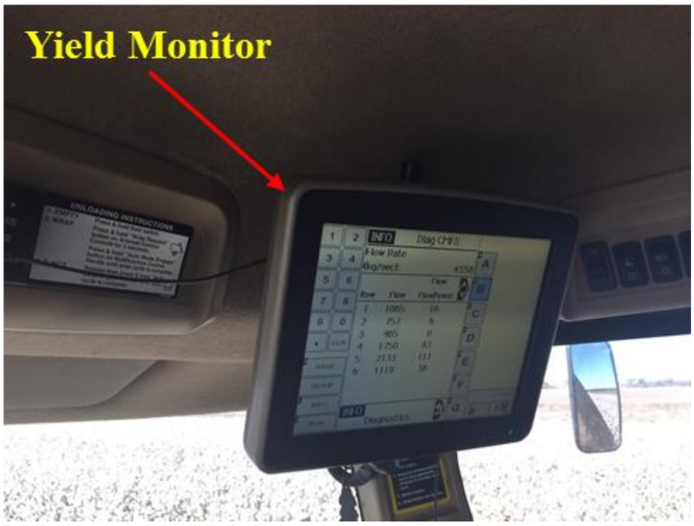


Figure 3.17: Harvest monitor displaying individual cotton rows data

Figure 3.18: Mass Flow Sensors

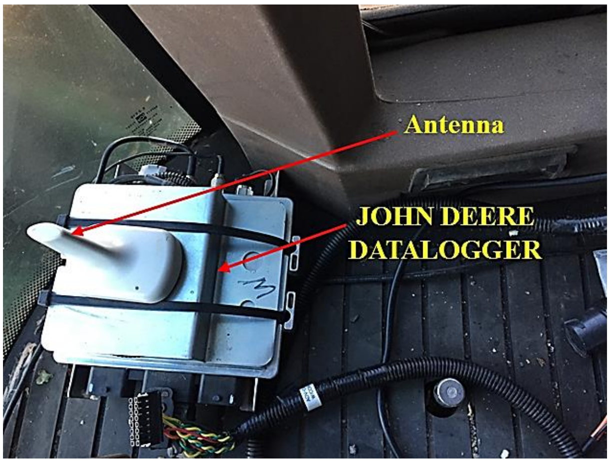


Figure 3.19: The JOHN DEERE-DATALOGGER logged in CAN-BUS

Figure 3.20: CAN-BUS Connector

3.3.3.2. Machine-picked cotton

The experimental sites were selected on the basis of traffic history. The sites were used annually for the production of cotton and harvested by the JD 7760. In this study, the influence of compaction due to JD7760 traffic on cotton yield was assessed based on the JD7760 traffic in the previous harvest season. In RTF, the positions of cotton rows cultivated in 2016 were the same as that were harvested in 2015. It was determined by using GreenStar data and GPS coordinates to identify location information including boundaries, dimensions, latitude, longitude, positions of cotton rows and furrows and roads. In CTF, cotton rows and furrows locations were previously determined because harvester had the same track width in order to restrict the wheel traffic in the permanent lanes. To achieve the aim of this research, cotton yield was estimated by two novel methods (during the harvest seasons in 2016 and 2017) to investigate the influence of JD7760 compaction on the cotton yield, row by row, as follows:

- Harvest season 2016: A field trial was undertaken in Koarlo in May 2016. In this experiment, a new methodology was designed for harvesting cotton with the JD7760 at the single row level. The plants were cut from the individual cotton rows using a petrol hedge trimmer, except for one row which was left in each spot, as shown in Figure 3.21. In addition, plant trash was removed from the field. When harvesting began, the first picking unit of the JD7760 harvested a single cotton row that was left in the first spot along 50 m^2, while the other five picking units were neutral. The picker was stopped before reaching the next spot, and the harvested cotton was collected manually from the machine and stored in sealed bags. The same processes were repeated for the subsequent spots of the other rows (Figure 3.22). The lint yield was estimated in USQ laboratory. It was done by separating cottonseeds from lint by the hand for each spot in each row and then weighed by a sensitive electronic scale and calculated as kg per metre squared. The calculated lint yield for each row was converted into (bale/ha). Each bale per hectare is equal to 227 kg lint.

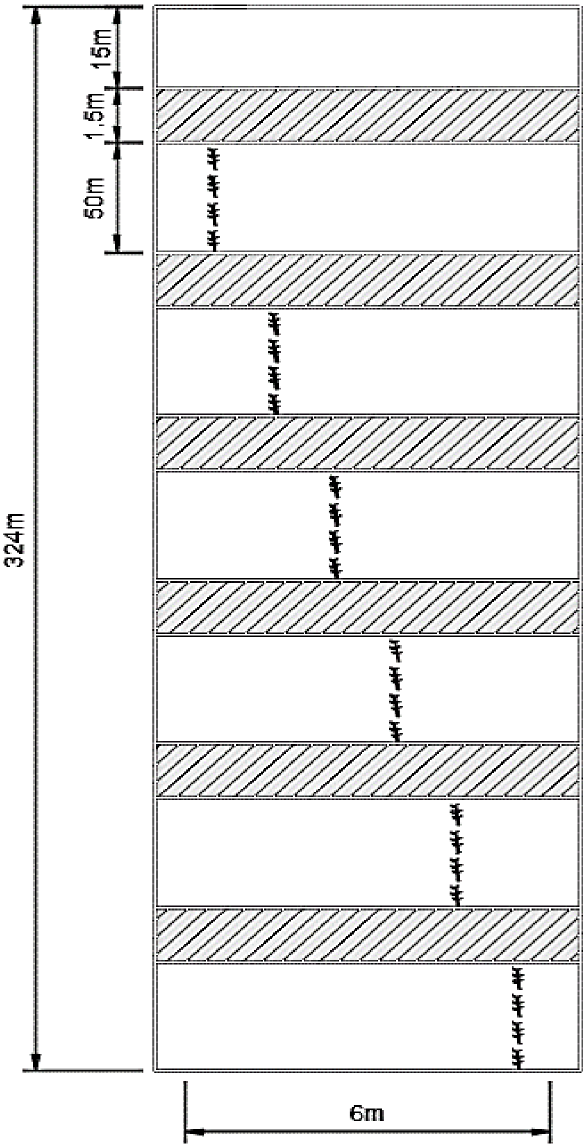


Figure 3.21: The scheme of the field trial design (1.0 row spacing)

Figure 3.22: Individual harvest stages at Koarlo in 2016

- Harvest season 2017: Three field trials were conducted at Koarlo, Undabri, and Yambacully in May 2017. These trials were designed in similar fashion to that at Koarlo in 2016, in terms of selecting the paddocks and replicates. Figures 3.23 and 3.24 show the experimental design under RTF (1.0 m spacing) and CTF (1.5 m spacing).

  In these trials, all picking units of the harvester were used to pick six cotton rows at once. Six flow mass sensors were installed on the ducts of the harvester to measure the amount of yield passing through the ducts during the picking operation. In addition, the JOHN DEERE-DATALOGGER was logged into the CAN-BUS connector to extract the individual row yield data from the harvester. The console received the data from the sensors and displayed them individually on the harvester's monitor. The JOHN DEERE-DATALOGGER transferred the information to the Processing Unit Central of the John Deere

Company in Chicago, USA by a precise antenna. The data was processed and set up as an excel spreadsheet for further measurements in order to compute the cotton yield row by row.

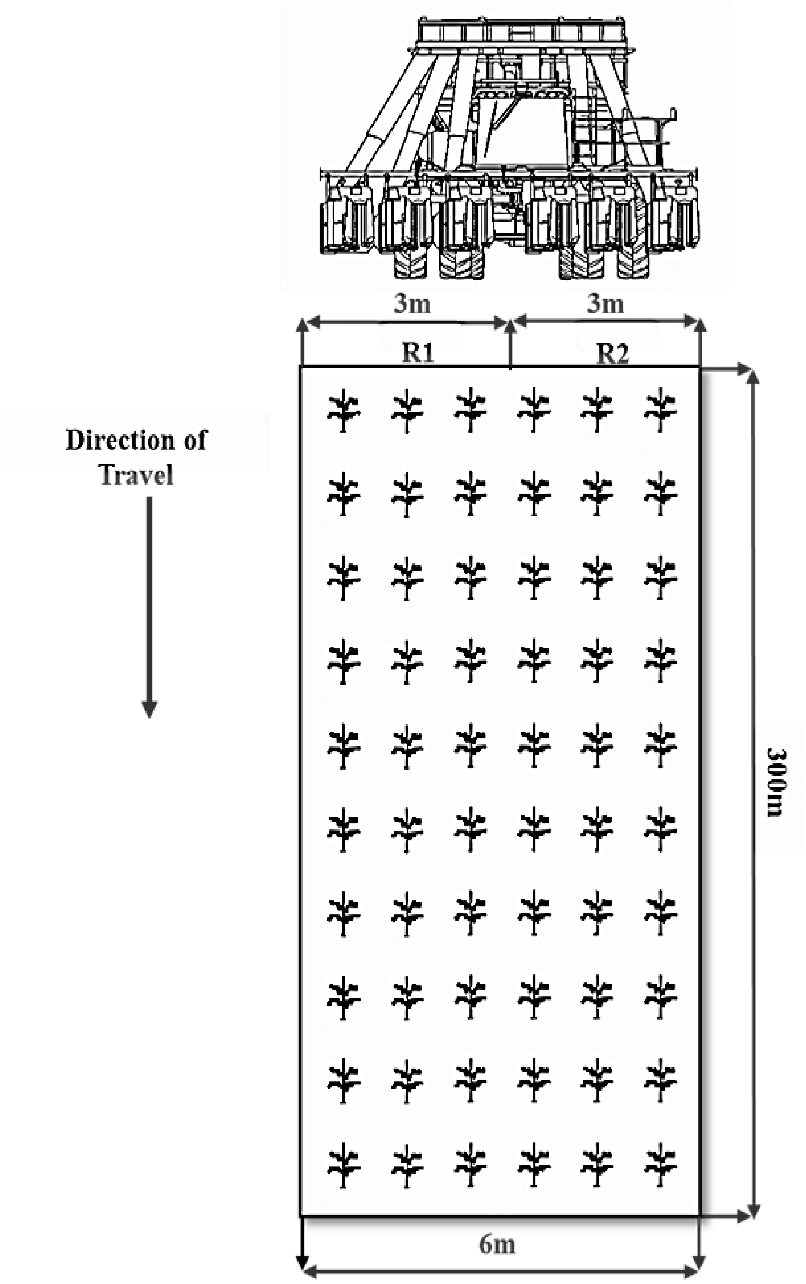


Figure 3.23: Trial design schematic of each plot subjected to the JD7760 standard configuration (6 m frontage with dual-wheel). R1 and R2 represent the replication in each plot

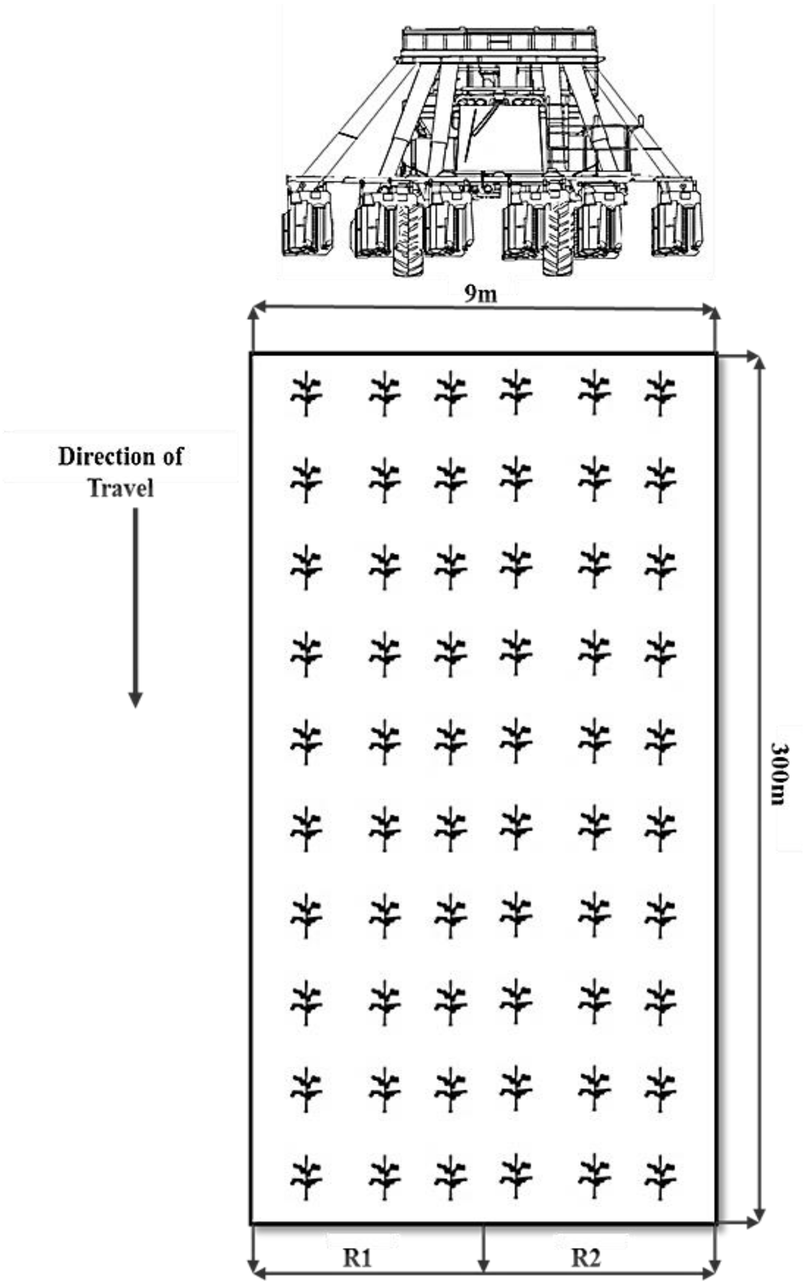


Figure 3.24: Trial design schematic of each plot subjected to the JD7760 modified configuration (9 m frontage with a single wheel). R1 and R2 represents the replication in the plot

3.3.3.3. Hand-picked cotton

A hand-picked harvesting method was employed to obtain an accurate and reliable estimation of the yield of individual rows. In the 2016 harvest season, the hand-picked method was undertaken at Koarlo by choosing six longitudinal cotton rows from the replicates of each paddock randomly. Three metres square were separately determined in each individual row. Thereafter, seed cotton were collected manually and stored in sealed bags. The lint yields were weighed using a sensitive electronic scale and calculated as kg per metre squared and then converted into bale per hectare. This method was also carried out at Koarlo, Undabri, and Yambacully during the 2017 harvest season.

3.3.4. Calculation of harvest losses

The approach for measuring harvest losses adopted in this study followed that used by Faulkner et al. (2011). It was done by assigning a linear segment (7.5 m) to each cotton row in all paddocks. In each segment, three metres were chosen for the hand-picked section and a 1.5 m distance from the end of the hand-picked spot was left (uncropped). Another three metres were also selected for the machine-picked section and the seed cotton left in the ground were cleaned before harvesting (Figure 3.25 and 3.26). The first 3.0 metres of each spot were picked by hand, while remaining the 3.0 metres were harvested with the JD7760. Cotton left on the plant and on the ground was collected by hand to measure harvest efficiency using Equation 3, as was suggested by Faulkner et al. (2011):

$$L = \left[\frac{P+G}{H}\right] \times 100\% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Where:

L= Harvest lost in percentages

P= Cotton lint left on plants in 3.0 m length due to machine picked (gram)

G= Cotton lint on the ground in 3.0 m length of row after the harvest by JD7760 (gram)

H= The amount of cotton lint in 3.0 m handpicked.

Figure 3.25: Scheme of harvest efficiency measurement methodology of single cotton row

Source: Adopted by the researcher from (Faulkner et al., 2011).

Figure 3.26: Segment 3.0 m for machine picked to measure harvest efficiency

3.4. Statistical analysis tool

Analysis of variance (ANOVA) was used to determine differences between means by using the software package (Statistical Package for Social Scientists) IBM SPSS version 23.0 (IBM, 2016). One-way ANOVA, two-way ANOVA, descriptive statistics, correlation and regression analysis were employed to assess the impact of the JD7760 harvester traffic on soil compaction and cotton yield. Analysis of Covariance (ANCOVA) was also used to correct the SPR for soil water content and *Pb*. Significant difference was tested using the least significant difference (LSD) and Tukey tests. The differences between the means of random factors were considered to be significant if the probability level was 0.05 or less. The independent variables were seasonal variability, traffic systems (RTF and CTF), before and after harvester traffic, the position of the cotton row and furrow, row spacing, soil depth, and harvester. The dependent variables were soil water content, dry bulk density, soil penetration resistance, cotton yield, and harvest loss. The statistical analysis processes were carried out after close consultation with the USQ’s Statistical Consulting Unit (Kabir 2017, Pers comm). Furthermore, the attached file (CD) includes field experiments data (Part I presents the data across the overall field and Part II presents the individual data of cotton rows and furrows).

3.5. Conclusion

This chapter has detailed the specific methods used to investigate the influence of soil compaction due to JD7760 traffic on the cotton yield at the level of individual rows and furrows. The experimental arrangements for each objective have been described. Site description, field selection, experiment design, parameters, equipment used, experimental procedures and laboratory work have also been presented in detail. Data collection and statistical analysis have been explained.

Field trials were carried out at three separate sites (Koarlo, Undabri and Yambacully). Soil properties (soil water content, dry bulk density and soil penetration resistance) were measured and Vertosol behaviour was also monitored. Two novel methodologies of machine harvesting were performed to gather the individual row yield data from the JD7760 cotton picker.

Chapter 4. Results and discussions: Soil properties in an overall field as influenced by rainfall, seasonal variability and harvester traffic

4.1. Introduction

The previous chapter presented the research methodologies that were used to collect and analyse field data. This chapter discusses the findings of monitoring Vertosols behaviour under random traffic farming (RTF) and controlled traffic farming (CTF) systems within the period between October 2016 and May 2017. Results of the impact of harvester traffic on Vertosols between different individual cotton rows, and at different soil depths in the rows are discussed in the following two chapters.

Given that Vertosols shrink and swell with drying and wetting cycles, respectively, it is important to investigate the potential changes in dry bulk density over the growing season. This helps to understand the extent of change in dry bulk density from one harvest traffic instance to the next. In this chapter, the influence of rainfall, seasonal variability and harvester traffic on Vertosol properties (soil water content, dry bulk density, and penetration resistance) across the field are discussed. RTF under 1.0 m row spacing was utilised in Koarlo and Undabri. CTF (1.5 m row spacing) was adopted in Yambacully. Before the October trials, the total amount of rainfall was 112 mm in Koarlo, whilst about 122 mm was recorded at both Undabri and Yambacully. The temperature ranged between 40–42 ˚C in January 2017 (Australia Government 2018). Harvester traffic occurred in May 2017. In all the study sites, the observations of October 2016 reflected the history traffic across the field. The significant and key findings of this chapter are shown in the discussion sections.

In this chapter, two-way ANOVA was used to compare the means of the treatments during October 2016, January 2017 and May 2017 (before and after traffic). The significant difference was tested using Tukey and LSD test at $P \leq 0.05$ level. The error bars presented are for an ANOVA at 95% confidence interval at all figures. The different lowercase letters (a, b and c) in the same row in the figures and tables in Chapters 4, 5, 6, 7 and 9 refer to significant differences at $P \leq 0.05$ (i.e. probability level between the values is 0.05 or less implies that there is a significant difference between the values, thus they take different letters, irrespective of an increase or decrease between the values. A probability level higher than 0.05 between values implies no significant difference, therefore, values take the same letters). The symbol (*) refers to the significant difference between before and after harvester traffic ($P \leq 0.05$) at all figures. The attached file (CD), Part III includes all the results data for Chapters 4, 5 and 6.

4.2. Results

4.2.1. Soil water content

As previously mentioned, soil samples were collected across the cotton rows and furrows to represent the average field. In this study, soil water content (Swc) was calculated basis on gravimetric and then converted into volumetric soil water content in order to investigate the change in volumetric soil water dynamics due to Vertosols behaviour (shrink-swell) and compaction. Differences between treatments are presented as a percentage of the change in soil water content.

4.2.1.1. Koarlo site

The statistical analysis showed that Swc was significantly higher at $P \leq 0.05$ level in October 2016 than in January 2017, by approximately 13% at a depth of 0–30 cm (Figure 4.1). This suggests that significant rainfall in early October 2016 accumulated on the soil surface and began to infiltrate the soil, which then resulted in a recharging of the water profile of the soil. At the same time, variation of soil water content between different depths was related to Vertosol heterogeneity, clay minerals, and water flow through cracks (Ghosh et al., 2010; Yu et al., 2015).

As shown in Figure 4.1, it is apparent that soil water content was significantly lower in January 2017 (Summer in Australia) than May 2017 (both before and after traffic), by 10% at the soil surface. This was because of the considerable rainfall between January and May 2017 which increased the water profile. There was no significant difference in Swc between the before and after harvester traffic in May 2017 throughout the entire profile because soil cores were collected directly before and after traffic.

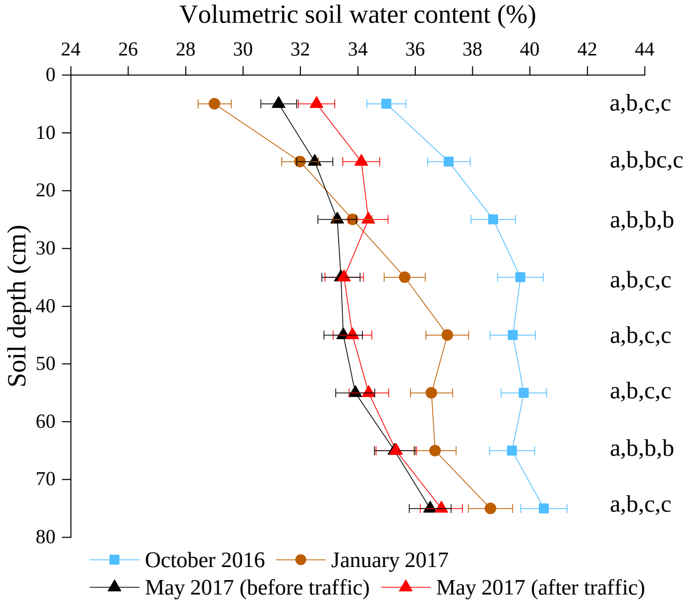


Figure 4.1: Change in volumetric soil water content at different soil depths in Koarlo during the period between October 2016 and May 2017 (after traffic)

4.2.1.2. Undabri site

As mentioned in the previous chapter, both Koarlo and Undabri had the same traffic farming system (RTF). Soil water content showed a similar trend to that in Koarlo (Figure 4.2). It was significantly higher in October 2016 than January 2017, by approximately 10% at the 0–30 cm soil depth, and lower in January 2017, by 14% in comparison to May 2017 (before and after traffic). In addition, no significant difference was found in soil water content between before and after harvester traffic in May 2017 throughout the soil profile. The reasons were similar to those highlighted for Koarlo site (above).

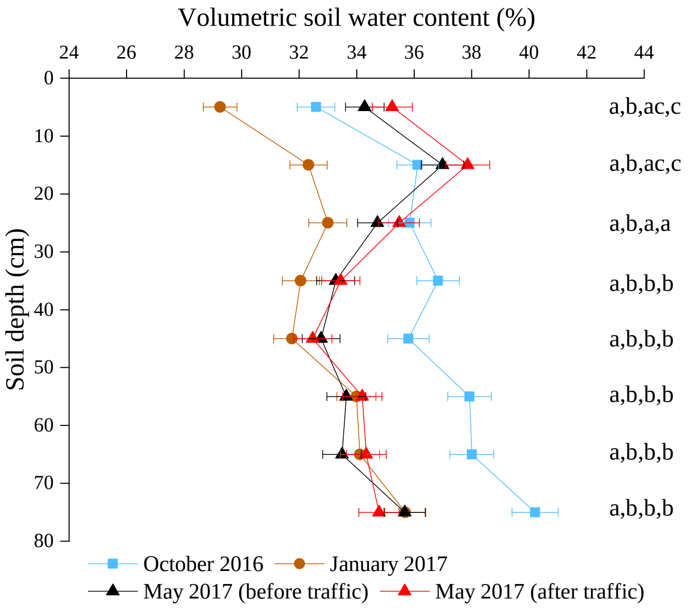


Figure 4.2: Change in volumetric soil water content at different soil depths in Undabri during the period between October 2016 and May 2017 (after traffic)

4.2.1.3. Yambacully site

In this site, a controlled traffic system (CTF) with 1.5 m row spacing was adopted. The data analysis showed that soil water content was also significantly higher in October 2016 than in January 2017, by 13% for the 0–30 cm depth due to rainfall (Figure 4.3). Additionally, the soil profile was significantly drier in January 2017 than in May 2017 (before and after traffic), by 7% in the topsoil. A possible explanation is that the 1.5 m row spacing may have permitted a greater amount of dry wind and radiation to reach the ground, thereby increasing the evaporation rate and decreasing Swc from October 2016 to January 2017 when rain fell again (Figure 4.4). Harvester traffic did not induce a significant change in soil water content throughout 0–80cm depth.

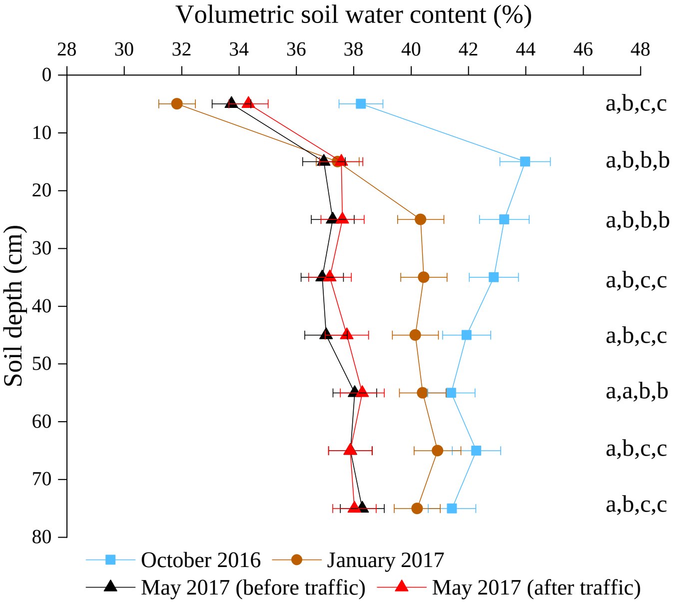


Figure 4.3: Change in volumetric soil water content at different soil depths in Yambacully during the period between October 2016 and May 2017 (after traffic)

Figure 4.4: CTF Yambacully (1.5 m row spacing) in January 2017

4.2.2. Dry bulk density

4.2.2.1. Koarlo site

Due to the shrink-swell characteristic of Vertosols their soil density changes with changes in water content (Bennett et al., 2016). In particular, dry bulk density increases at dry conditions due to (volume) shrinkage, while it decreases under wet conditions due to the swell characteristic (Virmani et al., 1982). Table 4.1 and Figure 4.5 show that *Pb* ranged between 1.28 to 1.56 g/cm^3 in the period between October 2016 and May 2017 (after traffic). The observations revealed that because of increased temperature and moisture evaporation, *Pb* increased significantly from October 2016 to January 2017, by 3% at the 0–20 cm depth. Then the rainfall events between January and May 2017 led to a decrease in *Pb*, by 6% in the 0–20 cm depth. Harvester traffic in May 2017 resulted in an increase in *Pb*.

Looking at Figure 4.6, significant compaction was induced after one pass of the JD7760 harvester, resulting in an increase in *Pb*, from 1.32 to 1.41 g/cm^3 and from 1.47 to 1.50 g/cm^3 in the 0–30 cm and 40–50 cm depths respectively, when compared to before traffic in May 2017. This suggests that traffic from the heavy harvester was the main source of the surface and subsurface compaction.

Table 4.1: Changes in *Pb* at the Koarlo site during the study period

Soil depth (cm)	October 2016	January 2017	May 2017 (before traffic)	May 2017 (after traffic)
	Pb (g/cm^3)			
0-10	1.30a	1.34b	1.28a	1.35c
10-20	1.40a	1.43a	1.34b	1.42a
20-30	1.47a	1.48a	1.39b	1.45a
30-40	1.52ac	1.53a	1.45b	1.48bc
40-50	1.55a	1.55a	1.47b	1.50b
50-60	1.51a	1.52a	1.47b	1.50ab
60-70	1.50a	1.51a	1.49a	1.52a
70-80	1.55a	1.55a	1.53a	1.56a

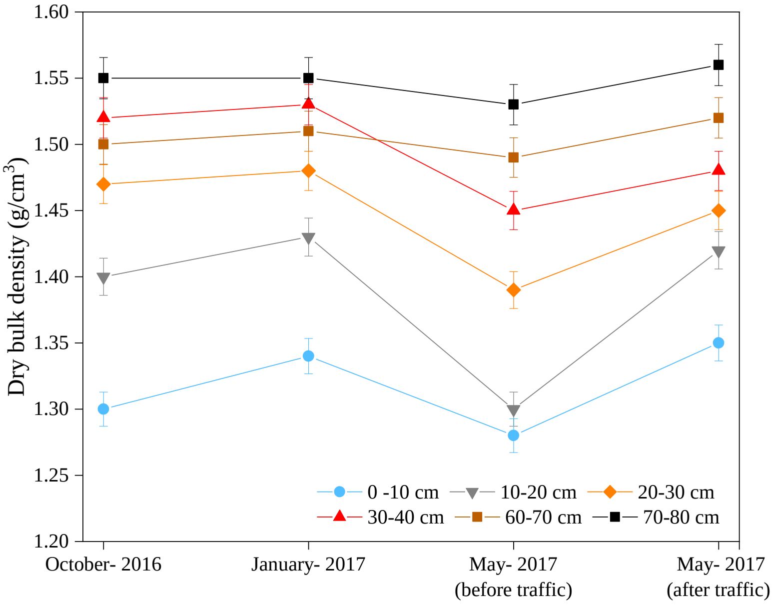


Figure 4.5: Changes in *Pb* at different soil depths at the Koarlo site during the period between October 2016 and May 2017 (after traffic)

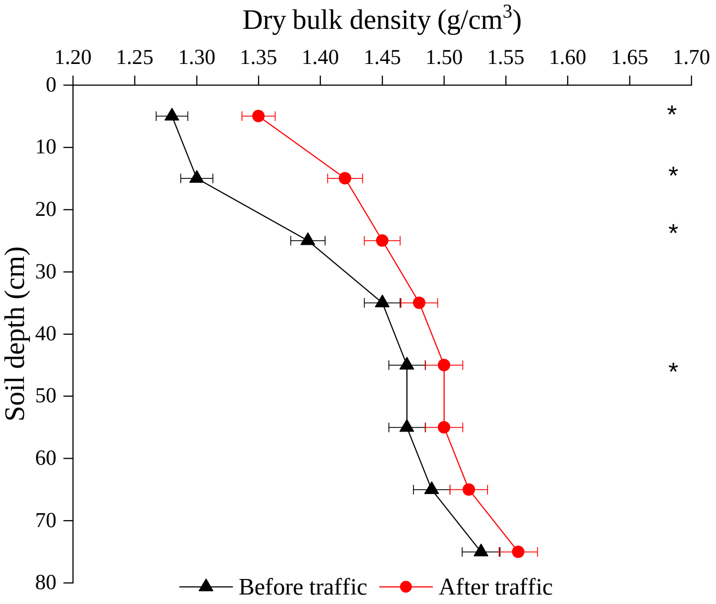


Figure 4.6: Changes in *Pb* with depth due to harvester traffic (JD7760)

4.2.2.2. Undabri site

It can be noted from Table 4.2 and Figure 4.9 that dry bulk density values possess a similar trend to those in Koarlo. The *Pb* values increased significantly, by 3% from October 2016 to January 2017 in the topsoil, and then decreased towards May 2017 (before traffic), by 9% in the depth of 0–30 cm. Significant compaction was observed after harvester traffic, which resulted in increased dry bulk density from 1.30 to 1.36 g/cm^3 at the surface layer compared to before traffic (Figure 4.8).

Table 4.2: Changes in *Pb* at the Undabri site during the study period

Soil depth (cm)	October 2016	January 2017	May 2017 (before traffic)	May 2017 (after traffic)
	Pb (g/cm^3)			
0-10	1.31a	1.35b	1.21c	1.27d
10-20	1.41a	1.46b	1.32c	1.37d
20-30	1.46a	1.50b	1.41c	1.46a
30-40	1.49ab	1.50b	1.42c	1.46a
40-50	1.48a	1.49a	1.43b	1.47a
50-60	1.55a	1.55a	1.45b	1.49c
60-70	1.55a	1.57a	1.46b	1.50c
70-80	1.60a	1.61a	1.50b	1.52b

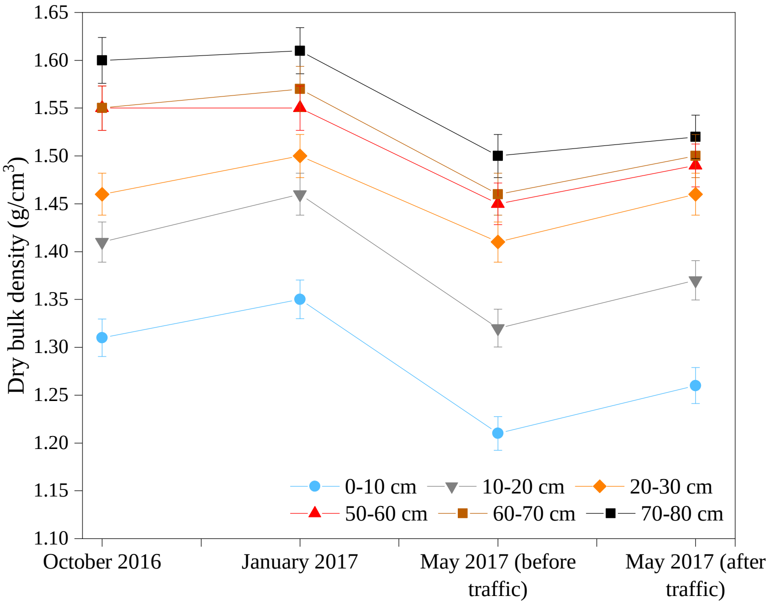


Figure 4.7: Changes in *Pb* at different soil depths at the Undabri site during the period between October 2016 and May 2017 (after traffic)

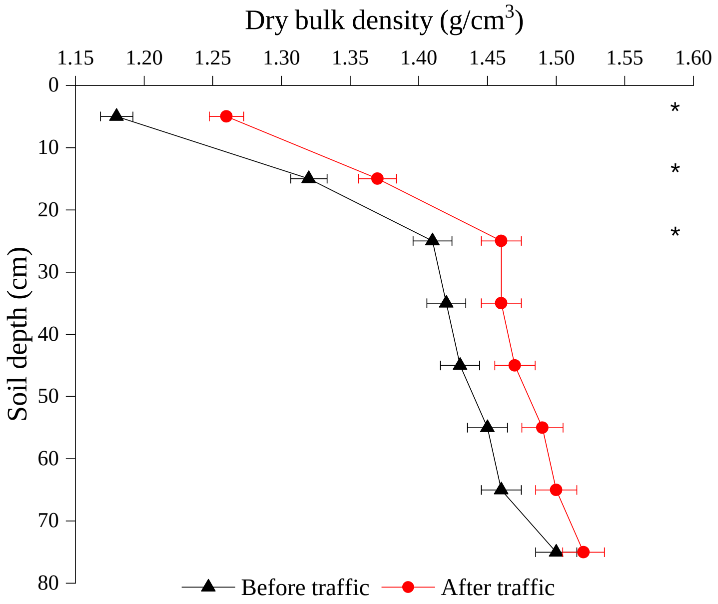


Figure 4.8: Changes in *Pb* with depth due to harvester traffic (JD7760)

4.2.2.3. Yambacully site

Table 4.3 and Figure 4.9 reveal that *Pb* ranged between 1.23 and 1.54 g/cm^3 during the study period. Dry bulk density was found to be significantly lower in October 2016 than January 2017 throughout the 0–30 cm depth, and also decreased from 1.37 to 1.31 g/cm^3 from January to May 2017 (before traffic) in the 0–30 cm depth. This suggests that increasing soil water content due to rainfall events at the beginning of October 2016 activated the swell property which led to a decreased *Pb*, while increased temperature due to seasonal variability resulted in more evaporation, which led to increased *Pb* due to shrinkage of the Vertosol (Daniel & Wu 1993; Chinn & Pillai 2008). Furthermore, Figure 4.10 shows that traffic from the CTF7760 harvester caused significant compaction that led to increased *Pb* from 1.28 to 1.33 g/cm^3 in the depth of 0–20 cm, suggesting that the JD7760 traffic, regardless of RTF or CTF, was the major source of soil compaction (Bennett et al., 2017).

Table 4.3: Changes in *Pb* at the Yambacully site during the study period

Soil depth (cm)	October 2016	January 2017	May 2017 (before traffic)	May 2017 (after traffic)
	Pb (g/cm³)			
0-10	1.23a	1.27b	1.23a	1.28b
10-20	1.37a	1.41b	1.32c	1.37a
20-30	1.40a	1.44b	1.37c	1.40a
30-40	1.42a	1.46b	1.40a	1.43ab
40-50	1.42a	1.46b	1.42a	1.45ab
50-60	1.44a	1.48b	1.45ab	1.47ab
60-70	1.47a	1.50a	1.47a	1.48a
70-80	1.49a	1.51a	1.49a	1.51a

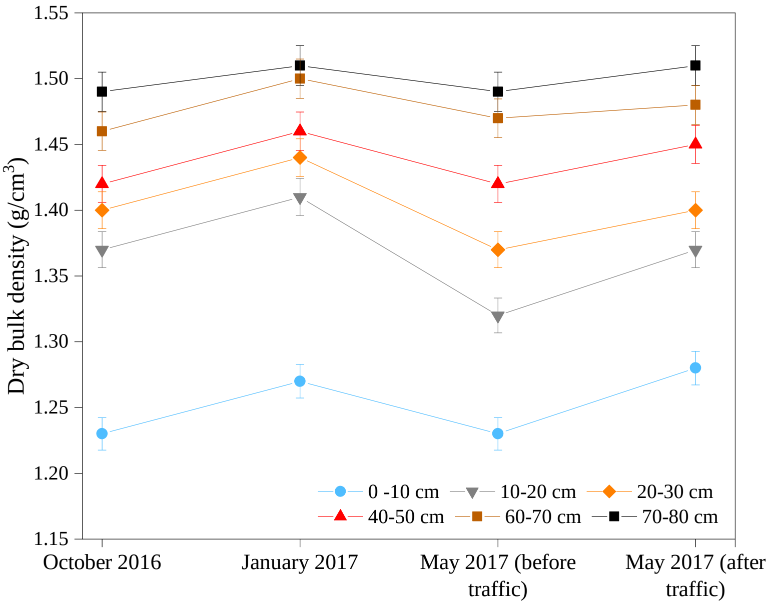


Figure 4.9: Changes in *Pb* at different soil depths at the Yambacully site during the period between October 2016 and May 2017 (after traffic)

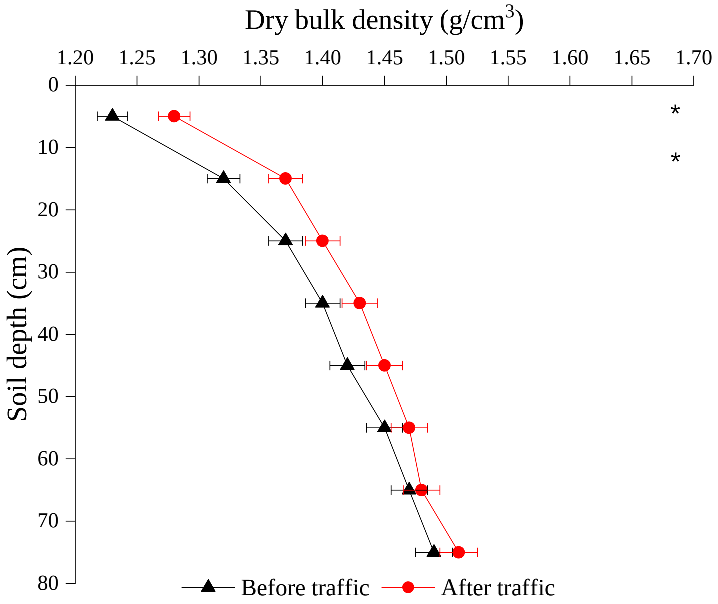


Figure 4.10: Changes in *Pb* with depth due to harvester traffic (JD7760)

4.2.3. Soil penetration resistance

Tables 4.4, 4.5 and 4.6 show Analysis of Variance for soil penetration resistance in Koarlo, Undabri and Yambacully during the period between October 2016 and May 2017 (after traffic). In addition, plots labelled A, B, C, and D in Figures 4.11 to 4.13 represent soil penetration resistance for October 2016, January 2017, May 2017 (before traffic), and May 2017 (after traffic), respectively, while plots E, F, G, and H refer to their corresponding variations in water content for the study areas.

4.2.3.1. Koarlo site

The results reveal a lower SPR in October 2016 than in January 2017, by 39% at the 0–30 cm depth (Figure 4.11 A and B), suggesting that high water content due to rainfall in early of October 2016 led to swelling of the soil, and therefore alleviated compaction effects (Bennett et al., 2016). Increasing temperature from October 2016 to January 2017 resulted in Vertosol shrinkage which led to a significant increase in soil penetration resistance by 23% in the topsoil compared to May 2017 (before traffic) (Figure 4.11 B and C). Figure 4.11 E and F shows that Swc decreased significantly from October 2016 to January 2017 due to evaporation, until rain fell again in the period between January and May 2017. Traffic from the JD7760 caused major compaction, which resulted in increased SPR, by 52% in the depth of 0–40 cm (Figure 4.11 C and D).

Table 4.4: Analysis of Variance for soil penetration resistance in Koarlo during the study period

Multiple Comparisons

Dependent Variable: SPR

(I) Time	(J) Time	Mean Difference (I-J)	Std. Error	Sig.[b]
Octber-2016	Jan-2017	-486.286*	102.025	.000
	May -17 before harvest	-426.857*	102.025	.003
	May-17 after harvest	-1532.143*	102.025	.000
Jan-2017	Octber-2016	486.286*	102.025	.000
	May -17 before harvest	59.429	102.025	.003
	May-17 after harvest	-1045.857*	102.025	.000
May -17 before harvest	Octber-2016	426.857*	102.025	.000
	Jan-2017	-59.429	102.025	.000
	May-17 after harvest	-1105.286*	102.025	.000
May-17 after harvest	Octber-2016	1532.143*	102.025	.000
	Jan-2017	1045.857*	102.025	.000
	May -17 before harvest	1105.286*	102.025	.000

*. The mean difference is significant at the 0.05 level.

b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

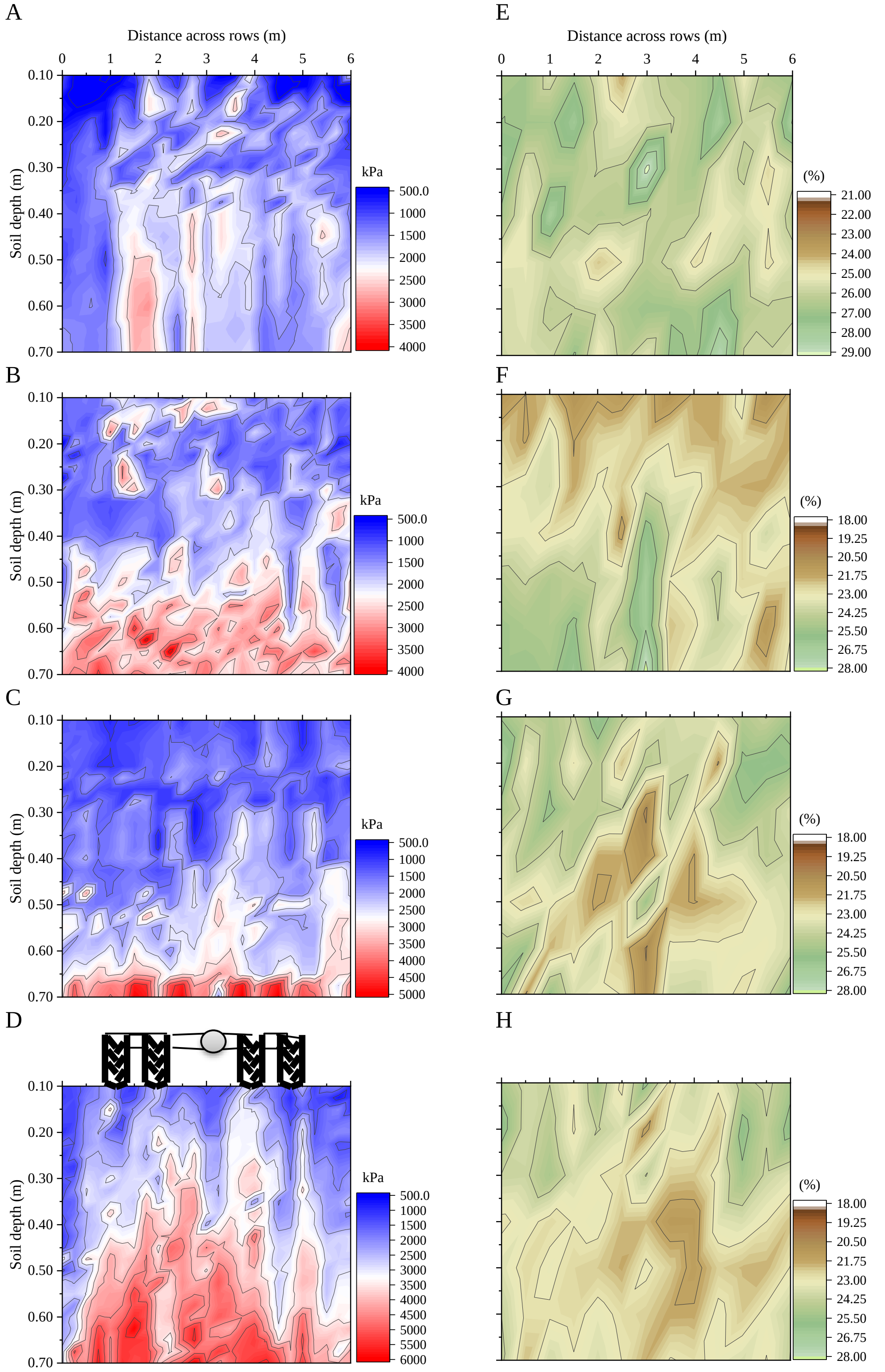


Figure 4.11: Soil penetration resistance maps at Koarlo during the study period: soil penetration resistance (A-D) and soil water content (E-H)

4.2.3.2. Undabri site

A similar trend was found in soil penetration resistance to that in Koarlo (Figure 4.12). The values increased significantly, from 1445 to 3143 kPa in the 0–30 cm depth, from October 2016 to January 2017 (Figure 4.12 A and B). The period between January 2017 and May 2017 (before traffic) showed a significant decreased in SPR, by approximately 44% at the 0–30 cm surface layer (Figure 4.12 B and C). Moreover, significant compaction was observed after one pass of the JD7760 harvester, which resulted in increased penetration resistance, from 3473 to 4250 kPa throughout the 20–60 cm depth (Figure 4.12 C and D).

Table 4.5: Analysis of Variance for soil penetration resistance in Undabri during the study period

Multiple Comparisons

Dependent Variable: SPR

(I) Time	(J) Time	Mean Difference (I-J)	Std. Error	Sig.^{b}
Octber-2016	Jan-2017	-1382.857*	101.016	.000
	May -17 before harvest	-388.714*	101.016	.001
	May-17 after harvest	-1179.571*	101.016	.000
Jan-2017	Octber-2016	1382.857*	101.016	.000
	May -17 before harvest	994.143*	101.016	.000
	May-17 after harvest	203.286	101.016	.045
May -17 before harvest	Octber-2016	388.714*	101.016	.001
	Jan-2017	-994.143*	101.016	.000
	May-17 after harvest	-790.857*	101.016	.000
May-17 after harvest	Octber-2016	1179.571*	101.016	.000
	Jan-2017	-203.286	101.016	.045
	May -17 before harvest	790.857*	101.016	.000

*. The mean difference is significant at the 0.05 level.

b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

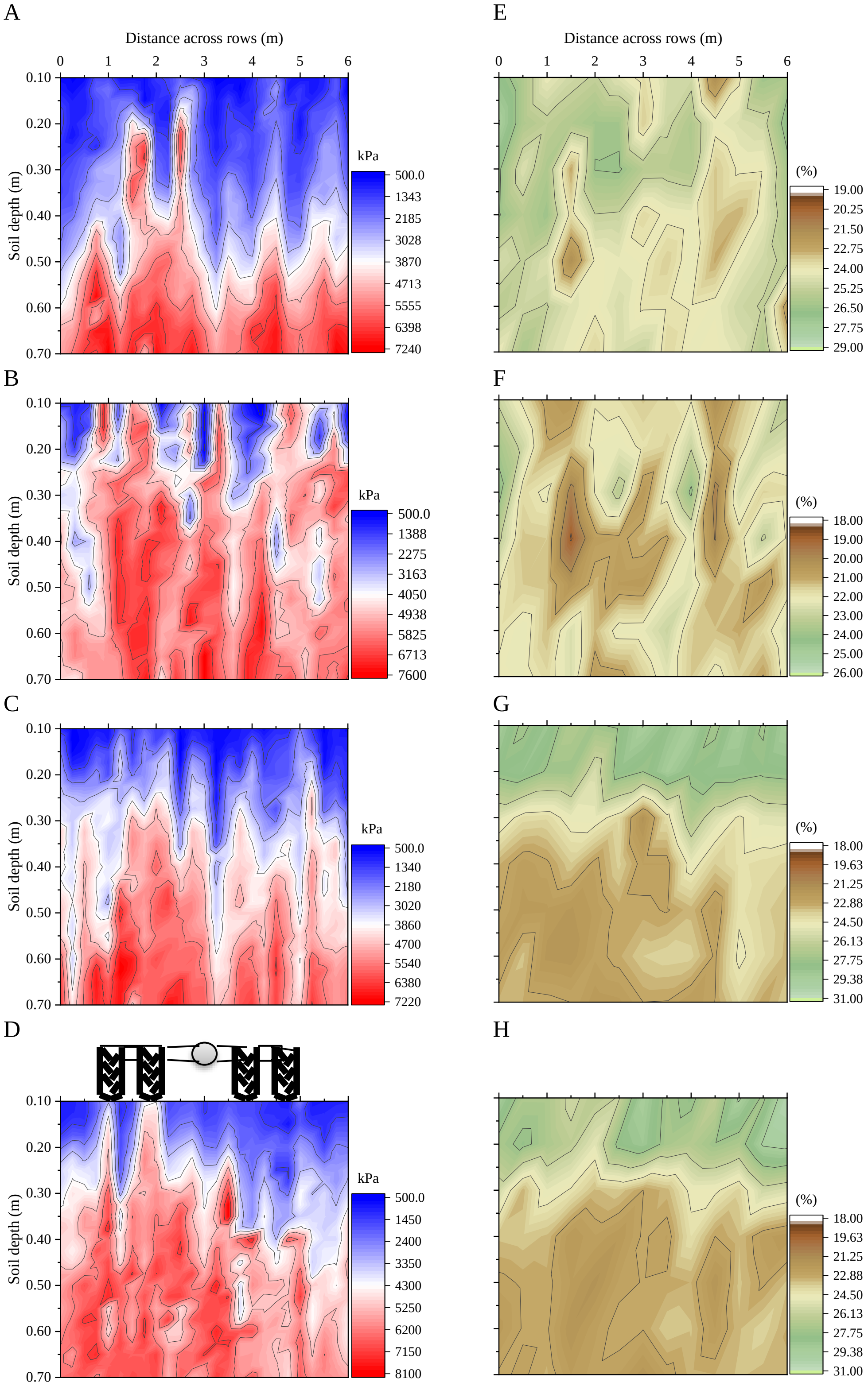


Figure 4.12: Soil penetration resistance maps at Undabri during the study period: soil penetration resistance (A-D) and soil water content (E-H)

4.2.3.3. Yambacully site

Figure 4.13 A, B and C, shows that there was a significant increase in soil penetration resistance from October 2016 to January 2017, by approximately 37% in the 10–30 cm depth, and then it decreased towards May 2017 (before traffic), by 28% in the depth of 10–20 cm. In addition, significant compaction occurred after a single pass of the CTF7760 harvester, which resulted in an increase of soil penetration resistance from 944 to 1427 kPa in the depth of 0–30 cm (Figure 4.13 C and D).

Table 4.6: Analysis of Variance for soil penetration resistance in Yambacully during the study period

Multiple Comparisons

Dependent Variable: SPR

(I) Time	(J) Time	Mean Difference (I-J)	Std. Error	Sig.[b]
Octber-2016	Jan-2017	-679.571*	142.858	.000
	May -17 before harvest	-712.143*	142.858	.001
	May-17 after harvest	-1410.857*	142.858	.000
Jan-2017	Octber-2016	679.571*	142.858	.000
	May -17 before harvest	-32.571	142.858	.000
	May-17 after harvest	-731.286*	142.858	.004
May -17 before harvest	Octber-2016	712.143*	142.858	.001
	Jan-2017	32.571	142.858	.000
	May-17 after harvest	-698.714*	142.858	.000
May-17 after harvest	Octber-2016	1410.857*	142.858	.000
	Jan-2017	731.286*	142.858	.004
	May -17 before harvest	698.714*	142.858	.000

*. The mean difference is significant at the 0.05 level.

b. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

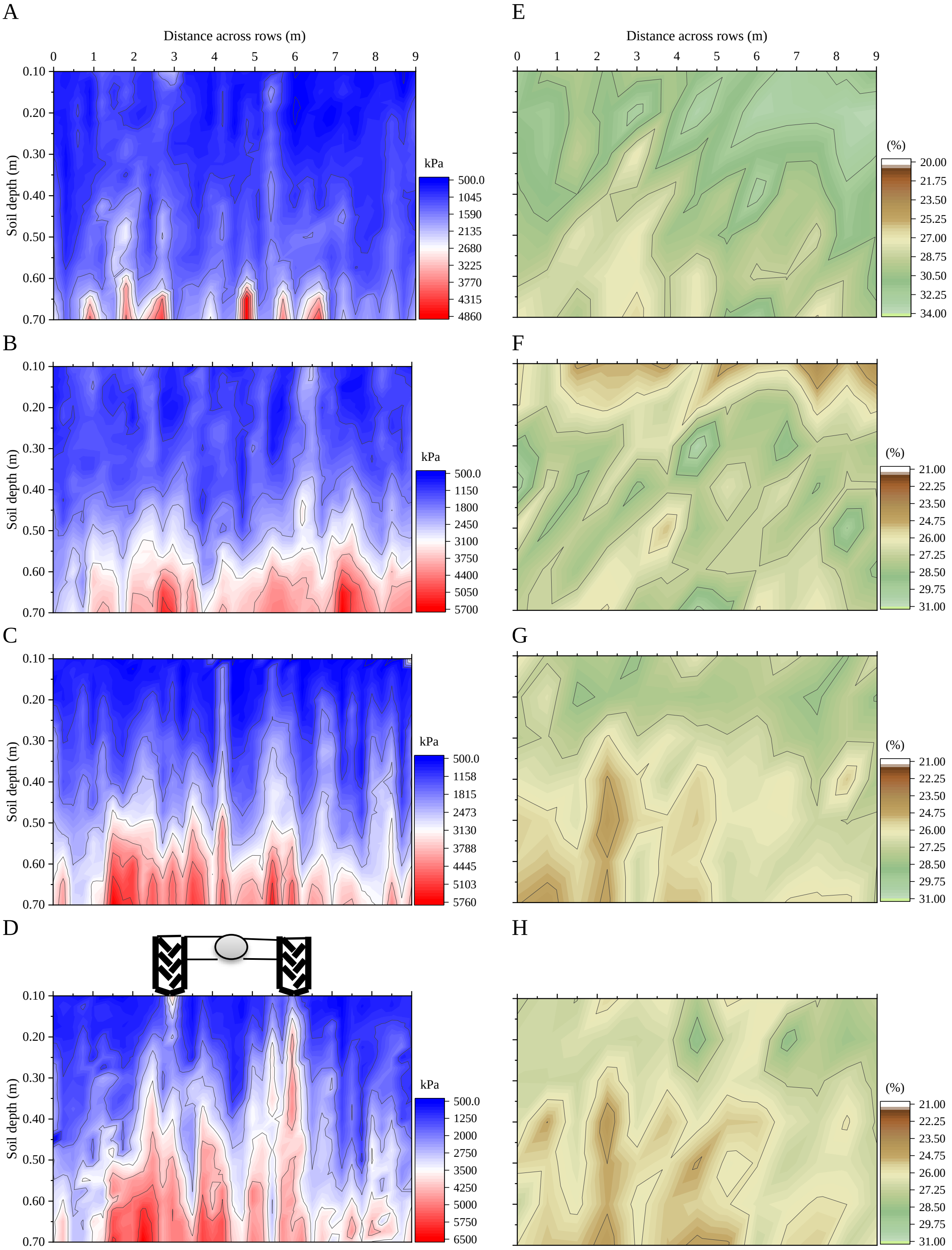


Figure 4.13: Soil penetration resistance maps at Yambacully during the study period: soil penetration resistance (A-D) and soil water content (E-H)

4.2.4. Covariance analysis between soil penetration resistance, soil water content and *Pb*

Among the soil parameters affecting soil penetration resistance of a specific soil, the soil water content (Swc) and dry bulk density (*Pb*) are the most considerable (Bennie, 1988; Moraes et al., 2012). To analyse soil SPR, it considered soil water content and *Pb* as covariables in May 2017 (after traffic) because their regression coefficient was significantly different. In this study, the means of SPR, Swc, and *Pb* were averaged across all depths and replications for the studied sites across the entire profile (Yasin et al., 1993). Results from the analysis of Covariance (ANCOVA) revealed that SPR had strongly significant difference ($P \leq 0.05$) with both Swc and *Pb* for Koarlo, Undabri and Yambacully throughout the depth of 0–70 cm (Tables 4.4, 4.5 & 4.6). There was an exponential dependence of the SPR with soil water content and a power dependence with the *Pb* values and the fitted parameters were well correlated. It was found a significant reduction in the values of SPR when Swc was higher, while increased with increasing *Pb* at all sites. This suggests that the cohesion and adhesion forces between the soil particles and aggregates were declined with increasing Swc leading to SPR reduction, besides, the water acts as a lubricant, reducing the friction between the soil and the steel cone penetrometer (Hillel, 1982; Silva et al., 2016).

Figure 4.14 also shows that the effects of changing soil water contents on the values of SPR are clearly apparent than *Pb* in May 2017 (after traffic) at all sites. There was a negative correlation coefficient between the SPR and Swc at R^2= 0.205, R^2= 0.640 and R^2= 0.077 and 95% confidence intervals of (-696.870, -288.472), (-795.969, -578.892) and (-632.030, -101.066) for Koarlo, Undabri, and Yambacully respectively Figure 4.14 (A, B & C). These results support inferences widely cited in the literature that Swc has an impact on SPR measurements. In contrast, it was observed a positive correlation coefficient between SPR and *Pb* at R^2= 0.493, R^2= 0.641 and R^2= 0.492 and 95% confidence intervals of (4821, 10629.597), (15298.845, 21017,009) and (4768.969, 10303,734) for the Koarlo, Undabri and Yambacully sites respectively (Figure 4.14 D, E & F). The validity of these results is confirmed that SPR is more sensitive to soil water content at *Pb*, and more sensitive to *Pb* at lower soil water content.

Table 4.4: Analysis of Covariance (ANCOVA) between SPR, Swc and *Pb* for Koarlo after harvester traffic in May 2017

(SPR*Swc)			**Coefficients**[a]			
Model		Unstandardised Coefficients		Standardised Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-14290.729	2398.644		-5.958	.000
	Swc	-492.671	102.769	-.453	-4.794	.000
a. Dependent variable: SPR						

(SPR*_Pb_)			**Coefficients**[a]			
Model		Unstandardised Coefficients		Standardised Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	8459.168	2133.638		3.965	000
	Pb	7725.373	1461.628	.489	5.285	.000
a. Dependent variable: SPR						

Table 4.5: Analysis of Covariance (ANCOVA) between SPR, Swc and *Pb* for Undabri after harvester traffic in May 2017

(SPR*Swc)			**Coefficients**[a]			
Model		Unstandardised Coefficients		Standardised Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-21081.865	1341.854		15.711	.000
	Swc	-687.430	54.625	-.800	-12.585	.000
a. Dependent variable: SPR						

(SPR*_Pb_)			**Coefficients**[a]			
Model		Unstandardised Coefficients		Standardised Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-21663.387	2058.733		-10.523	000
	Pb	18157.927	1438.909	.801	12.619	.000
a.Dependent variable: SPR						

Table 4.6: Analysis of Covariance (ANCOVA) between SPR, Swc and *Pb* for Yambacully after harvester traffic in May 2017

(SPR*Swc)			**Coefficients**[a]			
Model		Unstandardised Coefficients		Standardised Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	11986.111	3529.398		-3.396	.001
	Swc	-366.548	133.611	-.279	-2.743	.007
a.Dependent variable: SPR						

(SPR*_Pb_)			**Coefficients**[a]			
Model		Unstandardised Coefficients		Standardised Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-8330.822	1970.153		-4.229	000
	Pb	7536.352	1392.759	.498	5.411	.000
1. Dependent variable: SPR						

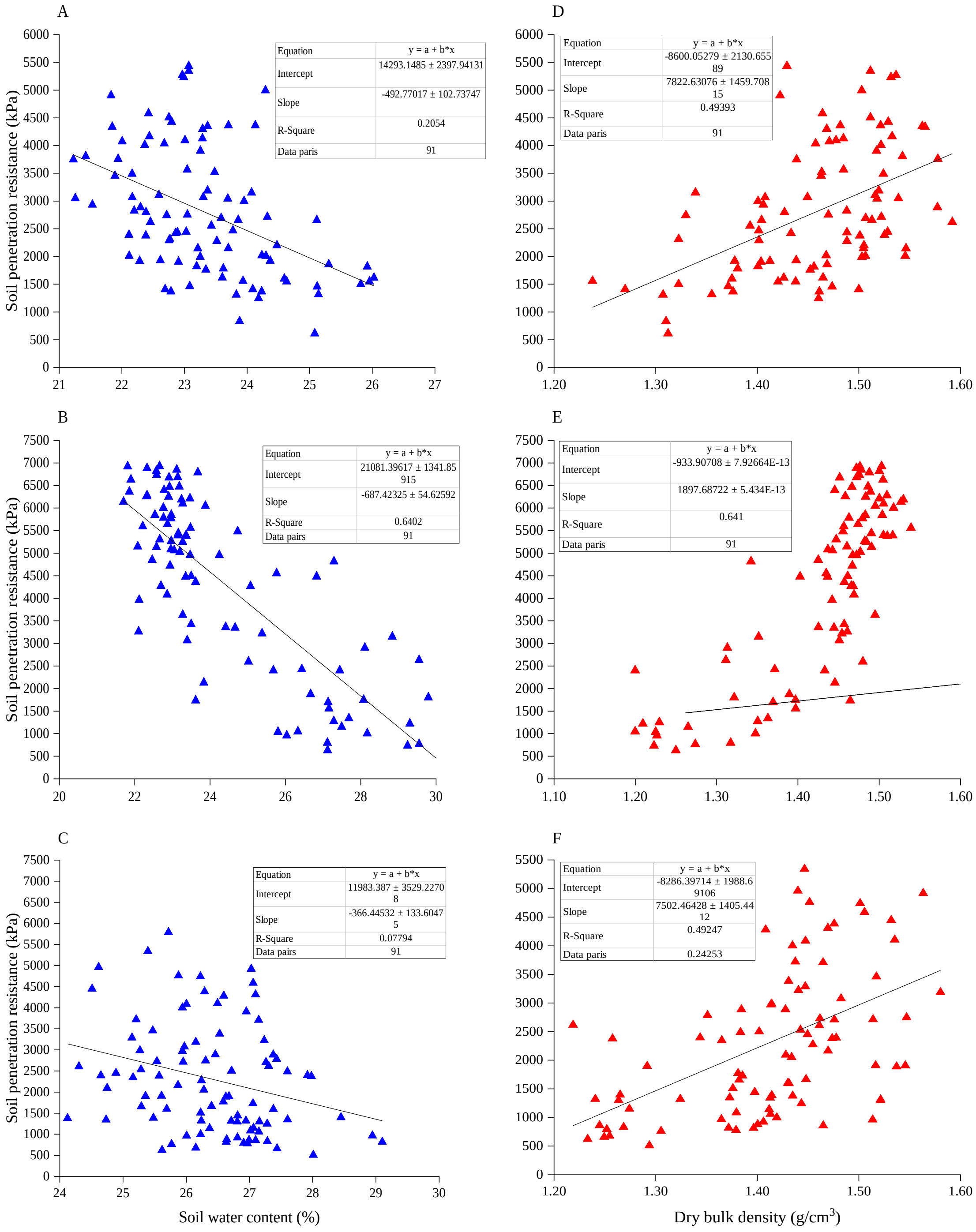
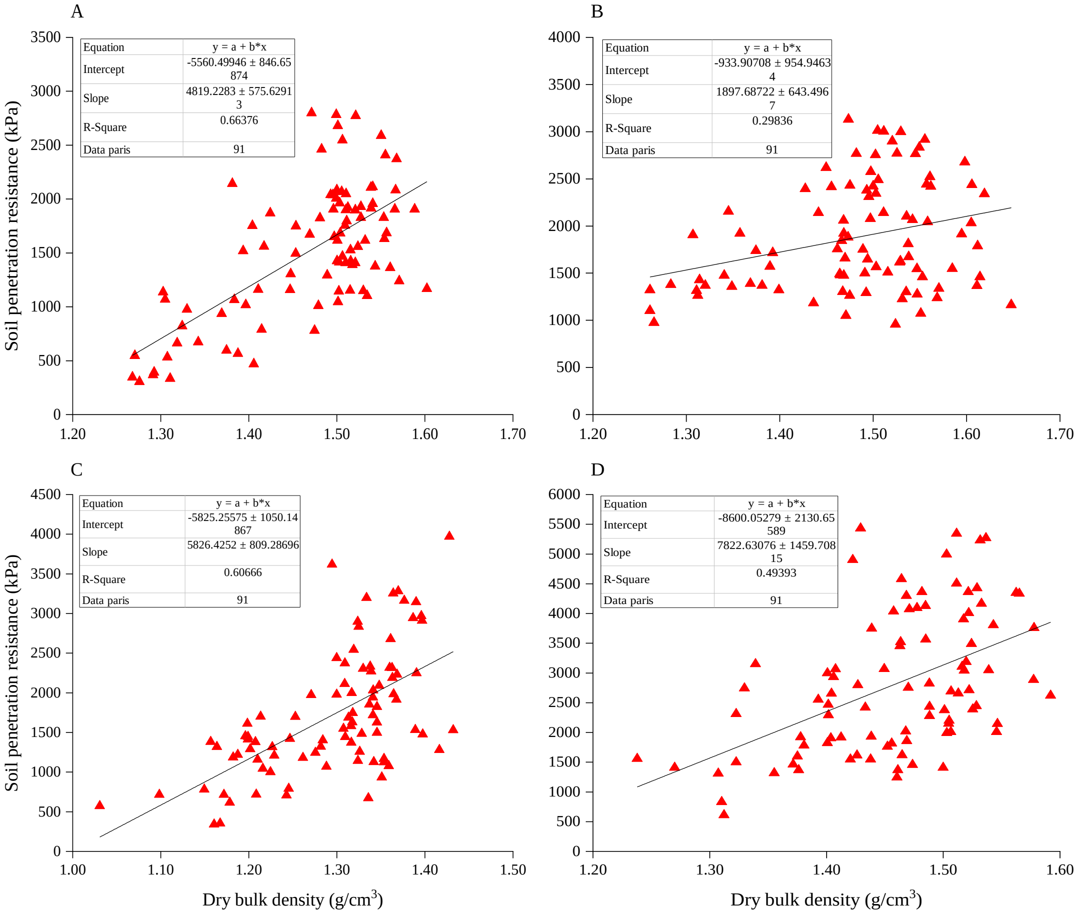


Figure 4.14: Relationship between SPR (kPa) and soil water content (%) and *Pb* (g/cm^3) after harvester traffic in May 2017 for the study areas. The letter (A, B & C) refer to the relationship between SPR and Swc for Koarlo, Undabri and Yambacully respectively. The letter (D, E & F) refer to the relationship between SPR and *Pb* for Koarlo, Undabri and Yambacully respectively

4.2.5. Correlation and regression analysis between soil penetration resistance and *Pb*

Figures 4.15 and 4.16 reveal a positive linear correlation between SPR and *Pb* detected for the Koarlo (RTF) and Yambacully (CTF) sites. In RTF, it was found that SPR had a moderate correlation with *Pb* in October 2016 and May 2017 (before traffic), while there was a weak correlation in January 2017 and May 2017 (after traffic). As shown in Figure 4.15 (A-D), the CTF Yambacully site had also a moderate correlation between SPR and *Pb* in October 2016, January 2017 and May 2017 (before traffic), while it was relatively low in May 2017 (after traffic). These were because that dry bulk density had a significant impact on SPR measurements (Bennie, 1988). However, small differences in the values of soil bulk density affected differently the response of soil resistance as a function of moisture (Van Quang & Jansson, 2012).



A

Equation	y = a + b*x
Intercept	-5560.49946 ± 846.65874
Slope	4819.2283 ± 575.62913
R-Square	0.66376
Data paris	91

B

Equation	y = a + b*x
Intercept	-933.90708 ± 954.94634
Slope	1897.68722 ± 643.4967
R-Square	0.29836
Data paris	91

C

Equation	y = a + b*x
Intercept	-5825.25575 ± 1050.14867
Slope	5826.4252 ± 809.28696
R-Square	0.60666
Data paris	91

D

Equation	y = a + b*x
Intercept	-8600.05279 ± 2130.65589
Slope	7822.63076 ± 1459.70815
R-Square	0.49393
Data paris	91

Figure 4.15: Relationship between SPR (kPa) and *Pb* (g/cm^3) for Koarlo during the study period. The letters A, B, C, and D refer the correlation for October 2016, January 2017, May 2017 (before traffic), and May 2017 (after traffic), respectively

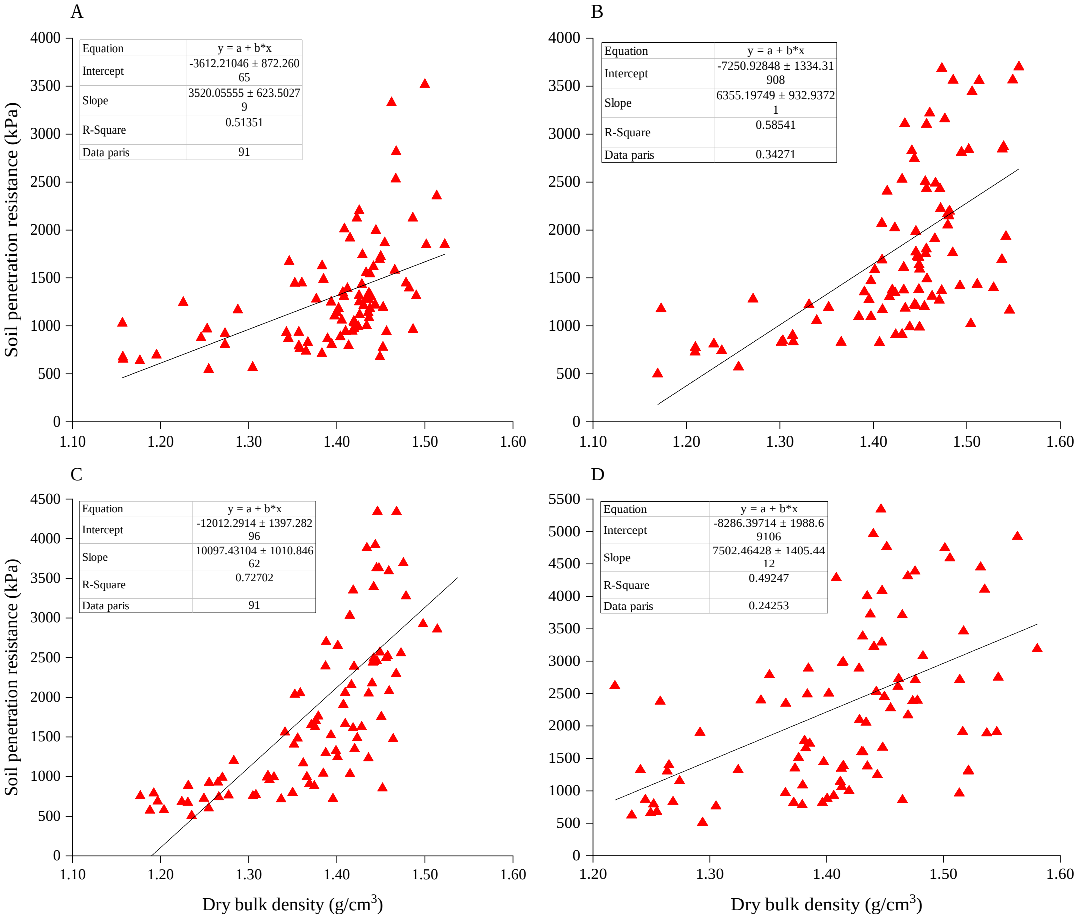


Figure 4.16: Relationship between SPR (kPa) and *Pb* (g/cm^3) for Yambacully during the study period. The letters A, B, C, and D refer the correlation for October 2016, January 2017, May 2017 (before traffic), and May 2017 (after traffic), respectively

One again, in this study, linear regression models were used to predict soil penetration resistance variables from the measured dry bulk density after harvester traffic in May 2017 for Koarlo (RTF) and Yambacully (CTF). The tentative hypothesis was that increase *Pb* causes increasing SPR values. The regression analysis revealed that the predicted SPR values increased positively with the increment in *Pb* (R-squared= 1) for both systems (Figure 4.17 A and B). This suggests that the independent variables (*Pb*) in the model predicted 100% of the variation in the dependent variable (SPR) because the R-squared value equals 1. This implied that the dependent of a variable was always predicted by the independent variable (Montgomery et al., 2012; Ober, 2013; Hoffmann & Shafer, 2015). Furthermore, it is reported that SPR showed a similar trend to *Pb*, in particular when the soil was at the same moisture conditions (Bennie, 1988).

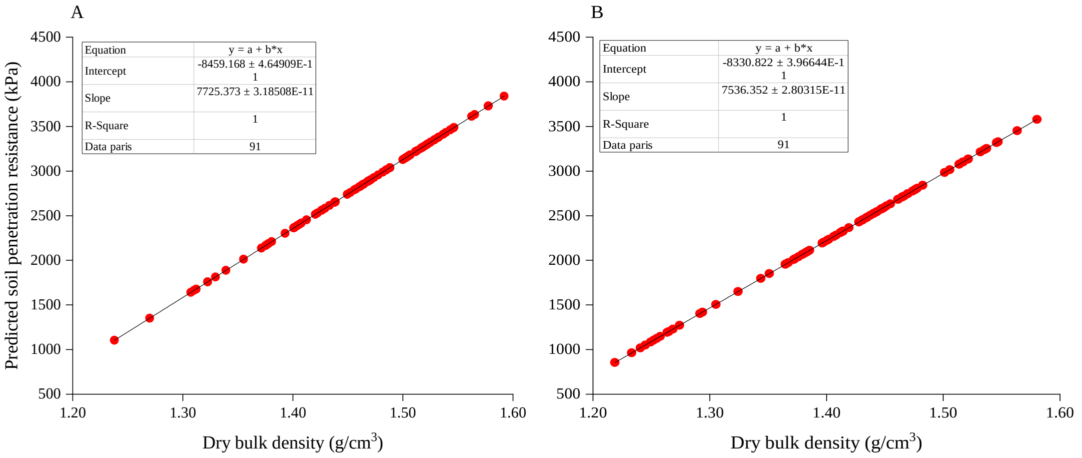


Figure 4.17: Linear regression between predicted soil penetration resistance (kPa) and bulk density (g/cm3) after JD7760 traffic in May 2017. A represents Koarlo site and B represents the Yambacully site

4.3. Discussion

4.3.1. Soil water content

Soil water content is a critical factor that can directly affect soil properties and crop growth (Mosaddeghi et al., 2000; Keller 2004). Soil water variability is affected by complex interactions among several factors (Yu et al., 2015). These include variations in topography, soil properties, vegetation type and density, mean water content, depth to water table, precipitation depth, solar radiation and other meteorological factors (Baroni et al., 2013). McKenzie (1998) reported that soil texture and irrigation method used have a direct impact on variation of soil water in the profile. Furthermore, the differences in soil water content due to differences in soil texture are more pronounced under wet conditions rather than dry (Famiglietti et al., 1998).

Among Australian soils, Vertosol is widely utilised for irrigated and dryland cotton production (Jutzi, 1988; Isbell, 2016). This soil has the ability to self–mulch as a consequence of repeated wetting and drying (McKenzie & McBratney, 2001). The process occurs during drying when these Vertosols fragment to form a thin surface layer (<50 mm) of water stable aggregates less than 5 mm (Ahmad, 1983; Jutzi, 1988; Coulombe et al., 1996). However, Vertosol heterogeneity affects the distribution of soil water through variations in texture, organic matter content, structure and the existence of macroporosity, all of which affect the fluid transmission and retention properties of the soil column (McGarry, 1996; Famiglietti et al., 1998). Addtitonally, water holding capacity and drainage are issues (Ghosh et al., 2010).

In this study, Swc was expressed on a volumetric basis. The observations revealed that Swc was higher in October 2016 than in January 2017, by approximately 13% in the surface soil at Koarlo, Undabri, and Yambacully. This suggests that the soil held more water due to the rainfall events at the beginning of October 2016 which led to a re-wetting of the soil profile compared to subsequent periods. The variations in the soil water between the different depths were highly related to Vertosol heterogeneity, clay minerals and a low infiltration rate. This was considered to be a major issue in terms of water stabilisation, and led to an obstruction in water movement in the soil profile (Hillel, 1998; McKenzie, 1998; Chinn & Pillai, 2008; Li et al., 2009).

All field experiments showed that the Vertosol profile was drier in January 2017 (before the rainfalls) than in May 2017 (before and after traffic) for all sites in the 0–30 cm soil depth. However, the studied areas had different soil textures (Table 3.5) and irrigation systems. These results may be explained by the fact that was because of the lack of vegetation in the earlier growing stage and increasing temperatures between October 2016 and January 2017. This allowed a higher amount of solar radiation and dry wind to reach the ground, resulting in more evaporation until January 2017, after which the rains fell again (Roberton & Bennett, 2017). On the other hand, the depth of 30–50 cm showed a slight decline in soil water content, by approximately 8% for Koarlo and Yambacully, respectively, from January 2017 to May 2017 (before and after traffic), suggesting that the crop absorbed the water during the growth stages (Figures 4.1 and 4.3). Furthermore, there was no significant difference in soil water content throughout the entire profile for both systems (RTF and CTF) before and after harvester traffic in May 2017 (sampling was done directly before and after traffic). In summary, the key findings are:

- Rainfall events in early October 2016 resulted in a re-wetting of the soil profile, which resulted in 13% higher Swc, in the topsoil than subsequent periods at all sites

- The Yambacully site experienced more rainfall in October 2016 before the experiment, and had a higher water content than the other two conventional traffic sites, by 17% throughout the entire profile

- The Undabri site was most affected by increased temperatures from October 2016 to January 2017, recording 13% lower Swc compared to Yambacully in the topsoil

- Controlled traffic farming had a lower sensitivity to seasonal variability. This was demonstrated by a lower rate of moisture loss (7%) compared to 18% under RTF at the Koarlo and Undabri sites in the 0–30cm depth for the period between January 2017 and May 2107

- Traffic from the JD7760, regardless of random or controlled traffic farming, did not significantly affect soil water content throughout the entire profile.

4.3.2. Dry bulk density

In general, the dry bulk density of soils indicates the soil quality and degree of compaction, which have a direct impact on soil properties and crop growth (Nawaz et al., 2013; Hugar & Soraganvi, 2014; Vero et al., 2014). Among Australian soils, Vertosol is known to have a high clay content and strong shrink-swell capacity (Hulugalle & Scott, 2008). It is strongly affected by changes in the soil water during the period between cultivation and harvest (Kamara & Haque, 1988). Furthermore, Vertosol has the ability to self-repair after several dry-wet cycles (Chinn & Pillai, 2008). However, it responds readily to compaction at different profile depths (Chan et al., 2006).

As mentioned, the density of Vertosol is significantly affected by wet-dry cycles, in particular, soil density increases in dry conditions due to shrinkage, while it decreases under wet conditions due to swelling (Virmani et al., 1982; Novara et al., 2012). In this study, the field results showed that rainfall events earlier in October 2016 had a clear effect on *Pb* at all sites. The values were significantly lower in October 2016 than January 2017 for Koarlo, Undabri and Yambacully in the surface layers (Tables 4.1, 4.2 and 4.3). A possible explanation for this is that rainfall recharged the water profile and increased soil water content before the soil samples were taken, thereby resulting in swelling, which consequently decreased dry bulk density and provided some natural remediation (Bennett et al., 2017). On the other hand, the surface soil showed higher dry bulk density in January 2017 than in May 2017 (before traffic), by approximately 6%, 9% and 5% for Koarlo, Undabri and Yambacully, respectively. This was because from October 2016 to January 2017, soil temperature gradually increased, resulting in moisture loss until the next rainfall events. This led to re-distributed particle volume in the topsoil, which caused soil particles to move independently of each other due to shrinkage. Thus, soil pores decreased and *Pb* increased as a result (McKenzie & McBratney, 2001; Newton, 2014).

Furthermore, the JD7760 cotton picker traffic caused significant compaction, which resulted in increased dry bulk density in Koarlo, Undabri and Yambacully at the surface soil. This suggests that the heavier harvester, regardless of random or controlled traffic, was a key source of soil compaction, resulting in a narrowing of the soil pores and increased *Pb* in both surface and sub-surface layers (Braunack et al., 2012; Jobbagy et al., 2014; Bennett et al., 2017; Ungureanu et al., 2019). Overall, it was found that:

- The topsoil exhibited high sensitivity to the wet-dry cycles which resulted in significant changes in *Pb* values under both CTF and RTF

- Rainfall events in early October 2017 and May 2017 (before traffic) resulted in swelling of the Vertosol which led to significantly decreased *Pb* and provided some natural remediation in the topsoil under both RTF and CTF, relative to January 2017

- Increased temperature due to seasonal variability (from October 2016 to January 2017) resulted in Vertosol shrinkage which led to significantly increased *Pb* in the surface soil at all fields in comparison to May 2017 (before traffic)

- Harvester traffic caused significant compaction, which resulted in a significant increase in dry bulk density in the surface layer for both RTF and CTF

- Traffic from the CTF harvester induced lower soil compaction on the overall field compared to traffic by the standard JD7760 configuration.

4.3.3. Soil penetration resistance

The relationship between soil penetration and compaction can often be used to estimate soil compaction (Perumpral, 1987; Costantini, 1995). Cone index is generally connected to soil type, bulk density, and soil water content. It has a linear correlation with *Pb* when the soil is at the same moisture conditions (Bennie, 1988). However, *Pb* does not have a key impact on soil penetration resistance in the short-term (Van Quang & Jansson, 2012). Consequently, soil water content can be an important factor affecting SPR. Penetration resistance ranges between 3.7–4.2 MPa when Swc is approximately 16% (Jobbagy et al., 2014).

The results of this study showed that there was a strong negative correlation between soil penetration resistance and soil water content, while there was a positive correlation between soil penetration resistance and *Pb* in depth of 0–70 cm at all sites. The values of soil penetration resistance were significantly lower in October 2016 than in January 2017 in the topsoil under both farming systems (RTF and CTF). It was also lower in May 2017 (before traffic) than in January 2017, by approximately 23%, 44% and 28% for Koarlo, Undabri and Yambacully topsoil, respectively. As indicated in the previous section, this could be attributed to the rainfall events during the early parts of October 2016 and in the period between January 2017 and May 2017 (before traffic). These rainfall events recharged the water profile of the soil and increased Swc. The increase in Swc caused the soil to swell and provided some natural alleviation of compaction, leading to lower soil strength (Radford et al., 2000; Junior et al., 2014; Bennett et al., 2017). Significant moisture loss due to an increase in temperature occurred between October 2016 and January 2017, causing the Vertosol to shrink. Shrinking led to an increase in the cohesive strength and frictional resistance of the soil, thus, the significantly higher soil penetration resistance in January 2017 (Landsberg et al., 2003; Wilson et al., 2010; Farzaneh et al., 2012; Van Quang & Jansson, 2012).

Traffic from the JD7760 regardless of the farming system (RTF or CTF), resulted in increased soil penetration resistance in the surface soil. This suggests that field traffic was the major source of soil compaction (Horn et al., 1995). In general, the main results are:

- Increasing soil water content due to rainfall caused the Vertosol to swell, providing some degree of natural compaction alleviation and decreasing soil penetration resistance in October 2016 relative to subsequent periods for both RTF and CTF

- Vertosol shrinkage due to dry conditions resulted in a significant increase in soil penetration resistance in topsoil at all sites throughout the soil profile

- Both traffic systems showed a higher soil penetration resistance after one pass of the harvester

- Harvester traffic on the site under CTF had the lowest soil penetration resistance in the 0–70 cm depth relative to RTF at both Koarlo and Undabri.

4.4. Conclusion

The behaviour of Vertosol in response to factors such as rainfall, seasonal variability and harvester traffic under two different cotton farming systems (RTF and CTF) was monitored in this chapter. First, it was found that the soil responded significantly to variations in the listed factors. This, in turn, affected the potential for plant growth and yield. Furthermore, it was found that increasing Swc due to rainfall resulted in swelling in the topsoil under both RTF and CTF. The higher moisture and the swelling of the soil led to a slight decrease in *Pb* and soil resistance and provided some compaction alleviation. This translates positively in terms of seed germination and plant nutrition. The CTF site at Yambacully experienced more rainfall in October 2016, leading to a significant decrease in compaction impacts compared to the other two conventional traffic or RTF sites.

On the other hand, for all sites, dry conditions related to seasonal variability resulted in a significant increase in *Pb* and soil penetration resistance in the topsoil due to shrinkage. An increase in *Pb* and soil penetration resistance result in the obstruction of root penetration and plant growth. Site under CTF exhibited lower sensitivity to seasonal variability which showed a lower rate of moisture loss (7%) in the topsoil for the period between January 2017 and May 2107, as compared to RTF sites at Koarlo and Undabri (18%). Moreover, significant compaction was observed after one pass of the JD7760 in the depth of 0–30 cm, regardless of the farming system (RTF or CTF). Compaction, due to the CTF7760 harvester traffic in the cultivated area, was significantly lower than that of the standard JD7760 configuration. The lower compaction effect of the CTF7760 is considered desirable for preserving soil quality and cotton crop performance in Vertosol.

Chapter 5. Results and discussions: Comparison of the effect of harvester traffic on different individual rows

5.1. Overview

The previous chapter presents the results and discussions of the impact of rainfall, seasonal variability, and harvester traffic on Vertosols behaivour. This chapter presents results on the impact of JD7760 traffic on soil characteristics in individual cotton rows and furrows under RTF and CTF. It starts with the results of the effect of harvester traffic on Swc, *Pb*, and soil penetration resistance followed by a discussion of the overall results and conclusion. The significant and key findings are presented in the discussion section of this chapter.

5.2. Results

In this chapter, the results of the three study sites, Koarlo, Undabri and Yambacully, are presented. Random traffic farming (RTF) was practiced at the Koarlo and Undabri study sites, while controlled traffic farming (CTF) was adpoted at the Yambacully site. Figure 5.1 shows: (1) row and furrow positions under RTF and CTF; and (2) the wheel track of the JD7760 standard configuration and the CTF7760 harvester. The letters R1, R2 and R3, 6 and 8 in the figures represent Row 1, Row 2 and Row 3, while F1, F2, and F3 represent Furrow 1, Furrow 2 and Furrow 3, respectively.

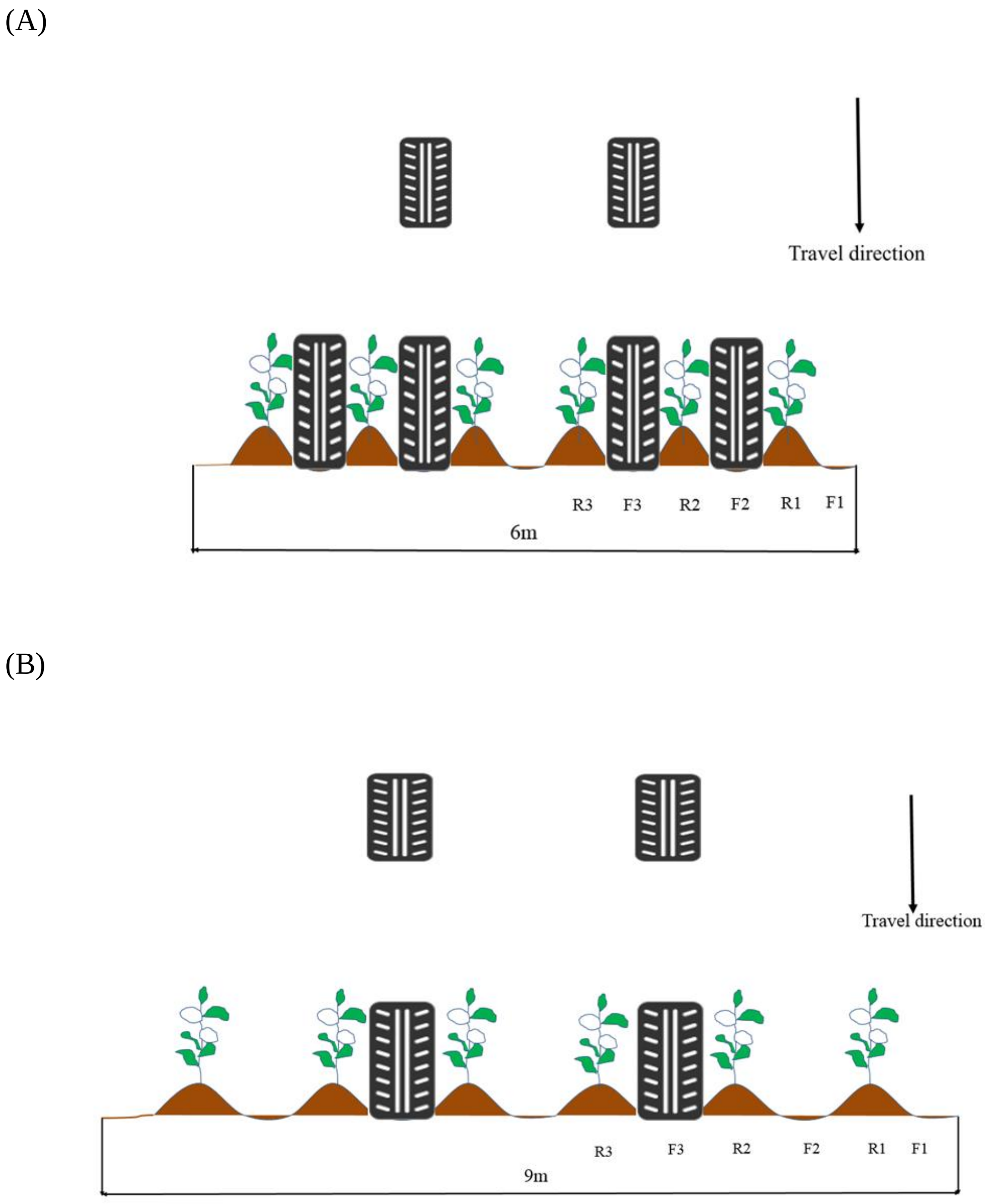


Figure 5.1: The wheel track of the JD7760. (A) represents the standard configuration under 1.0 m row spacing (RTF), and (B) represents the controlled traffic configured CTF7760 (1.5 m row spacing). The letters R1, R2 and R3 represent Row 1, Row 2 and Row 3, while F1, F2, and F3 represent Furrow 1, Furrow 2 and Furrow 3, respectively

Source: Schematic designed by the researcher.

5.2.1. Soil water content as influenced by John Deere 7760 traffic

5.2.1.1. Koarlo site

The results presented in Figure 5.2 show that soil water content (Swc) was significantly lower in Row 1 and Row 3 than Row 2, by 6% in the top 10 cm layer of the soil, while no significant difference was observed between Row1 and Row 3 in the surface soil. This was because Row 2 was located between the inner and outer wheels of the front dual-wheels of the JD7760 and experienced some compression from the wheels as shown in Figure 5.3. This led to a reduction in pore size distribution and decreased porosity, thus restricting water movement.

The statistical analysis shows that there was no significant difference (P≤0.05) in the Swc of Furrow 1, Furrow 2 and Furrow 3 in the top 20 cm depth (Figure 5.4). However, Furrow1 had a lower Swc than Furrow 2 and Furrow 3 in the top soil. This was because the JD7760 wheel traffic in Furrow 2 and Furrow 3 induced significant compaction which caused changes in the structural arrangement of the soil and resulted in a decline in Swc relative to Furrow 1.

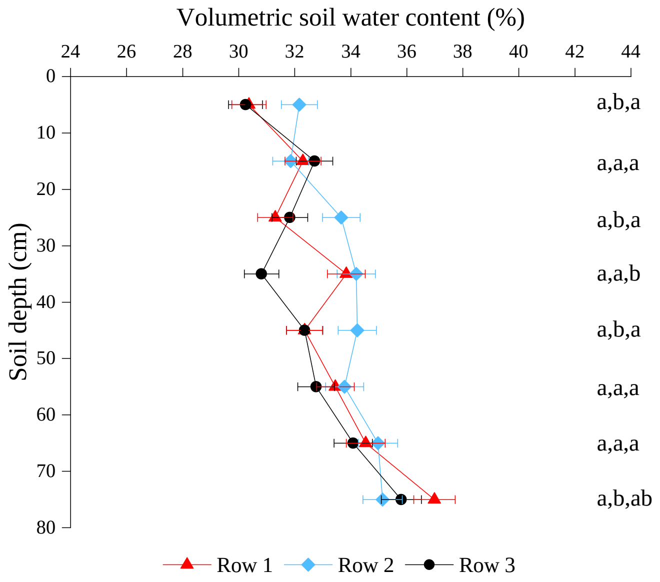


Figure 5.2: Comparison of volumetric soil water content between individual rows in soil depths at the Koarlo site after harvester traffic

Figure 5.3: Row 2 as influenced by inner and outer dual-wheel traffic of JD7760

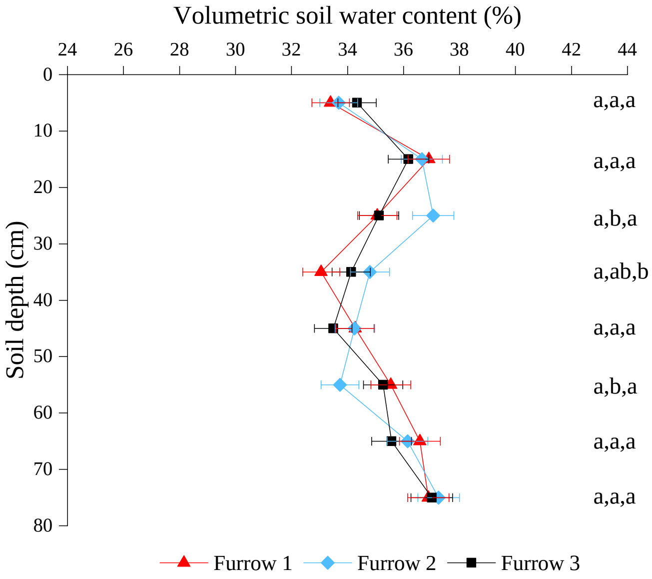


Figure 5.4: Comparison of volumetric soil water content between individual furrows in soil depths at the Koarlo site after harvester traffic

5.2.1.2. Undabri site

Soil water content in the 0–20 cm depth was significantly higher in Row 1 than in Row 2 and Row 3, by approximately 6%. No difference in Swc was found between Row 2 and Row 3 in the 0–30 cm depth (Figure 5.5). There was also no significant difference in Swc between Furrow 1, Furrow 2 and Furrow 3 in the 0–30 cm depth (Figure 5.6).

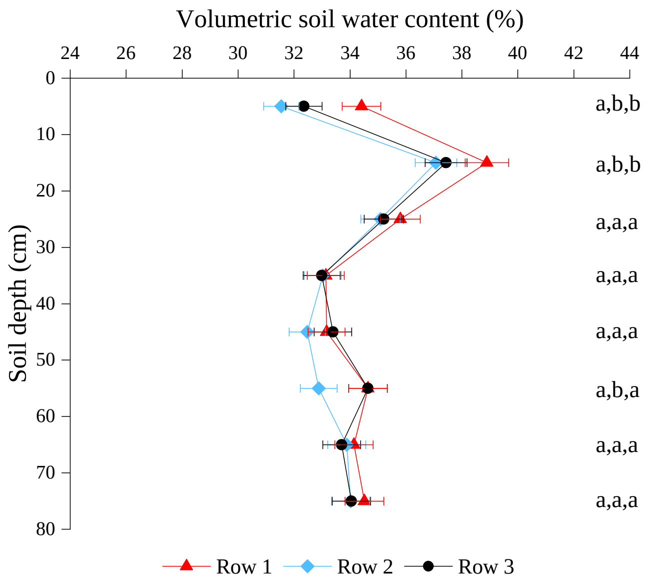


Figure 5.5: Comparison of volumetric soil water content between individual rows in soil depths at the Undabri site after harvester traffic

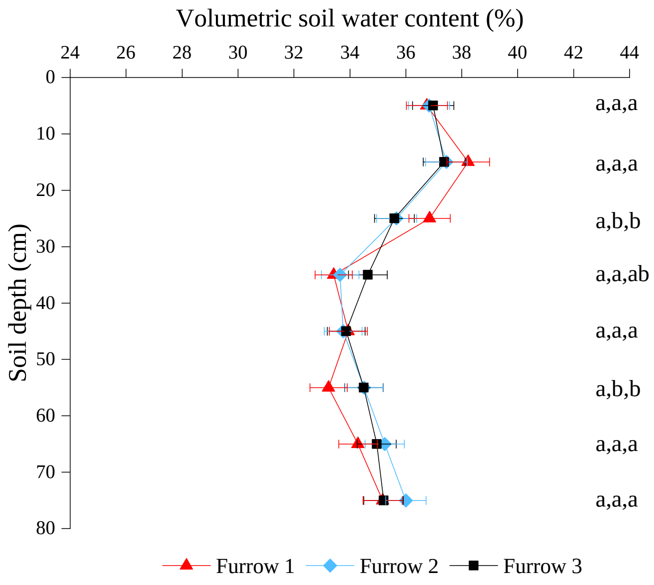


Figure 5.6: Comparison of volumetric soil water content between individual furrows in soil depths at the Undabri site after harvester traffic

5.2.1.3. Yambacully site

As shown in Figure 5.7, soil water content was significantly lower in Row 1 than in Row 2 and Row 3, by 9% in the depth of 10–30 cm. There was no significant difference in Swc when comparing Row 2 and Row 3 throughout the 0–30 cm depth. This was because Row 2 and Row 3 were adjacent to a permanent traffic lane under the CTF system, and the sides that faced the wheels of the cotton picker were usually subjected to traffic. This resulted in an increased rut depth that increased the effective surface area of the row exposed to sunshine, causing greater evaporation from the row. Thus, the Swc of Row 2 and Row 3 were lower compared to Row 1 (see Figure 5.8).

No significant difference in Swc was observed between Furrow 1 and Furrow 2 in the top 40 cm layer. Both Furrow 1 and Furrow 2 had a lower water content than Furrow 3, by about 8% throughout the 0–40 cm depth (Figure 5.9). This was because Furrow 1 and Furrow 2 were not subjected to harvester traffic under CTF and therefore experienced no soil structural damage due to traffic (Figure 5.1 B).

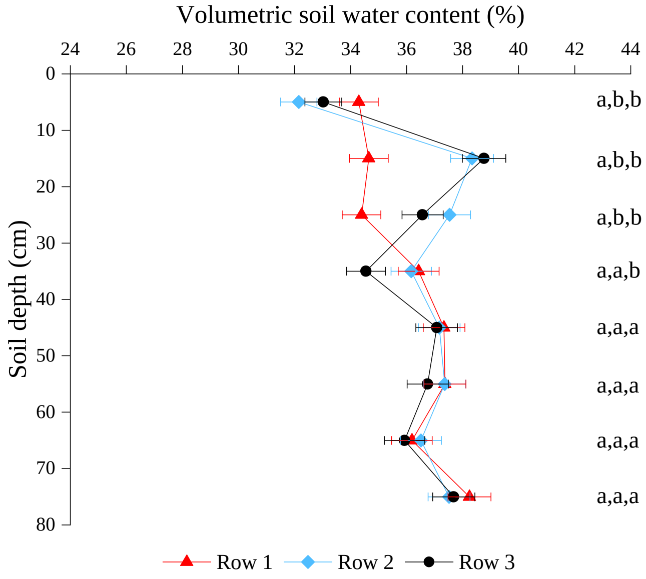


Figure 5.7: Comparison of volumetric soil water content between individual rows in soil depths at the Yambacully site after harvester traffic

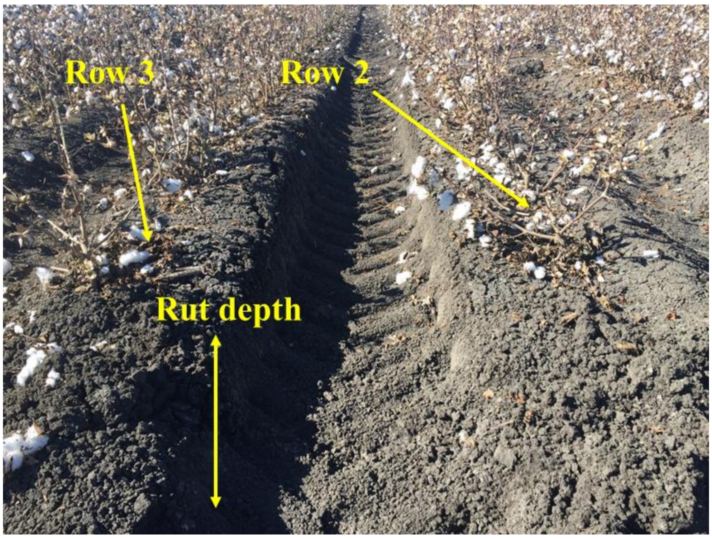


Figure 5.8: Rut depth after a single pass by the CTF7760 harvester in Yambacully

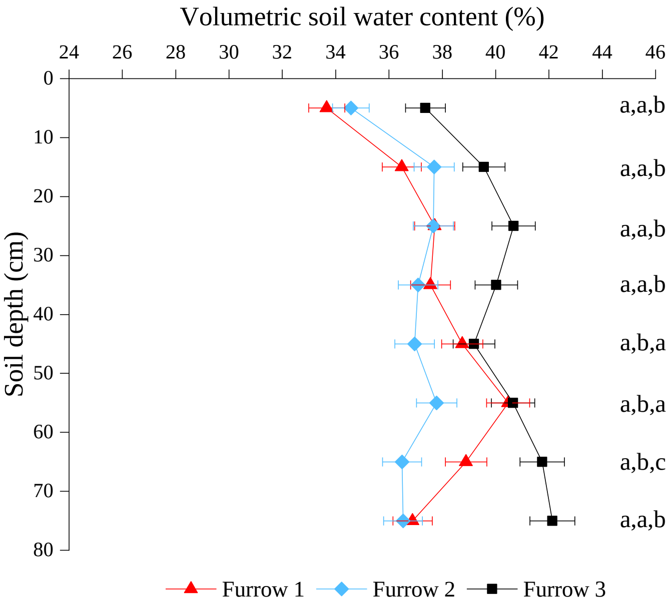


Figure 5.9: Comparison of volumetric soil water content between individual furrows in soil depths at the Yambacully site after harvester traffic

5.2.2. Change in dry bulk density due to harvester traffic

5.2.2.1. Koarlo site

Figure 5.10 shows variations in dry bulk density (*Pb*) between individual cotton rows at different profile depths. Row 1 showed a lower *Pb* than Row 2 and Row 3, by 8% and 6% respectively in the depth of 0–30 cm. Dry bulk density measured in Row 3 was significantly lower than that of Row 2 by approximately 4% in the topsoil. As mentioned in the previous section, Row 2 was compacted by the inner and outer dual-wheel traffic, which led to a changed soil's structural arrangement and increased *Pb* relative to Row 1 and Row 3 (Figure 5.11).

In comparison, the *Pb* value was significantly lower in Furrow 1 (1.37 g/cm^3) than in Furrow 2 (1.41 g/cm^3) and Furrow 3 (1.51 g/cm^3) for the 0–20 cm and 0–70 cm depths respectively (Figure 5.12). There was a significant difference in *Pb* of Furrow 2 by 4% in the 10–40 cm soil layer in comparison to Furrow 3. This was because both Furrow 2 and Furrow 3 were subjected to significant compaction by the inner and outer dual-wheel traffic, leading to an increased *Pb* in the wheel track (Figure 5.13).

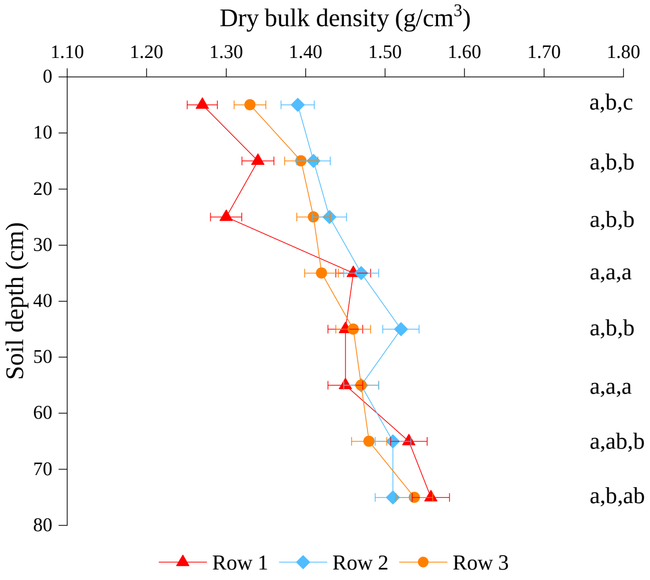


Figure 5.10: Change in *Pb* between individual rows in different depths at Koarlo after harvester traffic

Figure 5.11: Row 2 as influenced by the traffic of the dual-wheel of John Deere 7760 in Koarlo

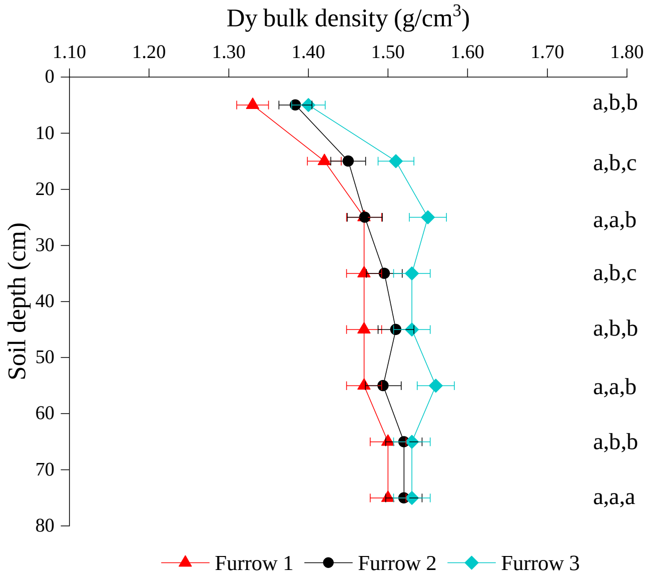


Figure 5.12: Change in *Pb* between individual furrows in different depths at Koarlo after harvester traffic

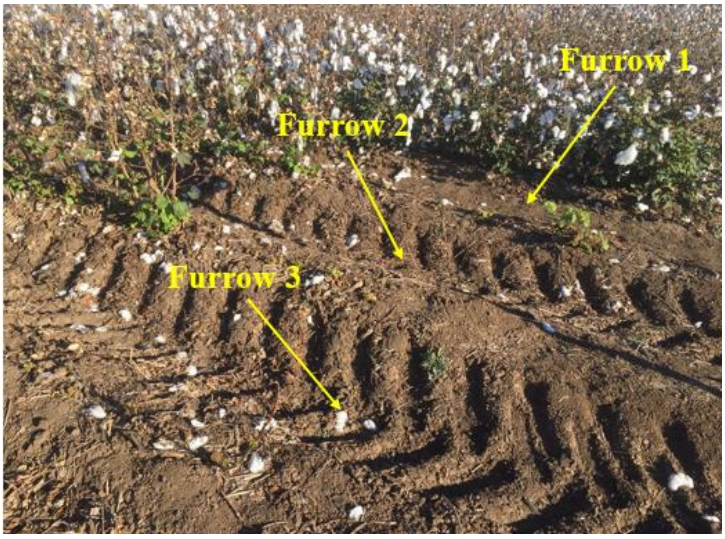


Figure 5.13: Furrow 2 and Furrow 3 after single traffic from JD7760 in Koarlo

5.2.2.2. Undabri site

Figure 5.14 shows that traffic from the JD7760 did not induce significant differences in dry bulk density between cotton rows in both the surface and subsurface layers. However, *Pb* was slightly higher in Row 1 than Row 2 and Row 3 in the topsoil. This result could be attributed to the historical compaction from random traffic which seemed to be equal in the different rows. Furthermore, Furrow 1 had a lower dry bulk density than Furrow 2 and Furrow 3, by 5% and 9% in the surface layer (Figure 5.15). The comparison between Furrow 2 and Furrow 3 showed a significantly higher *Pb* for Furrow 3 by approximately 4% at the depth of 0–20 cm. This suggests that both Furrow 2 and Furrow 3 were subjected to greater compaction by the dual-wheel traffic of the harvester than Furrow 1.

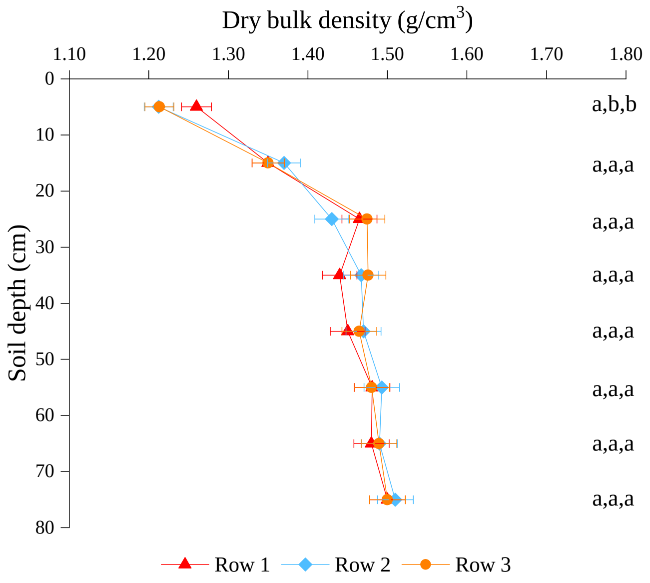


Figure 5.14: Change in *Pb* between individual rows in different depths at Undabri after harvester traffic

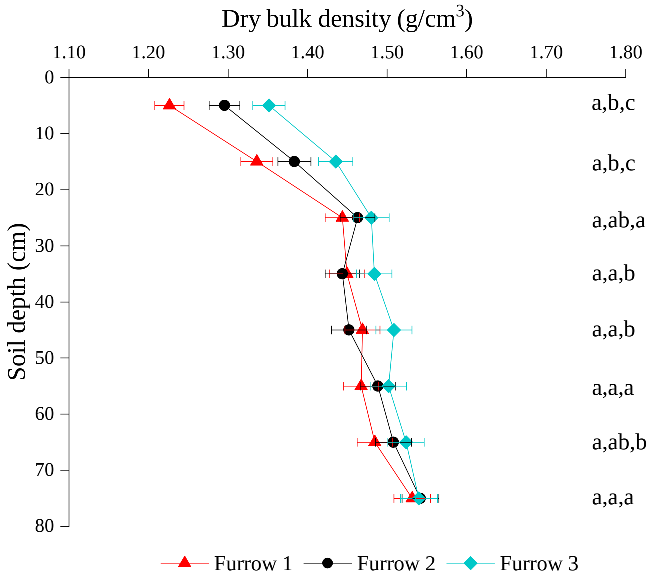


Figure 5.15: Change in *Pb* between individual furrows in different depths at Undabri after harvester traffic

5.2.2.3. Yambacully site

Figure 5.16 shows that *Pb* was significantly lower in Row 1 than in Row 2 and Row 3, by approximately 10% in the depth of 10–30 cm. There was no significant difference between the *Pb* of Row 2 and Row 3 in the surface layer. This suggests that the space between Row 1 and the permanent traffic lane (CTF) was sufficient to protect the soil structure, while the permanent traffic lane was between Row 2 and Row 3 (see Figure 5.1B). Consequently, significant compaction occurred, resulting in increased soil strength in the wheel track. This effect also expanded to reach Row 2 and Row 3.

Figure 5.17 further shows that there was no significant difference in the *Pb* of Furrow 1 and Furrow 2 throughout the 0–40 cm soil depth. However, the CTF7760 harvester traffic caused significant compaction in Furrow 3 which led to a higher *Pb,* by approximately 10% in the 0–80 cm depth than both Furrow 1 and Furrow 2. This was because both Furrow 1 and Furrow 2 were not subjected to harvester traffic (Figure 5.18).

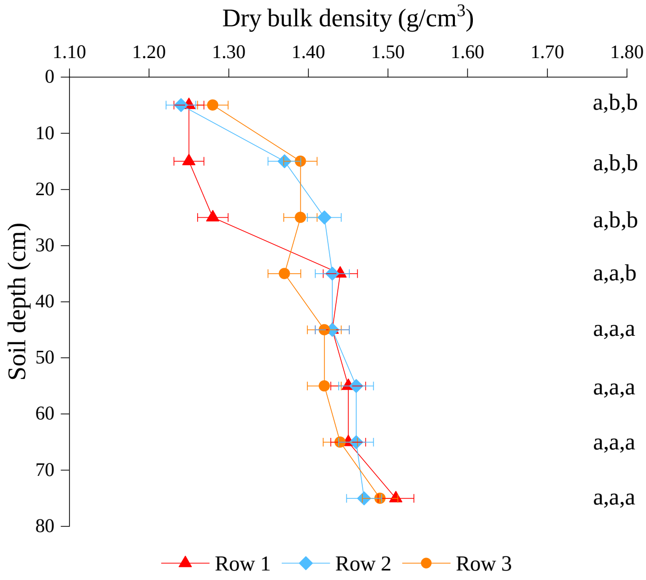


Figure 5.16: Change in *Pb* between individual rows in different depths at Yambacully after harvester traffic

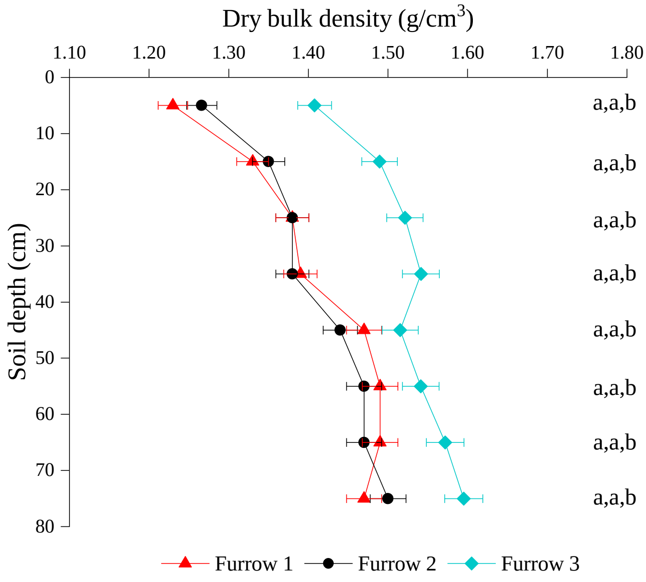


Figure 5.17: Change in *Pb* between individual furrows in different depths at Yambacully after harvester traffic

Figure 5.18: Furrow 3 as influenced by the CTF harvester at Yambacully

5.2.3. Influence of harvester traffic on soil penetration resistance

5.2.3.1. Koarlo site

Figure 5.19 shows that soil penetration resistance (SPR) was significantly lower in Row 1 than in Row 2 and Row 3, by 25% and 18% in the 10–20 cm depth, while it was significantly greater in Row 2 than in Row 3, by approximately 15% for the 20–30 cm depth. This was because the dual-wheel traffic resulted in increased soil strength underneath the wheel track which expanded to reach both sides of Row 2 (Raper et al., 2009; Braunack & Johnston, 2014; Keller et al., 2015).

Figure 5.20 also shows that Furrow 1 had a lower SPR than Furrow 2 and Furrow 3, by 69% and 78% in the 0–70 cm depth. There was a significantly lower SPR in Furrow 2, by 16% at the depth of 0–30 cm as compared to Furrow 3. These were because traffic from the JD7760 harvester produced significant compaction in the trafficked furrows by the dual-wheel, which then resulted in increased soil strength compared to Furrow 1. At the same time, the rear tyre traffic exerted an additional load after the inner dual-wheel traffic in Furrow 3, which led to a greater SPR in Furrow 3 than Furrow 2.

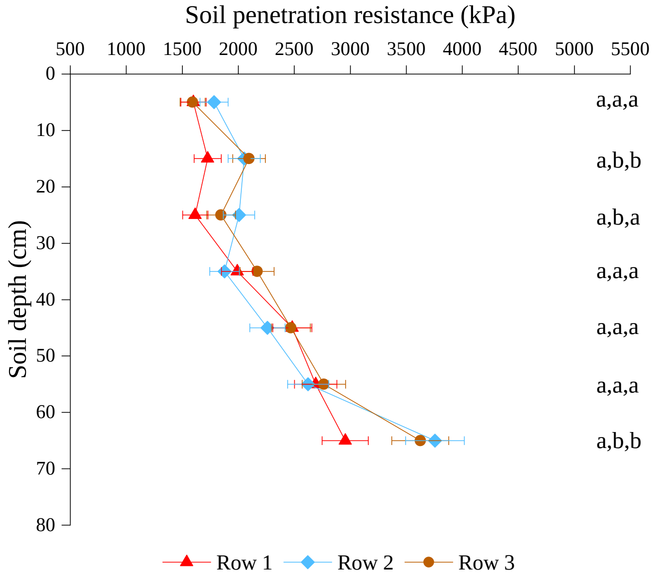


Figure 5.19: Change in soil penetration resistance between individual rows in different depths at the Koarlo site after harvester traffic

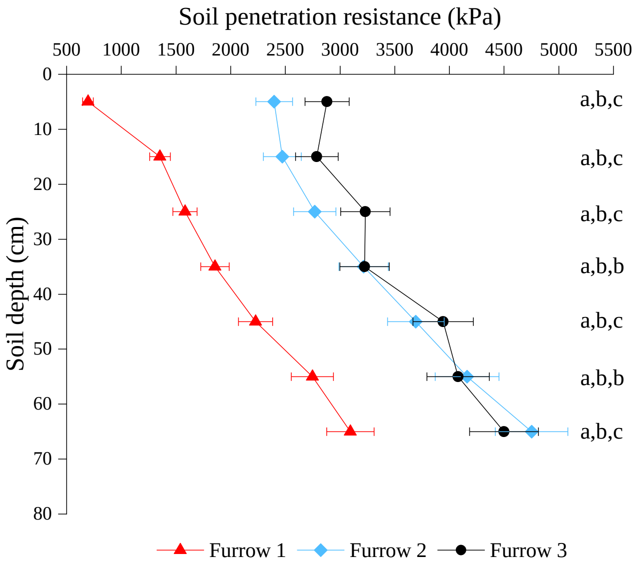


Figure 5.20: Change in soil penetration resistance between individual furrows in different depths at the Koarlo site after harvester traffic

5.2.3.2. Undabri site

Figure 5.21 shows that the SPR values followed a similar trend to those in the Koarlo site. Soil penetration resistance was significantly lower in Row 1 than both Row 2 and Row 3 by about 38% in the 0–20 cm depth and it was higher in Row 2, by 13% in the depth of 40–70 cm compared to Row 3. The results revealed that SPR was significantly lower in Furrow 1 than in Furrow 2 and Furrow 3, by 49 and 44% in the 0–70 cm soil depth (Figure 5.22). Furthermore, the comparison between Furrow 2 and Furrow 3 showed approximately 20% greater SPR for Furrow 2 in the 30–40 cm soil depth. The reasons were similar to those highlighted for the Koarlo site (above).

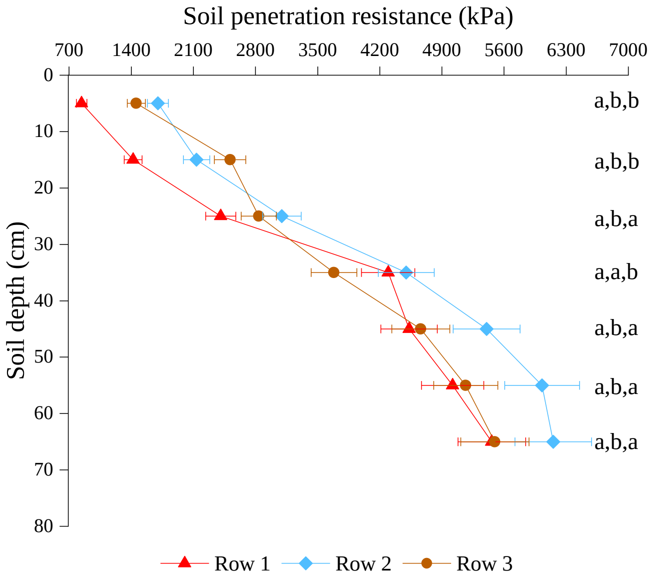


Figure 5.21: Change in soil penetration resistance between individual rows in different depths at the Undabri site after harvester traffic

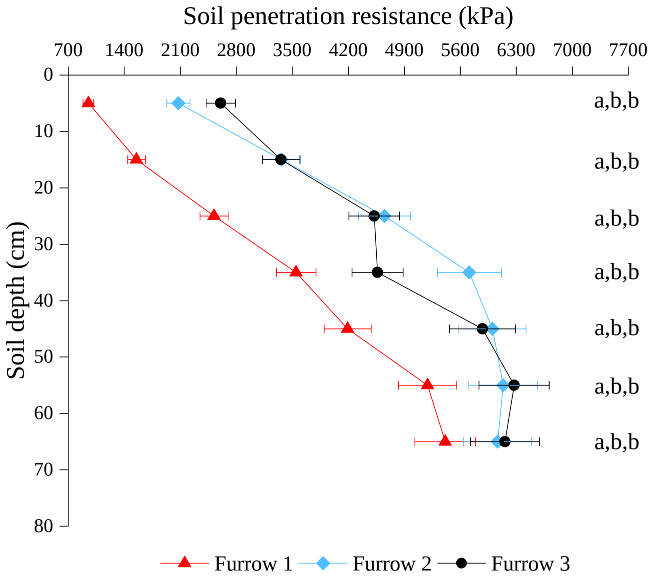


Figure 5.22: Change in soil penetration resistance between individual furrows in different depths at the Undabri site after harvester traffic

5.2.3.3. Yambacully site

Figure 5.23 shows that Row 1 had a lower SPR than Row 2 and Row 3 by 48% and 67%, respectively, in the 0–10 cm and 0–30 cm depths. Row 2 also had 26% lower SPR than Row 3 in the10–30 cm soil layer, which suggests that the space between Row 1 and the traffic lane was sufficient to protect the soil's structural arrangement (see Figure 5.1). At the same time, the traffic lane was between Row 2 and Row 3. This means that traffic from the CTF7760 harvester caused significant compaction, which then resulted in increased soil strength in the wheel track that expanded to reach neighbouring rows.

As expected, there was no significant difference in soil penetration resistance between Furrow 1 and Furrow 2 at the 0–30 cm depth (Figure 5.24). The experiment results reveal a higher SPR in Furrow 3 than in Furrow 1 and Furrow 2, by 83% and 96% in the 0–70 cm and 0–60 cm depths respectively. This was because Furrow 3, which was also the wheel track, was subjected to significant compaction by the single wheel traffic of the CTF7760 harvester, which led to greater soil strength than in Furrow 1 and Furrow 2.

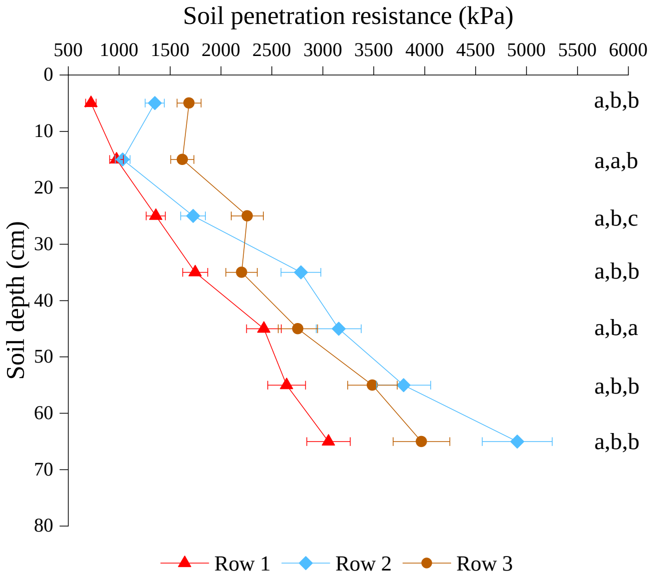


Figure 5.23: Change in soil penetration resistance between individual rows in different depths at the Yambacully site after harvester traffic

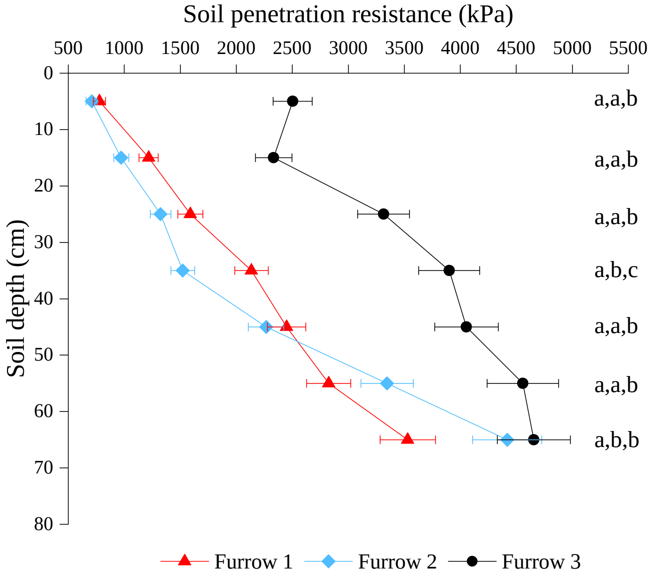


Figure 5.24: Change in soil penetration resistance between individual furrows in different depths at Yambacully after harvester traffic

5.3. Discussion

5.3.1. Harvester traffic effect on soil water content

Infiltration rate and water movement are strongly connected to changes in bulk density and porosity (Farzaneh et al., 2012). Harvester traffic is a key cause of changing soil structure which directly affects soil properties and compaction development (McGarry, 2003). Traffic from the JD7760 cotton picker at soil water content 21.4% causes significant compaction observable at 30 cm soil depth (Bennett et al., 2017).

This research found that soil water content varied significantly between the individual cotton rows and furrows after harvester traffic across the study areas. For example, in the Koarlo site, Row 2 had a higher Swc than Row 1 and Row 3, by 6% in the top 10 cm depth. However, Swc at the Undabri site was significantly higher in Row 1 by 6% in the 0–20 cm soil depth than Row 2 and Row 3. As well known, the volumetric water content increases linearly with soil bulk density increases. These results were because Row 2 in both sites was compressed by the inner and outer dual-wheel traffic, which then led to increased *Pb* and reduced pores size, and consequently a decline in volumetric soil water content (McKenzie & McBratney, 2001).

Row 1 at the CTF site in Yambacully had a lower Swc than Row 2 and Row 3, by 9% in the 10–30 cm, while there was no significant difference in Swc between Row 2 and Row 3. This was because the space between Row 1 and the traffic lane was sufficient to maintain soil's structural arrangement, while the permanent traffic lane was between Row 2 and Row 3. The wheels of the harvester created deep ruts on the sides of the rows. This increased the effective surface area of the rows exposed to the sun and allowed greater evaporation, thus decreasing Swc (Antille et al., 2016; Roberton & Bennett, 2017).

In comparison, Furrow 1 under RTF showed a lower Swc than Furrow 2 and Furrow 3 in the topsoil, while a slight change was observed in Swc between Furrow 2 and Furrow 3. This was the result of Furrow 2's profile being subjected to significant compaction by the outer dual-wheel traffic, which led to an increased *Pb*, and reduction in soil porosity which resulted in a lower Swc in comparison to Furrow 1. At the same time, Furrow 3 was influenced by both the inner dual-wheel and rear tyre traffic which caused more load that then led to less pore space available for water than in Furrow 1 and Furrow 2 (Hamza & Anderson, 2005; Seifu & Elias, 2019).

Furthermore, the CTF site at Yambacully did not show a significant difference in Swc between Furrow 1 and Furrow 2 from the surface soil to a depth of 40 cm. Furrow 1 and Furrow 2, however, had a lower Swc than Furrow 3 by 8% in depth of 0–40 cm. A possible explanation for this was that Furrow 1 and Furrow 2 were not subjected to harvester traffic, while Furrow 3 was the permanent lane of the CTF system, and was subjected to significant compaction that led to an increased *Pb*, rearranged soil particles and restricted water movement throughout the profile (Antille et al., 2016; Bennett et al., 2017). In summary, the key outcomes of this experiment are as follows:

- Row 2 under RTF was most influenced by harvester traffic, and showed a lower Swc than Row 1 and Row 3 by 6% in the surface soil (0–10 cm depth)
- Row 1 at the Yambacully CTF had a lower Swc than Row 2 and Row 3, by 9% in the 10–30 cm depth

- Furrow 2 and Furrow 3 at RTF was more sensitive to the JD7760 standard traffic, which showed 6% higher Swc at the depth of 0–10 cm than Furrow 1

- Traffic from the CTF7760 harvester did not cause a significant difference in Swc in either Furrow 1 and Furrow 2 throughout the 0–40 cm depth

- Furrow 3 was most sensitive to the CTF7760 harvester traffic, which resulted in a lower Swc by 8% in the 0–40 cm depth than Furrow 1 and Furrow 2.

5.3.2. Impact of JD7760 traffic on dry bulk density

Compaction leads to a redistribution of soil pores, change in soil physical properties and structural deterioration (Soane & Van Ouwerkerk, 1994; McKenzie, 2010; Shen et al., 2016). Compaction due to wheeled traffic is characterised by a reduction in total porosity in the wheel track at the surface layer (Hamza & Anderson, 2005). Frequent agricultural field traffic increases dry bulk density (*Pb*) by 32% and decreases total porosity up to 17% (Frey et al., 2009).

In this study, RTF was adopted at both Koarlo and Undabri, while CTF was used at Yambacully. The results reveal that Row 2 in Koarlo had a higher *Pb* than Row 1 and Row 3, by 8% and 3%, respectively, in the 0–30 cm soil depth, while there was no significant difference in *Pb* between cotton rows in both surface and subsurface soils at Undabri site. However, slight differences in *Pb* were observed in the topsoil of all 3 rows. This was because Row 2 was compacted by the traffic of the dual-wheel of the harvester, which led to changed soil's structural arrangement, soil porosity and increased *Pb* as a result (Osunbitan et al., 2005; Braunack & Johnston, 2014; Munkholm et al., 2016). The above observations at the Undabri site could be attributed to historical compaction due to the random harvester traffic that still existed and appeared to be equal among all rows (Alakukku, 1999).

Row 1 at the Yambacully CTF site showed a lower *Pb* than Row 2 and Row 3, by 10% in the depth of 10–30 cm, while no significant difference in *Pb* was observed between Row 2 and Row 3 in the 0–30 cm soil depth. This suggests that the space between Row 1 and the traffic lane of the CTF harvester was sufficient to the protect soil's structural arrangement, while the wheel track was between Row 2 and Row 3. Consequently, significant compaction occurred in the wheel track which resulted in increased soil strength, and this effect spread to Row 2 and Row 3.

Furthermore, this study shows that the JD7760 standard configuration traffic had a similar impact at both Koarlo and Undabri. The *Pb* values were significantly lower in Furrow 1 than in Furrow 2 and Furrow 3 at the 0–20, while *Pb* was slightly higher in the 10–40 cm soil depth for Furrow 3 than Furrow 2. Interestingly, traffic from the CTF7760 harvester did not have an impact on Furrow 1 and Furrow 2, whilst *Pb* significantly increased in Furrow 3, by approximately 10% throughout the 0–80 cm depth relative to Furrow 1 and Furrow 2. These results were because in Koarlo and Undabri, Furrow 1 was not subjected to harvester traffic, while both Furrow 2 and Furrow 3 were subjected to significant compaction by the dual-wheel traffic of the JD7760 standard configuration. This resulted in the compression of soil aggregates into a smaller size and increased *Pb*. The rear tyre traffic directly behind the inner dual-wheel passing through Furrow 3 exerted an additional load which led to higher a *Pb* in Furrow 3 than Furrow 2 (Ansorge & Godwin, 2008; Bennett et al., 2015). In contrast, the observations from the CTF site at Yambacully indicate that Furrow 3 was the traffic lane under the CTF system that was always subjected to considerable compaction, resulting in higher *Pb* than Furrow 1 and Furrow 2. Overall, the main findings are:

- Both harvesters' traffic systems induced significant compaction which led to increased *Pb* in the wheel tracks and this impact spread to adjacent rows throughout the depth studied

- Row 1 had the lowest *Pb* under CTF, by 10% in the depth of 10–30 cm than Row 2 and Row 3

- Under the RTF, Row 2 was most influenced by harvester traffic, which led to a higher *Pb* than in Row 1 and Row 3, by up to 8% in the depth of 0–20 cm

- The top 30 cm layer of the cotton rows was most sensitive to harvester traffic at both Koarlo and Yambacully

- Furrow 1 and Furrow 2 at the CTF site at Yambacully had a lower *Pb* than Furrow 3 by 10% throughout the 0–80 cm depth.

5.3.3. Change in soil penetration resistance due to harvester traffic

The relationship between soil penetration resistance and compaction can be employed as an indication of the degree of soil compaction (Perumpral, 1987; Costantini, 1995; de Vetten, 2014). Excessive use of machinery increased SPR to up to 5 MPa, which restricted the expansion of the root system and the absorption of water and nutrients (Rosolem et al., 2002; Lampurlanés & Cantero-Martinez, 2003). Primary traffic from the harvester caused significant compaction, which increased SPR to about 0.5 MPa at the surface layer (Landsberg et al., 2003).

This study revealed that SPR varied between cotton rows and furrows after one pass of the JD7760 harvester. This resulted in a similar trend in dry bulk density down the soil profile across the study sites. Row 1 at both Koarlo and Undabri showed a lower SPR, by approximately 22% and 38% than Row 2 and Row 3 in the top 20 cm depth of soil. Row 2 at both sites showed a 15% and 13% higher SPR in the 20–30 cm and 40–70 cm soil depths, respectively, than Row 3. These findings were expected because Row 2, which was located between the inner and outer dual-wheels, was compressed on both sides by the wheels, leading to a higher soil strength than Row 1 and Row 3 (Braunack & Peatey, 1999).

Row 1 at the CTF site at Yambacully showed a lower SPR than Row 2 and Row 3, by approximately 48% and 67%, respectively, in the 0–10 cm and 0–30 cm depths, while SPR was significantly higher (26%) in the 10–30 cm soil layer of Row 3 than Row 2. This suggests that the space between Row 1 and the traffic lane was wide enough to protect the soil’s structural arrangement, while the permanent traffic lane was between Row 2 and Row 3. Therefore, the wheel track was subjected to significant compaction which led to increased soil strength. This effect spread reached Row 2 and Row 3 (Braunack & Johnston, 2014; Antille et al., 2016; Bennett et al., 2017).

Furrow 1 at the both Koarlo and Undabri sites had a lower SPR by about two-thirds compared to Furrow 2 and Furrow 3 in the 0–70 cm depth after harvester traffic. In addition, SPR was lower in Furrow 2 at the surface soil than Furrow 3. This was because traffic from the JD7760 harvester caused significant compaction, which resulted in soil structural damage and higher soil strength in the wheel track than Furrow 1 (Figure 5.1 A).

Adopting CTF improved soil structure due to the minimisation and restriction of traffic to permanent lanes (Antille et al., 2016). The present study found that there was no statistical difference in SPR between Furrow 1 and Furrow 2 at the 0-30 cm layer of the soil profile after one pass of the CTF harvester. These furrows were not subjected to any traffic by the harvester, which provided some protection for the soil's structural arrangement. In contrast, significant compaction was observed in Furrow 3, which led to a greater SPR by 83% and 96% in the 0–70 cm and 0–60 cm depths respectively than Furrow 1 and Furrow 2. This was because Furrow 3 was subjected to the combined effects of the single front wheel and rear wheel traffic of the CTF7760 harvester, thus resulting in increased soil strength in the wheel track (McPhee et al., 2015). In brief, the key findings are:

- Row 1 under RTF had the lowest sensitivity to harvester traffic, showing a lower SPR than Row 2 and Row 3, by approximately 30% in the topsoil
- Row 1 had the lowest SPR after one pass from the CTF7760 harvester, by 57% in top 30 cm depth relative to RTF
- Furrow 2 and Furrow 3 under RTF were more sensitive to the JD7760 standard configuration traffic. They had approximately 75% greater SPR than Furrow 1 throughout the 0–70 cm depth
- Both Furrow 1 and Furrow 2 at the CTF site at Yambacully were less sensitive to harvester traffic. They had 83% and 96% lower SPR in the 0–70 cm and 0–60 cm soil depths than Furrow 3
- Traffic under the RTF system resulted in compacted soil by 75% of the field, while induced-compaction by the CTF harvester traffic was lower by 25%.

5.4. Conclusion

This chapter examined the impact of the John Deere 7760 harvester traffic on soil compaction at the single row level under two different cotton farming systems (RTF and CTF). It was found that wheeled traffic over the furrows resulted in reduced soil water content, and increased *Pb* and soil penetration resistance. In RTF conditions, the topsoil 0–20 cm layer of Row 2 was most influenced by harvester traffic which showed the highest *Pb* and soil penetration resistance compared to Row 1 and Row 3.

There was an increase in dry bulk density and soil penetration resistance underneath the wheel track of both RTF and CTF. This effect spread to adjacent rows, which directly affected cotton. There was no impact on Row 1 after one pass of the CTF7760 harvester throughout the 0–80 cm depth. Overall, CTF provided protection to about two-thirds of the farm in terms of soil's structural arrangement and reduced compaction effects compared to RTF.

Chapter 6. Results and discussions: The impact of harvester traffic at different soil depths in individual row

6.1. Introduction

The previous chapter explored the influence of JD7760 traffic on soil properties between individual cotton rows and furrows under two different farming systems. This chapter discusses the impact of the harvester traffic on soil water content (Swc), dry bulk density (*Pb*), and soil penetration resistance (SPR) at different soil depths across the individual rows and furrows. The following chapter will discuss the impact of soil compaction on cotton yield row by row.

As mentioned in previous chapters, random traffic farming (RTF) was practiced in Koarlo and Undabri. Controlled traffic farming (CTF) was adopted in Yambacully. In this chapter, two different fields at Koarlo are investigated; the first in 2016 and the second in 2017. Both Undabri and Yambacully were examined in 2017. The letters R1, R2 and R3 in the figures represent Row 1, Row 2 and Row 3, while F1, F2, and F3 represent Furrow 1, Furrow 2 and Furrow 3, respectively. The significant and key findings are presented in the discussion sections of this chapter. The symbol (*) indicates significant difference between treatments at $P \leq 0.05$ level.

6.2. The impact of harvester traffic on soil water content at different soil depths

Figure 6.1 shows Swc before and after harvester traffic in Row 1 for Koarlo in 2017. Overall, Swc before and after traffic was not significantly different ($P \leq 0.05$) throughout the entire profile for both RTF and CTF at all three sites. This was because Swc measurements were taken immediately before and after traffic.

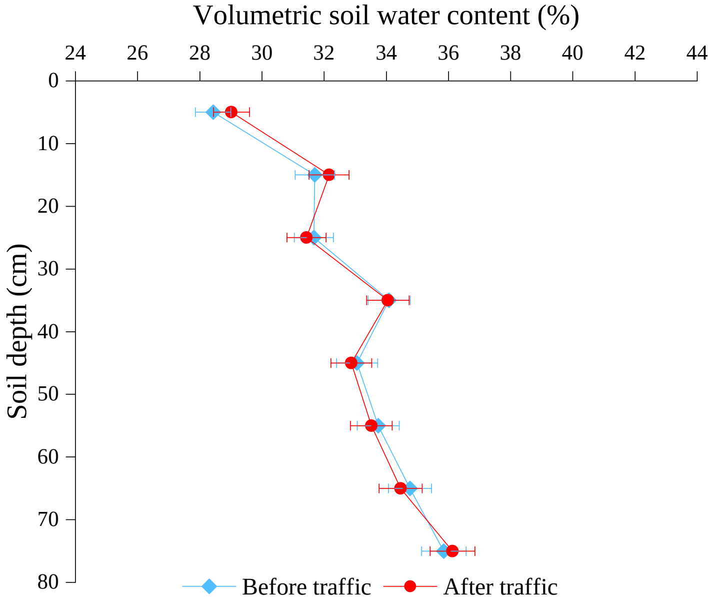


Figure 6.1: Volumetric soil water content before and after traffic in Row 1 at Koarlo in 2017

6.3. The impact of harvester traffic on dry bulk density at different soil depths

6.3.1. Random traffic farming

As mentioned earlier, RTF was practiced at the Koarlo and Undabri sites. The results show that *Pb* increased significantly in Row 1, from 0.91 to 1.0 g/cm^3 and from 1.22 to 1.30 g/cm^3 at Koarlo in 2016 and 2017, for the depths of 0–10 cm and 0–20 cm due to harvester traffic (Figures 6.2 and 6.3). A similar trend was observed at the Undabri site, where Row 1 showed a lower *Pb* before traffic than after traffic, by approximately 10% in the topsoil (Figure 6.4). This was because the outer wheel traffic caused significant compaction in the wheel track that resulted in increased soil strength which also spread to reach adjacent rows.

Figures 6.2 and 6.3 also reveal that *Pb* increased significantly after one pass of the JD7760 harvester in Row 2, by 10% at Koarlo in 2016 and 2017 in the 0–30 m depth. It as well increased by 5% in the 0–30 cm depth at Undabri. This was because Row 2 was compressed by both the inner and outer dual-wheel traffics, which led to change in soil’s structural arrangements and increased soil strength, thus increased *Pb* (see Figure 5.11).

A significant increase in *Pb* was observed in Row 3 after harvest, for Koarlo in 2016 (10%) and 2017 (6%), respectively in the 0–20 cm soil depth. Similarly, Undabri showed 5% higher *Pb* in Row 3 after one pass of the harvester in the 0–40 cm depth (Figure 6.4). This was also because the inner wheel and rear tyre traffic caused significant compaction in the wheel track, resulting in increased soil strength that spread widely to reach Row 3.

As Figures 6.2, 6.3 and 6.4 show, harvester traffic induced no significant difference in *Pb* in Furrow1 for both Koarlo and Undabri throughout the 0–80 cm soil depth. As would be expected, traffic from the JD7760 caused significant compaction, resulting in increased *Pb* in Furrow 2 and Furrow 3, by approximately 5% and 6% in Koarlo in 2016 and 2017 for the 0–70 cm depth respectively. The Undabri site was subjected to significant compaction by the dual-wheel of the harvester, which led to 5% increase *Pb* in both Furrow 2 and Furrow 3 throughout the 0–80 cm soil depth. This was because Furrow 2 and Furrow 3 were the traffic lanes under RTF that were subjected to significant compaction by the inner and outer dual-wheel traffic, which in turn resulted in increased soil strength and reduced soil pores and hence, increased *Pb*.

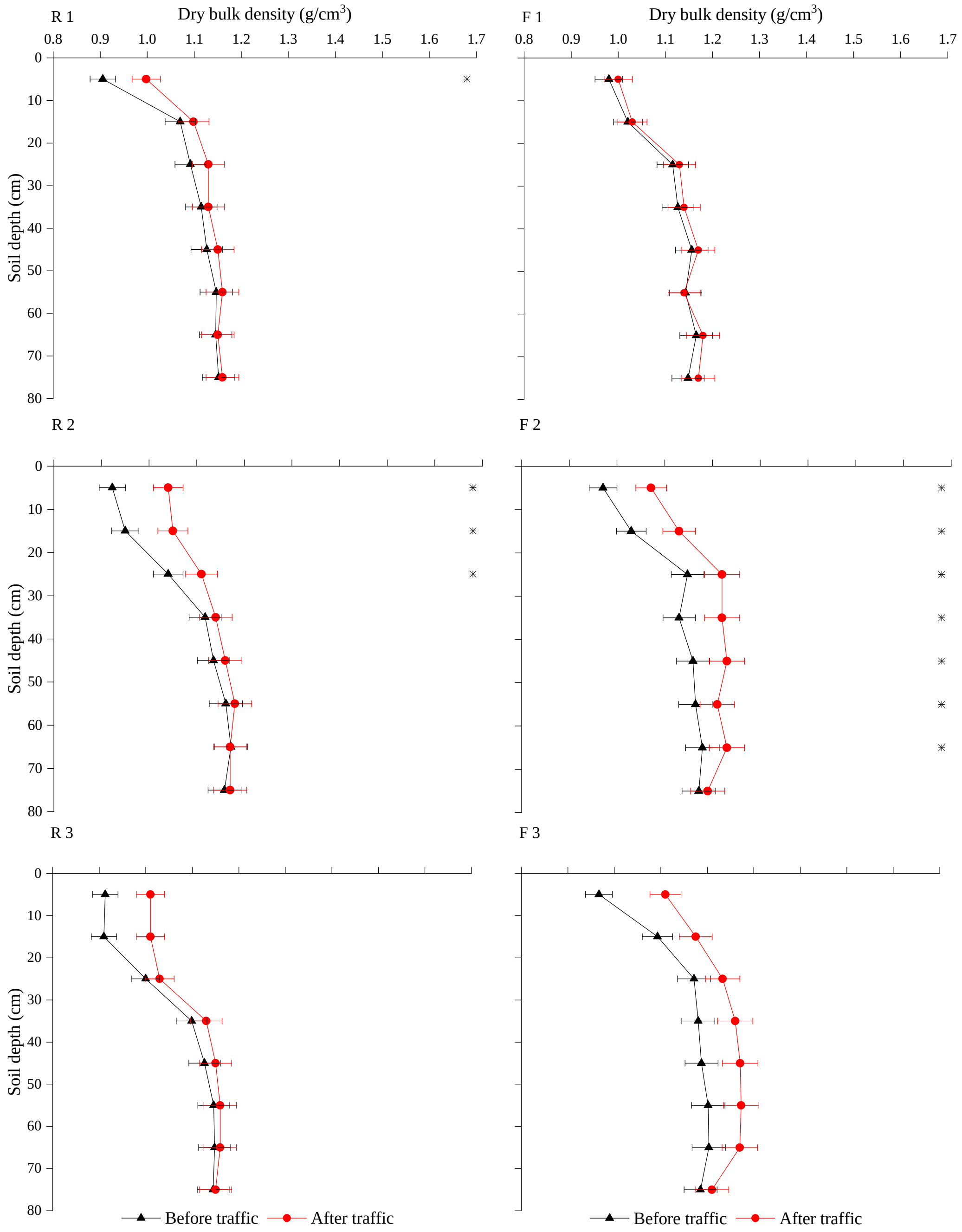


Figure 6.2: Before and after traffic comparison in *Pb* at individual cotton rows and furrows at Koarlo in 2016

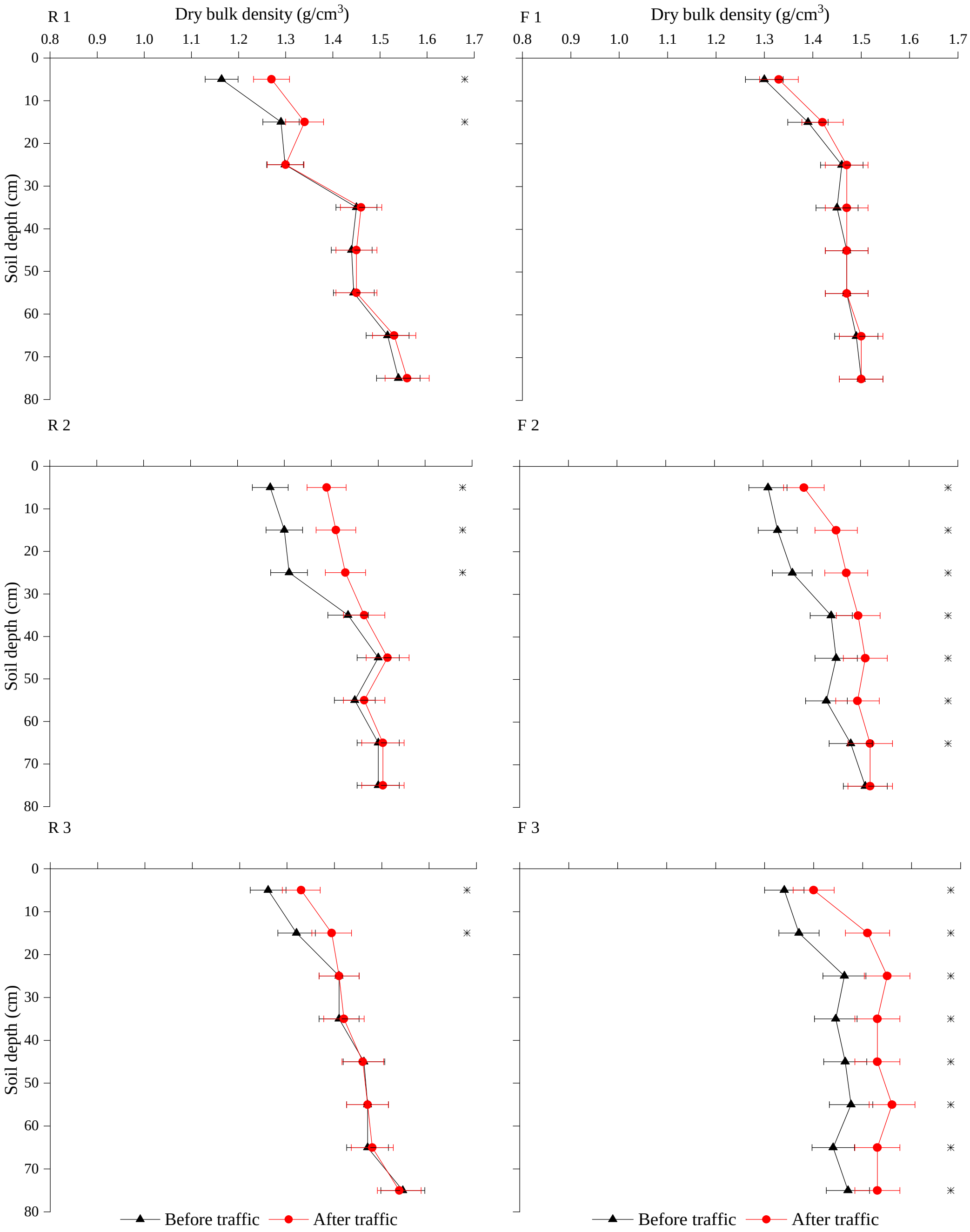


Figure 6.3: Before and after traffic comparison in *Pb* at individual cotton rows and furrows at Koarlo in 2017

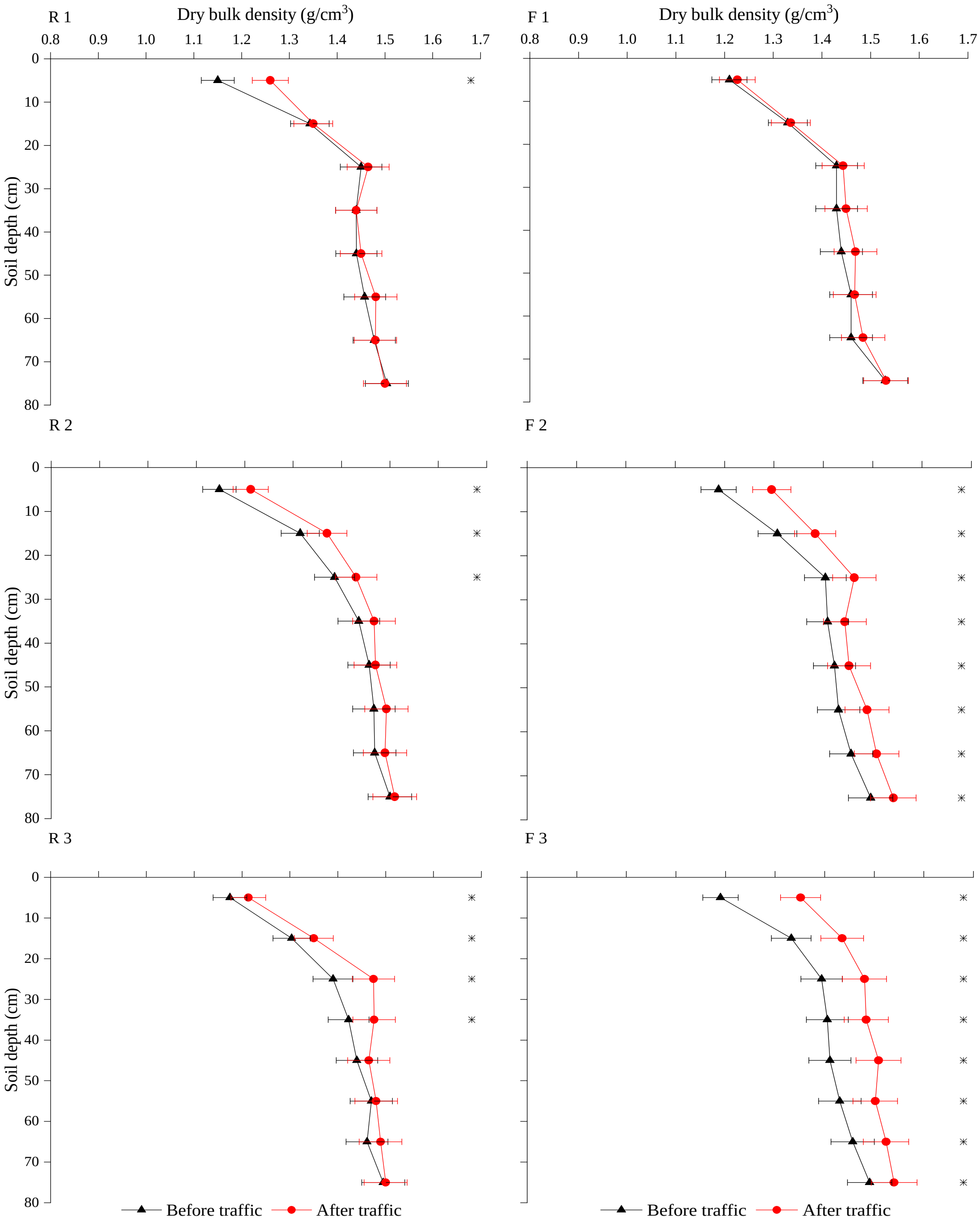


Figure 6.4: Before and after traffic comparison in *Pb* at individual cotton rows and furrows at Undabri

6.3.2. Controlled traffic farming

Figure 6.5 shows that harvester traffic caused no significant difference in *Pb* in Row 1 throughout the 0–80 cm soil depth, suggesting that the space between Row 1 and the traffic lane was sufficiently wide to protect the soil's structural arrangement. The results also reveal that, after one pass of the CTF7760 harvester, *Pb* increased significantly in Row 2 and Row 3, from 1.18 to 1.24 g/cm^3 and from 1.29 to 1.35 g/cm^3 in the 0–10 cm and 0–30 cm depths respectively (Figure 6.5). This was because the permanent traffic lane was located between Row 2 and Row 3. This implies that traffic from the CTF harvester induced significant compaction that had led to increased soil strength in the wheel track which expanded to reach neighbouring cotton rows, and thereby increased *Pb*. Furrow 1 and Furrow 2 did not show a significant difference in *Pb* throughout the 0–80 cm depth due to traffic. Moreover, one pass from the CTF7760 caused significant compaction in Furrow 3, which then led to an increased *Pb* from 1.42 to 1.52 g/cm^3 for the 0–80 cm depth. This was because Furrow 1 and Furrow 2 were not subjected to harvester traffic compared with Furrow 3 (Figure 5.17).

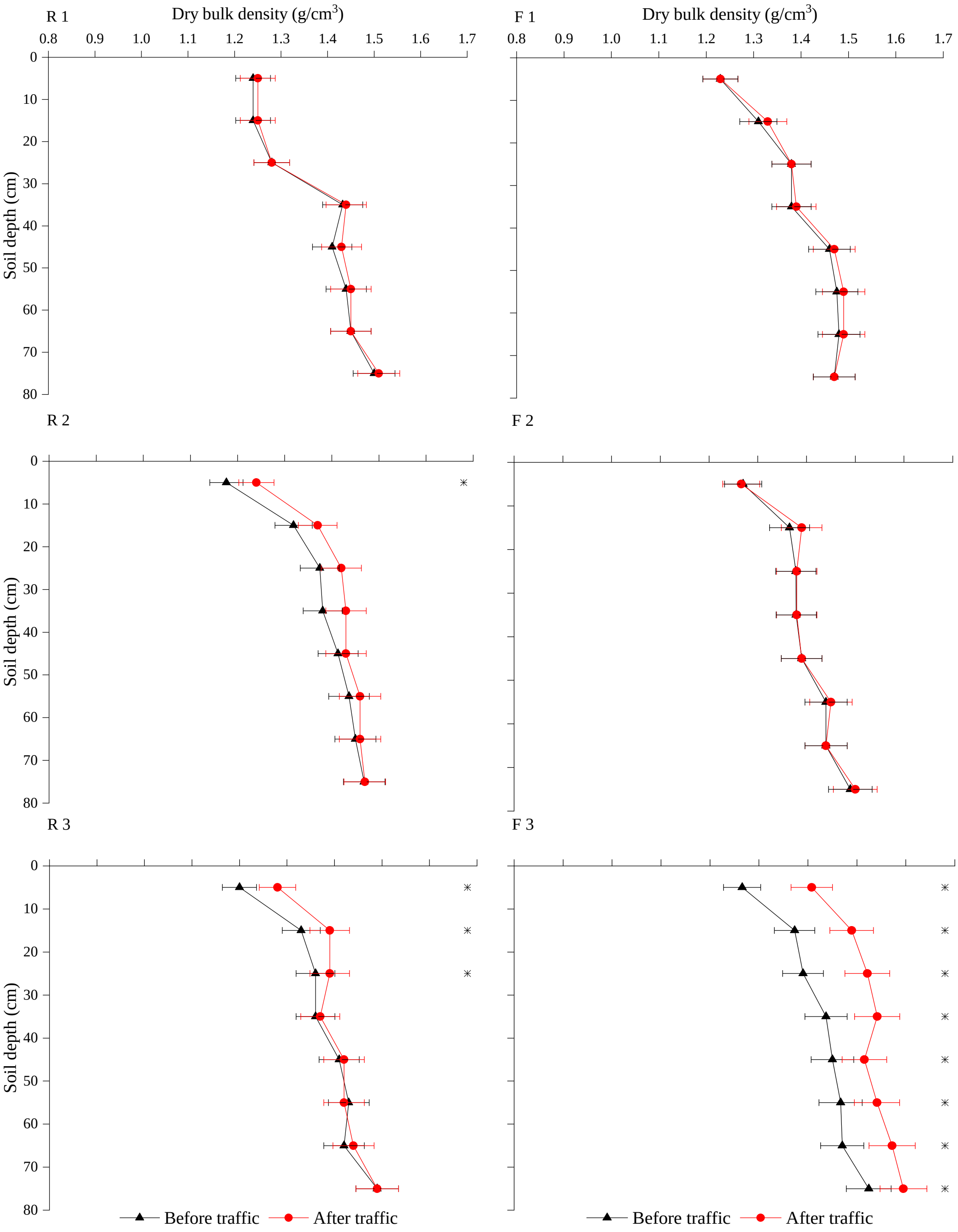


Figure 6.5: Before and after traffic comparison in *Pb* at individual cotton rows and furrows at Yambacully

6.4. The influence of JD7760 harvester traffic effect on soil penetration resistance at different soil depths

6.4.1. Random traffic farming

Overall, soil penetration resistance (SPR) showed a similar trend to *Pb* across the study areas. It can be seen from Figures 6.6 and 6.7 that SPR significantly increased in Row 1 after harvester traffic, by approximately 30% and 61% at Koarlo and Undabri in the 0–10 cm and 10–20 cm depths respectively. This was because the outer wheel traffic induced significant compaction in the wheel track, which resulted in increased soil strength that spread to Row 1.

After traffic, Row 2 in both Koarlo and Undabri showed a significant increase in SPR (45% and 50%) in the 0–30 cm and 10–40 cm depths respectively. This was because Row 2 was compressed by the dual-wheels which led to a change in the soil’s structural arrangement and increased SPR as a result. Row 3 also showed an increase in SPR after one pass of the JD7760 at both Koarlo and Undabri, by approximately 42% and 71%, respectively, in the 0–20 cm and 0–30 cm depths compared to before traffic (Figures 6.6 and 6.7). This was because the inner wheel and rear tyre traffic induced significant compaction in the wheel track, which resulted in increased soil strength that expanded to reach Row 3 (Braunack et al., 2012).

Furrow 1 at both sites did not show any significant difference in SPR for the 0–70 cm soil depth after traffic, because Furrow1 was not subjected to harvester traffic. Furthermore, for Koarlo, traffic from the JD7760 standard caused significant compaction that led to increased SPR in Furrow 2 and Furrow 3, to approximately 3435 kPa at the depth of 0–70 cm. SPR increased by 60% and 30% in Furrow 2 and Furrow 3 at Undabri throughout the 0–70 cm depth (Figures 6.6 and 6.7), which reveal that Furrow 2 and Furrow 3 were trafficked furrows under RTF.

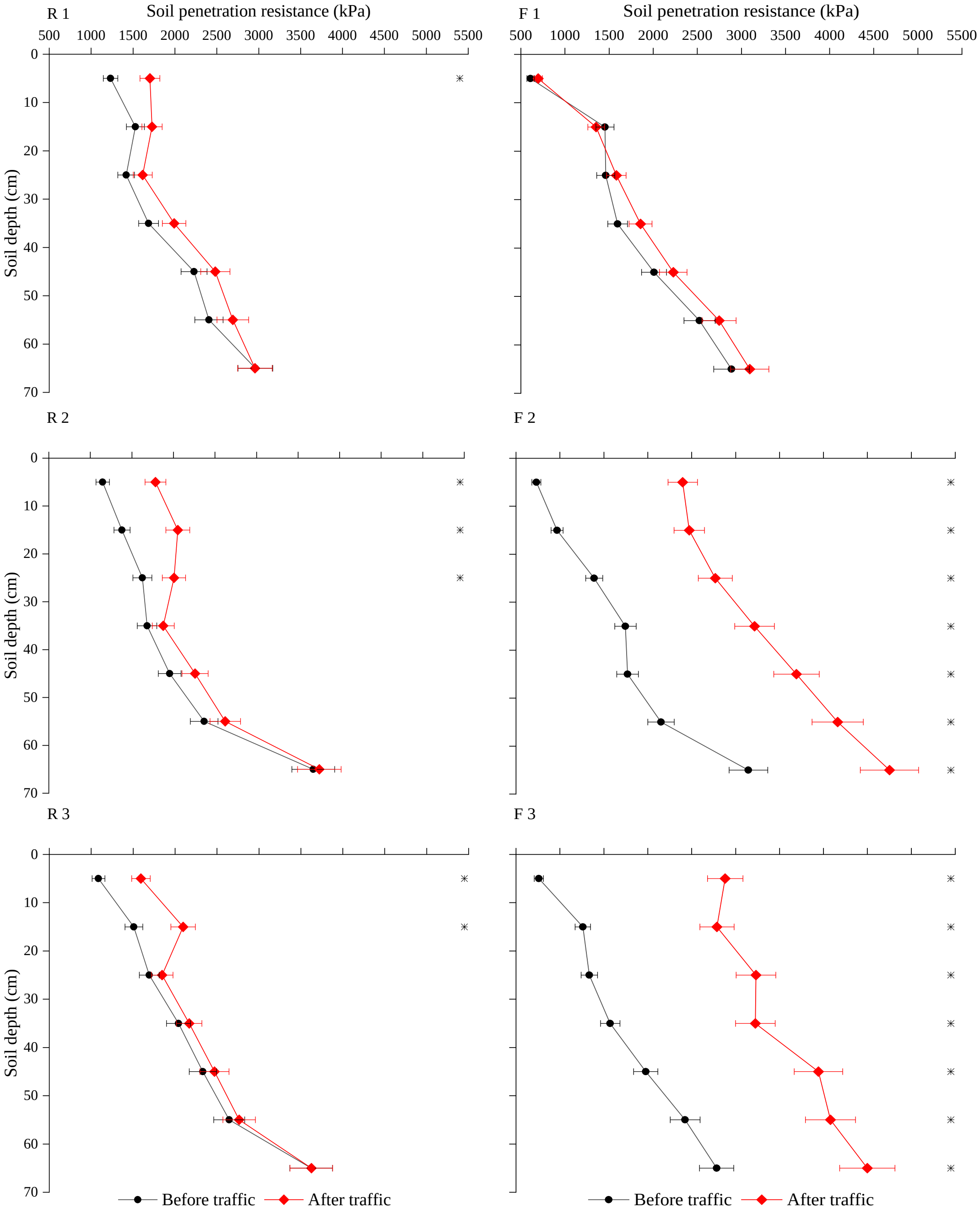


Figure 6.6: Effect of the JD7760 traffic on soil penetration resistance at Koarlo

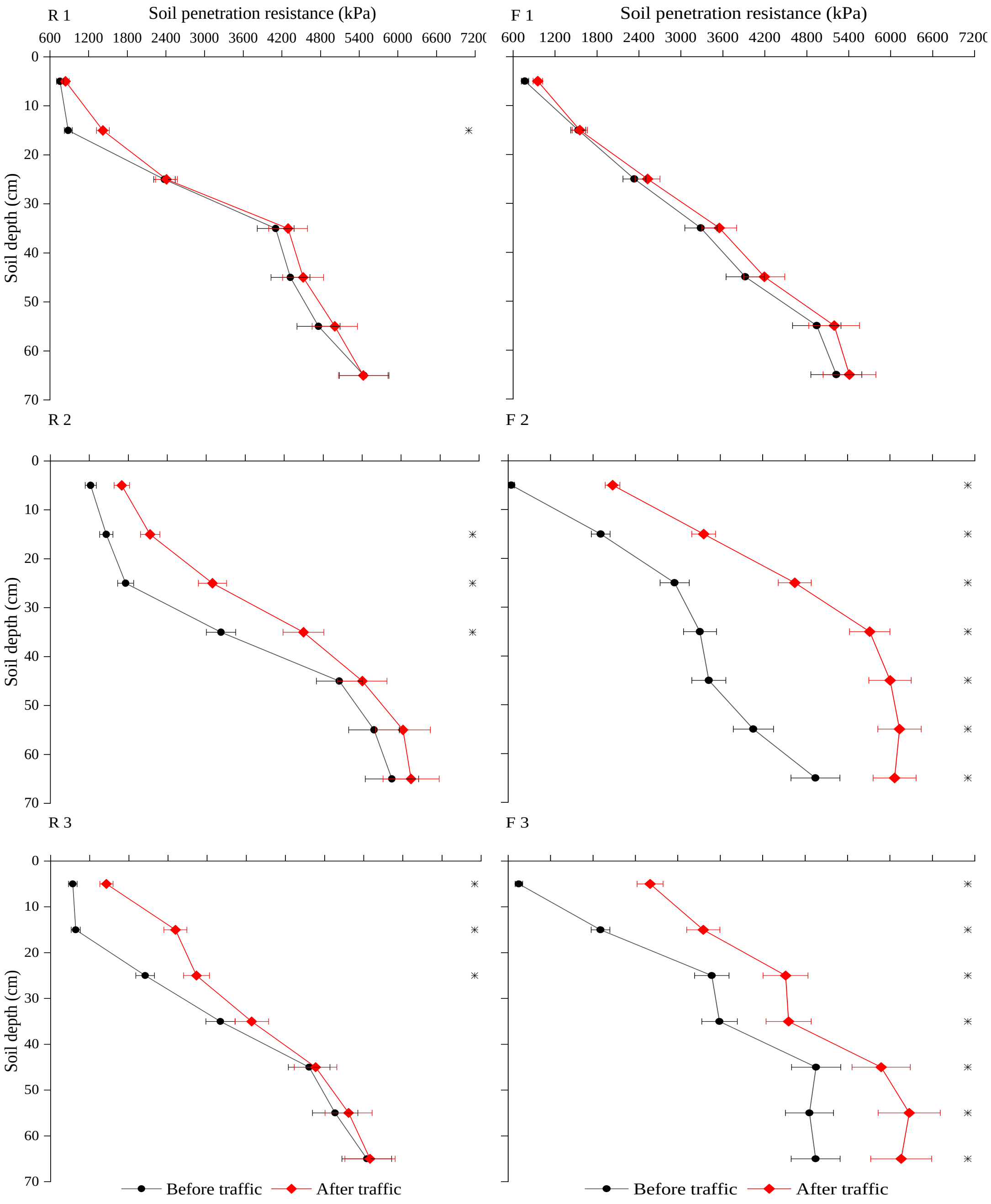


Figure 6.7: Effect of the JD7760 traffic on soil penetration resistance at Undabri

6.4.2. Controlled traffic farming

Figure 6.8 shows no significant difference in SPR in Row 1 after the CTF7760 harvester traffic throughout the 0–70 cm depth, suggesting that the space between Row 1 and the traffic lane was wide enough to protect the soil's structural arrangement. Soil penetration resistance increased significantly in Row 2 and Row 3, by approximately 90% for the 0–10 cm and 0–30 cm depths after harvester traffic. This was because the permanent traffic lane was between Row 2 and Row 3. Where traffic from the CTF7760 harvester occurred, significant compaction resulted in increased soil strength in the wheel track, which spread to adjacent rows.

Furthermore, the CTF7760 harvester traffic did not result in a significant difference in SPR in Furrow 1or Furrow 2 throughout the 0–70 cm depth compared to before traffic, suggesting that these furrows were not subjected to the harvester traffic. Significant compaction was observed in Furrow 3 after one pass of the CTF7760 harvester which increased SPR from 1801 to 3444 kPa at the depth of 0–60 cm (Figure 6.8). This indicates that traffic from the JD7760 induced significant compaction, which resulted in increased SPR in the trafficked furrows, regardless of RTF or CTF.

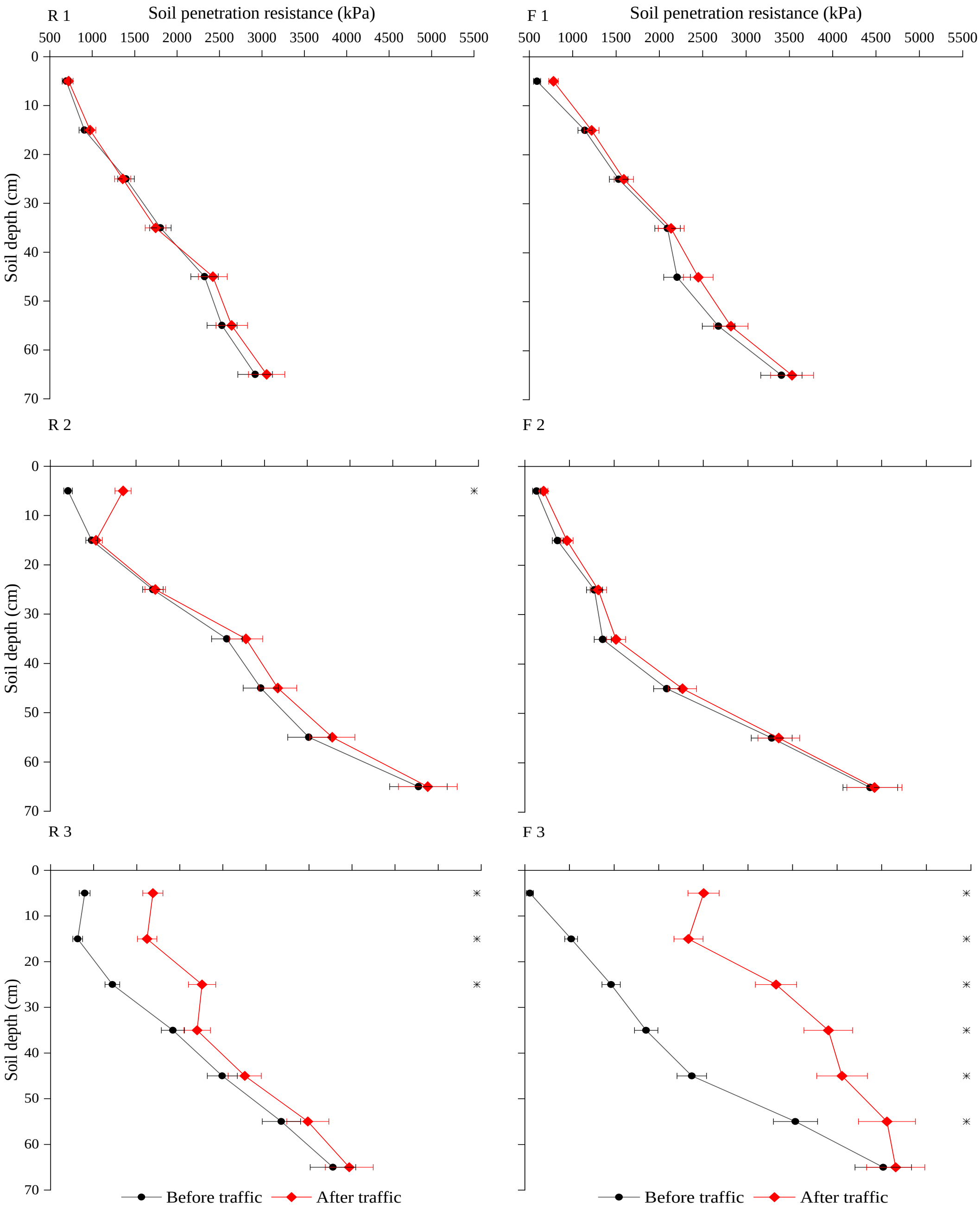


Figure 6.8: Effect of the CTF7760 on soil penetration resistance at Yambacully

6.5. Discussion

6.5.1. The impact of traffic system on *Pb* at different soil depths

Antille et al. (2015a) and Bennett et al. (2017) found that, with both RTF and CTF, traffic from the JD7760 harvester produces significant compaction when the soil water content is about 20.15% and tyre inflation pressure is at the recommended level. The main differences between the two systems are that: (1) around 50% of furrows are subjected to harvester traffic under the CTF7760 harvester; (2) approximately 66% of furrows are subjected to traffic under the JD7760 standard (Bennett et al., 2016).

This study found that one pass of the JD7760 standard configuration resulted in an increased *Pb* in Row 1, by 10%, 7% and 10% for Koarlo (in 2016 and 2017) and Undabri at the 0–10 cm and 0–20 cm depths. By contrast, Row 1 under CTF did not show any increase in dry bulk density throughout the 0–80 cm depth. This was because Row 1 under RTF was subjected to traffic of the outer dual-wheel which resulted in increased soil strength and reduced porosity in the wheel track that spread to the adjacent rows (Braunack et al., 2012). At the same time, the space between Row 1 and the traffic lane under CTF played a significant role in providing protection to the soil's structural arrangement (Bennett et al., 2017).

The current study demonstrates that, under both RTF and CTF, Row 2 and Row 3 were affected by harvester traffic. After traffic, Row 2 in Koarlo (2016 and 2017) showed an increase in *Pb* by 10% in the top 30 cm layer of the soil, while a 5% increase in Row 2 was observed at Undabri and Yambacully in the depths of 0–30 cm and 0–10 cm, respectively. In addition, *Pb* increased significantly in Row 3 after one pass of the JD7760 standard configuration, by 10% and 6% for Koarlo in 2016 and 2017 in the 0–20 cm soil depth, while it increased by 4% in Row 3 at Undabri throughout the 0–40 cm depth. A significant increase in *Pb* was also found in Row 3 under the CTF Yambacully from 1.30 to 1.35 g/cm^3 in the 0–30 cm depth.

These outcomes suggest that the inner and outer dual-wheel traffic of the JD7760 standard configuration compressed the sides of Row 2 in both Koarlo and Undabri, while Row 3 was influenced by the combined effect of the inner dual-wheel and rear wheel traffic. Conversely, for CTF at Yambacully, the permanent traffic lane was between Row 2 and Row 3. Consequently, traffic from the JD7760 harvester (regardless of traffic system) generated significant compaction, which then resulted in increased soil strength in the wheel track, which spread to the adjacent cotton rows (Braunack et al., 2012; Antille et al., 2016; Bennett et al., 2017).

Comparison of *Pb* before and after traffic in Furrow 1 did not show any significant difference for the Koarlo or Undabri sites throughout the 0–80 cm soil depth. There was also no difference in *Pb* in Furrow 1 and Furrow 2 at Yambacully after a single pass of the CTF7760 harvester because they were not subjected to wheel traffic in both systems during harvesting (Bennett et al., 2019). Traffic from the JD7760 standard configuration induced significant compaction which resulted in increased *Pb* in Furrow 2 and Furrow 3 for Koarlo and Undabri by 5% for the depth of 0–70 cm. Following the same trend, after one pass of the CTF7760 harvester, *Pb* significantly increased in Furrow 3 after one pass of the CTF7760 harvester, from 1.42 to 1.52 g/cm^3 for the 0–80 cm depth. This indicates that traffic from the JD7760 induced significant compaction, which resulted in an increased *Pb* in the trafficked furrows, regardless of RTF or CTF (Goutal et al., 2013; Bennett et al., 2017). Overall, the key findings of current investigations are:

- Traffic from the JD7760 caused significant compaction irrespective of the traffic system (RTF and CTF), which led to an increased *Pb* in the neighbouring rows and in the wheel track in the surface and sub-surface layers

- There was no significant difference in *Pb* in Row 1 after one pass of the CTF7760 harvester. The *Pb* of Row 1 under CTF was 7% lower in the surface layer than under RTF

- Row 2 was most sensitive to harvester traffic under RTF. Up to 5% higher *Pb* was recorded under RTF than CTF

- After one pass of the JD7760 standard harvester, dry bulk density significantly increased by 9%, 11% and 7% in Row 1, Row 2 and Row 3, respectively, in the surface layer

- Dry bulk density in Row 2 and Row 3 slightly increased by 5% in the 0–10 cm and 0–30 cm depths after the CTF7760 harvester traffic

- No significant difference in *Pb* in Furrow 1 was recorded under for either CTF or RTF throughout the 0–80 cm depth

- Furrow 2 under CTF at Yambacully was not subjected to compaction by wheel traffic and showed 8% lower *Pb* than under RTF throughout the studied depth

- Under both farming systems (CTF and RTF), Furrow 3 was most sensitive to harvester traffic. Furrow 3 showed approximately 7% higher *Pb* than Furrow 1 and Furrow 2 throughout the 0–80 cm depth.

6.5.2. The effect of harvester traffic on soil penetration resistance at different soil depths

Newton (2014) found that one pass of the JD 7760 picker can double SPR at different soil depths. In this study, the experiment results revealed that, after harvester traffic, SPR increased significantly in Row 1, by 30% and 61% at Koarlo and Undabri in the 0–10 cm and 10–20 cm depths, respectively. At the same time, harvester traffic did not significantly affect SPR in Row 1 under the CTF at Yambacully. This was because, at both Koarlo and Undabri, the outer dual-wheel traffic caused increased soil strength and reduced porosity in the wheel track which spread to Row 1. The space between Row 1 and the traffic lane at the CTF site played a significant role in providing protection for the soil’s structural arrangement (Braunack et al., 2012; Bennett et al., 2017).

Row 2 in both Koarlo and Undabri sites experienced a significant increase in SPR, by 45% and 50% for the 0–30 cm and 10–40 cm depths, while it increased by 42% and 71% in Row 3 in the top 30 cm layer of the soil due to harvester traffic. Following the same trend, SPR showed a significant increase in Row 2 and Row 3 after one pass of the CTF7760 harvester, by 90% in the 0–10 cm and 0–30 cm depths, respectively. This observation was because Row 2 under RTF was compressed by the dual-wheels during harvest traffic, which led to changed soil's structural arrangement. Row 3 was influenced by the inner front wheel and rear wheel traffic, which induced significant compaction in the wheel track that resulted in increased soil strength that reached Row 3. On the other hand, the permanent traffic lane under CTF was between Row 2 and Row 3, where harvester traffic caused significant compaction, which also reached the adjacent cotton rows (Row 2 and Row 3) and increased SPR as a result (McGarry et al., 1997; Braunack et al., 2012; Antille et al., 2016).

The results also reveal that, at both Koarlo and Undabri, SPR did not vary significantly in Furrow1 at the 0–70 cm depth after traffic, suggesting that Furrow1 was not subjected to wheel traffic during harvesting (Bennett et al., 2016). In addition, traffic under CTF conditions did not cause any signficant difference in SPR in both Furrow 1 and Furrow 2 throughout the 0–70 cm depth. This suggests that adopting CTF contributed to compaction avoidance and the minimisation of soil structural damage through restricted traffic lanes (Antille et al., 2016).

As would be expected, throughout the entire Koarlo profile, traffic from the JD7760 standard caused significant compaction that led to increased SPR in Furrow 2 and Furrow 3 to 3435 kPa, while it increased by 60% and 30% in Furrow 2 and Furrow 3 at Undabri in the 0–70 cm depth. Significant compaction was also observed in Furrow 3 after one pass of the CTF7760 harvester which resulted in an increased SPR from 1801 to 3444 kPa in the depth of 0–60 cm. These findings indicate that traffic of the heavy harvester (regardless of the traffic system) was the main source of compaction, particularly in furrows beneath the wheel track (Antille et al., 2016; Bennett et al., 2017). In summary, the main findings of this investigation are:

- Whether the JD7760 harvester was standard or modified, soil penetration resistance showed a similar trend to Pb in terms of soil compaction. This led to a significantly increased SPR in rows and furrows adjacent and underneath the wheel track at different soil depths

- Row 1 under CTF at Yambacully was not influenced by harvest traffic and showed the lowest SPR, by >100% in the 0–70 cm depth compared to the two RTF sites

- Row 2 under RTF was most sensitive to harvester traffic, which showed a higher SPR than under CTF, by approximately 24% in the top 30 cm layer of the soil

- Traffic of the CTF7760 harvester did not affect Furrow 1 and Furrow 2. Soil's structural arrangement of about two-thirds of the site was preserved as compared to 33% of the site under RTF

- Trafficked furrows under RTF were most sensitive to harvester traffic which resulted in approximately 31% increase in SPR in the 0–70 cm depth as compared to CTF.

6.6. Conclusion

The impact of harvester traffic on soil properties at different soil depths under two different cotton farming systems (RTF and CTF) across individual rows was investigated in this chapter. It was found that one pass of the harvester, regardless of RTF or CTF, had a negative effect on soil neighbouring the wheel track. This directly affects cotton performance. It was also found that there was no significant difference in Swc throughout the 0–80 cm depth across all treatments, for both RTF and CTF, before and after traffic. Traffic from the JD7760 standard configuration resulted in significantly increased soil penetration resistance and *Pb* in Row 1 at the depth of 10 cm. There was no significant effect on Row 1 after traffic of the CTF7760 harvester throughout the 0–80 cm depth. Row 2 and Row 3 were influenced by harvester traffic under both traffic systems, which resulted in increased *Pb* and SPR in the top 30 cm layer of the soil. Furthermore, Row 2 was most sensitive to harvester traffic under RTF, which resulted in higher *Pb* and SPR in the surface soil when compared to Row 2 under CTF.

There was no significant change in *Pb* and soil penetration resistance in Furrow 1 at both RTF sites throughout the 0–80 cm depth after harvester traffic. There was also no significant change in *Pb* and SPR in Furrow 1 and Furrow 2 after CTF7760 harvester traffic. Trafficked furrows at both RTF and CTF sites were sensitive to harvester traffic resulting in significant compaction in the 0–80 cm depth. However, traffic from the CTF7760 harvester covered 33% of the farm compared to 66% for the RTF sites. In summary, Chapters 4, 5 and 6 have answered research Question 1 and achieved Objective 1. Research Question 2 and 3, and Objectives 2 and 3 will be examined in the subsequent chapter.

Chapter 7. Results and discussions: The influence of harvester traffic on cotton yield

7.1. Introduction

Chapters 5 and 6 have examined the impact of JD7760 harvester traffic on soil compaction in individual cotton rows and furrows. This chapter will discuss the results of the effect of soil compaction from different traffic systems on cotton yield row by row. In this study, cotton yield was measured at Koarlo in 2016 and 2017, and at Undabri and Yambacully in 2017. The chapter starts by presenting the results and discusion of the impact of the JD7760 harvester traffic on cotton yield row by row (7.2). The section is subdivided into two parts. First, it shows the correlation between machine-picked and hand-picked methods for all sites. Second, it discusses the yield data of each site separately. The next section (7.3) compares and discusses the effect of the two farming systems (RTF and CTF) on individual cotton yield. Section 7.4 discusses the cotton farming systems based on the overall yield. Section 7.5 examines the efficiencies of harvesters (JD7760 standard configuration and CTF7760 modified harvester) based on harvest losses. The significant and key findings are highlighted in the discussion sections of this chapter.

7.2. Cotton yield of individual rows

7.2.1. Correlation analysis between machine-picked and hand-picked methods

Two harvesting methods machine-picking (mechanically in 2016 and by CAN-BUS in 2017) and hand-picking were employed in this project. The investigations showed that there was a strong correlation between machine-picked and hand-picked methods in terms of yield data, with R^2 values of 0.78 for Koarlo in 2016, and 0.97, 0.98 and 0.93 for Koarlo, Undabri and Yambacully, respectively, in 2017 (Figure 7.1). This correlation demonstrates that two machine-picking approaches performed well and showed a good agreement with the hand-picking method. However, the regression equation was based on 3 data pairs which considered as a limitation in this study. But the regression line was valid in the sense that at least provided a rough idea about the dependency of the two picking methods.

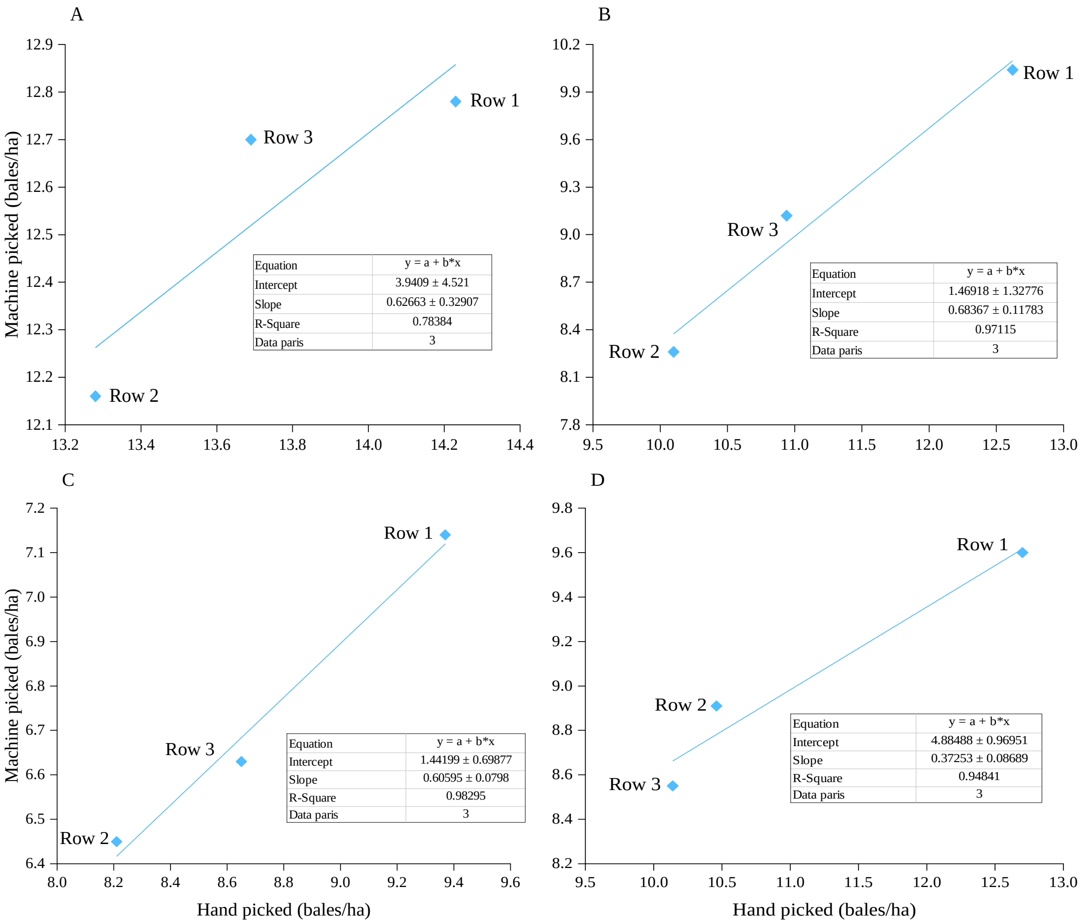


Figure 7.1: The correlation between the machined and hand-picked bales per hectare in individual cotton rows. A represents Koarlo in 2016 (mechanical method), while B, C, and D represent Koarlo, Undabri, and Yambacully in 2017 (using CAN-BUS) respectively

7.2.2. Results

In this study, lint yield was calculated to be 227 kg (500 pounds) cotton lint per ginned bale. This section compares and discusses the yield results of individual rows of each field for both the machine and hand-picked methods.The different letters (a, b and c) refer to the significant difference at P≤0.05 level between rows under the machine-picked method, while the values followed by different letters (x, y, and z) refer to significant differences (P≤0.05) for the hand-picked method.

7.2.2.1. Koarlo site

At this site, two field experiments were carried out in two different cotton fields. The first field trial was undertaken in 2016 and aimed to measure the row by row cotton yield mechanically. The second trial was conducted in 2017 and used CAN-BUS with the JD7760 to collect yield data. Figure 7.2 shows that the 2016 yield varied between cotton rows which were 12.78, 12.16 and 12.70 bales per hectare for Row 1, Row 2, and Row 3 respectively. The yield was significantly higher in Row 1 and Row 3 than in Row 2, by approximately 4%, while the yield in Row 1 did not show a significant difference when compared to Row 3. In 2017, the results revealed that Row 1 also produced a higher yield than Row 2 and Row 3, by 18% and 9% respectively, while Row 2 had a lower yield than Row 3, by approximately 10% (Figure 7.3).

Further investigations showed a similar trend for the hand-picked method in both years. Row 1 had a higher yield than Row 2, by 7% and 24% in 2016 and 2017 respectively (Figures 7.2 and 7.3). There was no significant difference in the yield in both Row 1 and Row 2 when compared to Row 3 in 2016 (Figure 7.2). In contrast, the results of 2017 indicated a lower yield in Row 2 than in Row 1 and Row 3, by 24% and 8% respectively (Figure 7.3).

These results were because the inner and outer dual-wheel traffic induced significant compaction underneath the wheel track, which led to increased soil strength that spread to neighbouring cotton rows. This influence resulted in soil structure damage and hindered root growth and, as a result, the actual yield declined. While the difference in yield between treatments was attributed to this particular effect, Row 2 was compacted by both the inner and outer dual-wheel traffic which led to increased soil strength and reduced porosity resulting in hindered root penetration and, therefore produced the lowest yield (Figure 7.4).

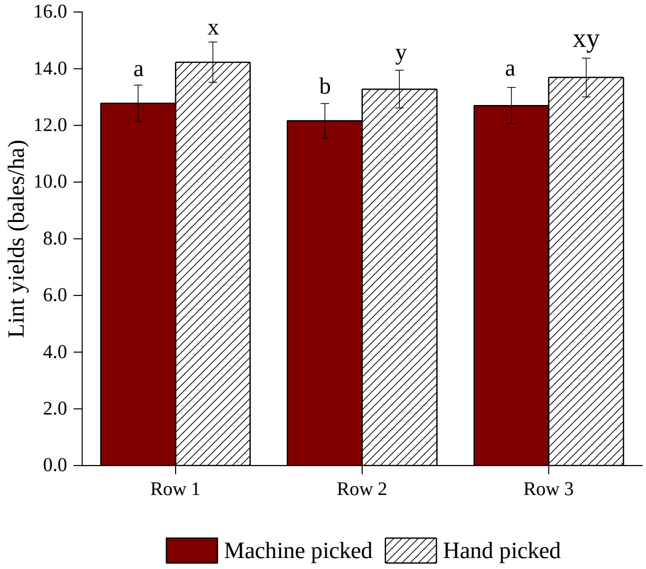


Figure 7.2: Individual cotton lint yields (bales/ha) harvested by the JD7760 and by hand at the Koarlo site during 2016

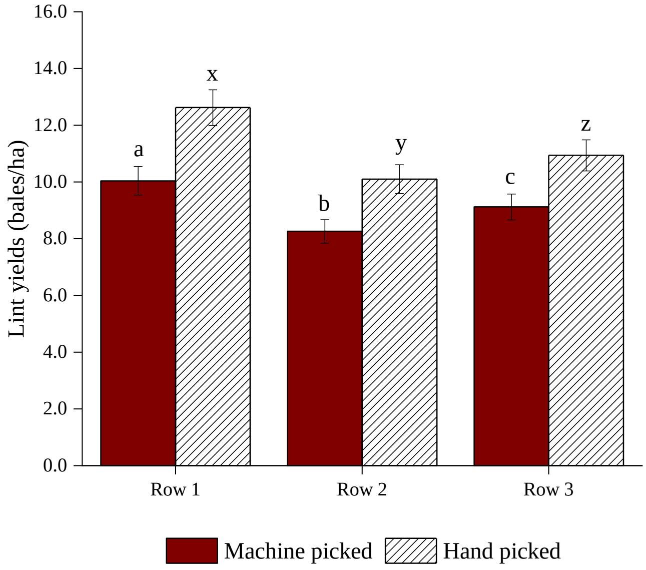


Figure 7.3: Individual cotton lint yields (bales/ha) harvested by the JD7760 and by hand at the Koarlo site during 2017

Figure 7.4: The effect of compaction on Row 2 at the Koarlo site in 2017

7.2.2.2. Undabri site

The CAN-BUS data showed that the yield in cotton rows varied between 6.63 to 7.14 bales/ha. The yield was significantly higher in Row 1 than in Row 2 and Row 3, by 10% and 7% respectively (Figure 7.5). There was no significant difference in yield between Row 2 and Row 3. The hand-picked method showed a higher yield in Row 1 than in Row 2 and Row 3, by approximately 12.3% and 7.6%. The comparison between Row 2 and Row 3 did not show a significant difference in the cotton yield (Figure 7.5). The reasons were similar to those highlighted for the Koarlo site (above).

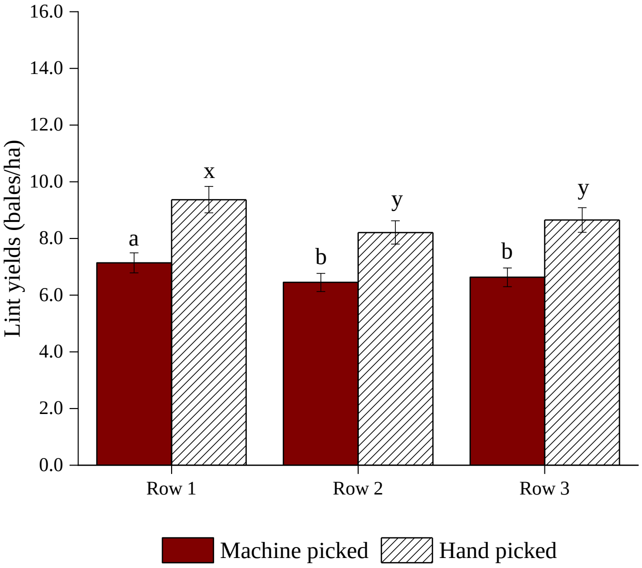


Figure 7.5: Individual cotton lint yields (bales/ha) harvested by the JD7760 and by hand at the Undabri site during 2017

7.2.2.3. Yambacully site

Figure 7.6 shows that Row 1 had a higher yield than Row 2 and Row 3, by 6% and 10% respectively. The comparison between Row 2 and Row 3 did not show a significant difference in the yield. Furthermore, the hand-picked method had a similar trend to that of the machine-picked method. Row 1 showed a significantly higher yield, by 18% and 20% than Row 2 and Row 3 (Figure 7.6). There was no significant difference in yield between Row 2 and Row 3. This suggests that the space between Row 1 and the traffic lane was sufficient to protect the soil's structural arrangement. This was reflected in the yield. Conversely, the permanent traffic lane was between Row 2 and Row 3, which resulted in increased soil strength beneath the wheel track which spread to the adjacent cotton rows. This resulted in soil deterioration and hindered root penetration, and so the yield declined (Braunack et al., 2012; McPhee et al., 2015; Bennett et al., 2017).

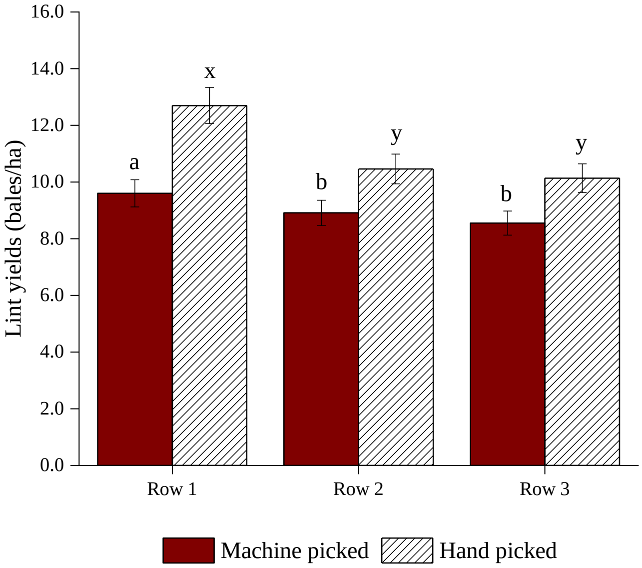


Figure 7.6: Individual cotton lint yields (bales/ha) harvested by the JD7760 and by hand with CTF Yambacully during 2017

7.2.3. Discussion

Improving cotton production is undoubtedly one of the greatest challenges facing the cotton industry worldwide. There are a number of factors that could affect cotton yield. These include farming systems used (irrigated and dryland), region, configuration of cotton rows (e.g. solid, single skip, double skip, wide row, and alternative skip), cultivar, plant stand, N, P, number of irrigations (irrigated systems) and in-crop rainfall (dryland system), season length (time between planting date and harvest date), days to defoliation and harvest method (Grzesiak, 2009; Braunack et al., 2013). In addition, irrigation water and poor land quality and fertilizer are important constraints that affect badly cotton productivity (Sheng et al., 2019). Nevertheless, soil compaction is a key source of yield decline (Hamza & Anderson, 2005). Reduction in plant growth and productivity is highly connected to the development of soil compaction (Azzi et al., 2017).

As mentioned earlier, RTF was practiced at both Koarlo and Undabri, while CTF was adopted at Yambacully. For the machine-picked method, 2016 Koarlo outcomes revealed a higher yield in Row 1 and Row 3 than in Row 2, by approximately 4%, while yield did not show any significant difference between Row 1 and Row 3. The results of Koarlo in 2017 also revealed that Row 1 achieved a higher yield than Row 2 and Row 3, by 18% and 9% respectively, while Row 2 had a lower yield than Row 3, by 10%. A similar trend was observed at Undabri, where cotton yield was significantly higher in Row 1 than in Row 2 and Row 3, by 10% and 7%, and not significantly different in yield between Row 2 and Row 3. The yield results of the hand-picked method showed a similar trend to that of the machine-picked method at both the Koarlo and Undabri sites. These results suggest that Row 2 at the two conventional sites was compacted by the dual-wheel harvester traffic, resulting in increased soil strength and reduced porosity. This hindered root growth and led to a reduction in water infiltration and nutrient uptake, thus producing the lowest yield when compared to Row 1 and Row 3 (Braunack et al., 2012; McPhee et al., 2015).

At the CTF site at Yambacully, Row 1 had a higher yield than Row 2 and Row 3, by 6% and 10% respectively, while there was no significant difference in yield between Row 2 and Row 3. This was because the space between Row 1 and the traffic lane was sufficient to protect the soil's structural arrangement, which reduced the impact of compaction and maintained the soil structure, water infiltration and nutrient uptake, which reflected positively on the yield obtained. On the other hand, the permanent traffic in the wheel track spread to the adjacent cotton rows, and yield declined when compared to Row 1 (Braunack et al., 2012; Bennett et al., 2017). Overall, the key findings of this investigaton are:

- With regards to the 2017 yield, there was a very strong correlation between hand-picked and machine-picked methods, which were R2 = 0.97, 0.98 and 93 for Koarlo, Undabri and Yambacully respectively
- At all sites, Row 1 achieved the highest yield for both CAN-BUS and hand-picked methods when compared to Row 2 and Row 3
- There was no significant difference in the yield between Row 2 and Row 3 for both harvest methods at Undabri and Yambacully
- Row 2 under RTF was the most sensitive to harvester traffic and produced the lowest yield when compared to Row 1 and Row 3
- Row 2 and Row 3 under CTF were affected more by harvester traffic and recorded about 10% lower cotton yield than Row 1.

7.3. The impact of traffic systems and row spacing on cotton yield

As mentioned before, RTF with 1.0 m row spacing was adopted at both Koarlo and Undabri, and both were harvested with the JD7760 standard configuration. CTF with 1.5 m row spacing was adopted in Yambacully and picked with the CTF7760 modified harvester. This section compares and discusses the outcomes of the impact of the traffic system and row spacing (1.0 m and 1.5 m) on the cotton yield, row by row, between the study areas for both the machine and hand-picked methods in 2017.

7.3.1. Traffic impact on the yield of Row 1

Figure 7.7 shows that there was no significant difference in the Row 1 yield at Koarlo and Yambacully. Row 1 in both Koarlo and Yambacully achieved a higher yield than Row 1 in Undabri, by 29% and 34% respectively. A similar trend was found for the hand-picked method, where Row 1 in Koarlo showed a significantly higher yield (25%) than Row 1 at Undabri. No significant difference was observed between Koarlo and Yambacully. As would be expected, the Row 1 yield was significantly lower (26%) at Undabri than Yambacully.

These results may be explained by the fact that, in general, 1.0 m row spacing produces a higher yield than 1.5 m spacing assuming there is no impact of the JD7760 traffic (Bennett et al., 2017). On the other hand, adopting CFT requires that all machinery be modified to have the same track width in order to restrict the wheel traffic to the permanent lanes. This implies that the space between Row 1 and the traffic lane under the CTF was sufficient to protect the soil's structural arrangement. This resulted in improved soil properties, increased water infiltration, and nutrient uptake, and thus the actual yield increased compared to RTF.

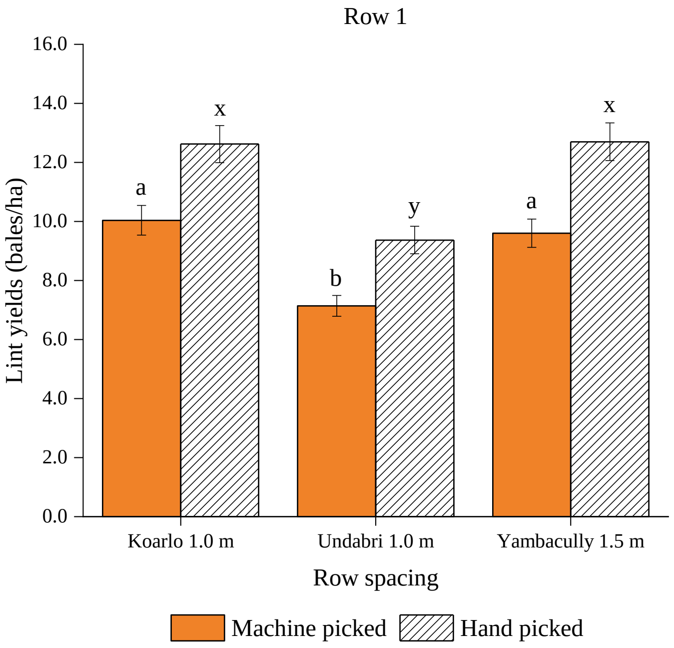


Figure 7.7: The impact of a traffic system (RTF and CTF) on cotton lint yields (bales/ha) in Row 1, which was harvested by the JD7760 standard, the CTF7760 modified, and by hand during 2017

7.3.2. Traffic impact on the yield of Row 2

Figure 7.8 shows that Row 2 produced a lower yield at Undabri than at both Koarlo and Yambacully, by 41% and 38% respectively. Row 2 did not show any statistical difference in yield between Koarlo and Yambacully. Furthermore, the hand-picked method also demonstrated a similar trend to that of the machine-picked method, where Row 2 in Undabri had a lower yield than Row 2 in Koarlo and Yambacully by approximately 25%. There was no significant difference in yield between Koarlo and Yambacully. This suggests that Row 2 under RTF was subjected to compaction due to the dual-wheel traffic of the JD7760 standard configuration, which resulted in increased soil strength and *Pb* in the root region. This resulted in smaller soil pores, lack of water infiltration and nutrient uptake, and thus the yield declined.

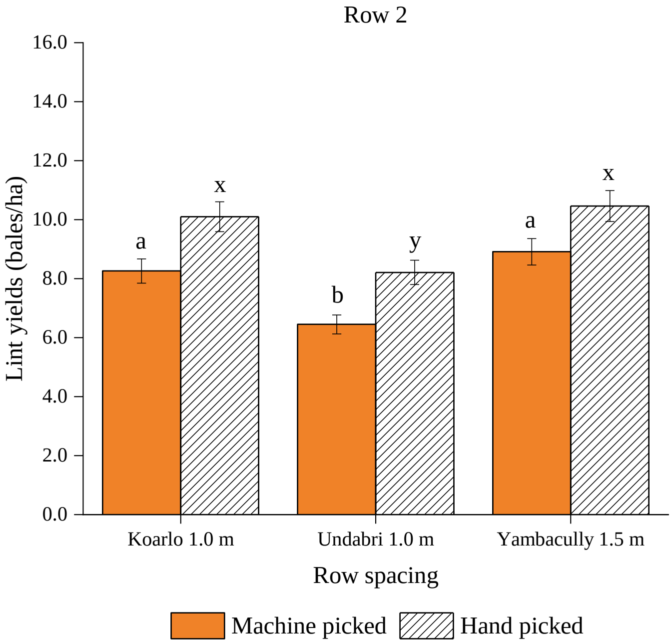


Figure 7.8: The impact of a traffic system (RTF and CTF) on cotton lint yields (bales/ha) in Row 2, which harvested by the JD7760 standard, the CTF7760 modified, and by hand during 2017

7.3.3. Traffic influence on the yield of Row 3

Figure 7.9 shows that Row 3 in Koarlo achieved a higher yield than Row 3 in Undabri, by approximately 20% and 14% for the machine and hand-picked methods respectively. Comparison between Koarlo and Yambacully did not reveal any significant difference in yield in Row 3 for both methods. The results show that Row 3 in Undabri had a lower yield than Row 3 in Yambacully, by 22% and 14% for the machine and hand-picked methods, respectively. As mentioned, 1.0 m row spacing produces a higher yield than 1.5 m spacing assuming there is no influence of the JD7760 traffic in terms of compaction (Bennett et al., 2017). This suggests that the impact of random machinery traffic was evident in Undabri, which was reflected in the lower yield of Row 3. This outcome was more obvious in Undabri than in Koarlo when compared to CTF at Yambacully.

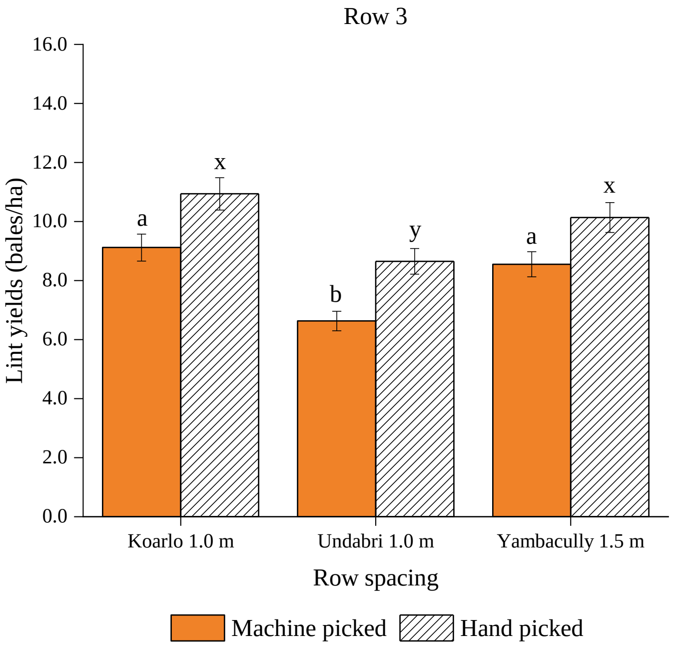


Figure 7.9: The impact of a traffic system (RTF and CTF) on cotton lint yields (bales/ha) in Row 3, harvested by the JD7760 standard, the CTF7760 modified, and by hand during 2017

7.3.4. Discussion

Trafficked middle rows are usually the areas of the field which are subject to the most intensive farm machinery traffic. They typically have *Pb* higher than nearby untrafficked middle rows or areas under the row. Compaction due to machinery traffic reduces pore space and increases soil strength (Rosolem et al., 2002; Lampurlanés & Cantero-Martinez, 2003). This leads to increased mechanical impedance and decreased water and oxygen availability (Ishaq et al., 2001). A high percentage of yield reduction is commonly observed with regions severely compacted by machinery traffic (Marshall et al., 2016; DeJong-Hughes, 2017). It was found that about one-third of yield decline occurs when soil profile is subjected to considerable compaction (Daniells, 1989). Compaction, due to harvest traffic, for example, causes 23% decline in cotton growth and yield (Lowry et al., 1970; Neale, 2008).

In this study, Row 1 did not show a significant difference in yield between Koarlo and Yambacully for both machine and hand-picked methods, while it produced a lower yield in Undabri than in Koarlo and Yambacully, by approximately 29% and 34% respectively. This could suggest that adopting RTF resulted in soil structure damage, which hindered root growth and led to a reduction in water infiltration and nutrient uptake, consequently the yield declined. In contrast, the space between Row1 and the traffic lane of the CTF was sufficient to protect the soil’s structural arrangement, which was reflected positively in Yambacully when compared to Koarlo and Undabri (Tullberg et al., 2007; Bennett et al., 2017).

This study also shows that the yield was significantly lower in Row 2 at both Koarlo and Undabri than at Yambacully, by about 17% and 14% for the machine and hand-picked methods respectively. This was because Row 2 under RTF was compacted by the inner and outer dual-wheel traffic of the harvester, resulting in increased soil strength, obstruction of root growth, reduction in water infiltration and nutrient uptake, and thus less yield compared to the CTF site at Yambacully (McPhee et al., 2015; Quigley, 2015).

Furthermore, Row 3 in Koarlo achieved a higher yield than Row 3 in Undabri, by approximately 20% and 14% for machine and hand-picked methods, respectively. The comparison between Koarlo and Yambacully did not show any differences in the yield of Row 3 for both harvest methods. The results revealed that Row 3 in Undabri had a lower yield than Row 3 in Yambacully, by 22% and 14% for the machine and hand-picked methods, respectively. This suggests that RTF resulted in soil structural deterioration, increased soil strength and decreased porosity and thus declined yield. However, Row 3 was influenced by the traffic of both the inner (front) and rear wheels of the JD 7760, regardless of RTF or CTF traffic, at all the study sites (Bennett et al., 2016). In summary, the main outcomes are:

- Row 1 achieved the highest cotton yield in both systems when compared to Row 2 and Row 3

- With machine picking, Row 1 in Koarlo showed a higher yield than Row 1 in Undabri and Yambacully by approximately 20% and 14%

- At Koarlo and Undabri (compared to the CTF Yambacully site), Row 2 was the most sensitive to the random traffic farming of the harvester, leading to 21% and 14% lower yield for both machine and hand-picked methods, respectively,

- For the machine-picked method, Row 3 at Undabri had a lower yield than Row 3 at Koarlo and Yambacully by 20% and 22%, respectively.

7.4. Cotton farming system assessment based on overall yield

7.4.1. Results

In this study, cotton yield was collected from individual rows and grouped to represent the average yield data. As shown in Figure 7.10, there was no significant difference in the overall yield between Koarlo (RTF) and Yambacully (CTF) for both machine-picked and hand-picked methods. The results also showed that Undabri had a lower yield than Yambacully, by 34% and 27% for the machine and hand-picked methods, respectively. This suggests that CTF with 1.5 m row spacing achieved a higher cotton yield due to the minimization of the impact of heavy machinery on the soil.

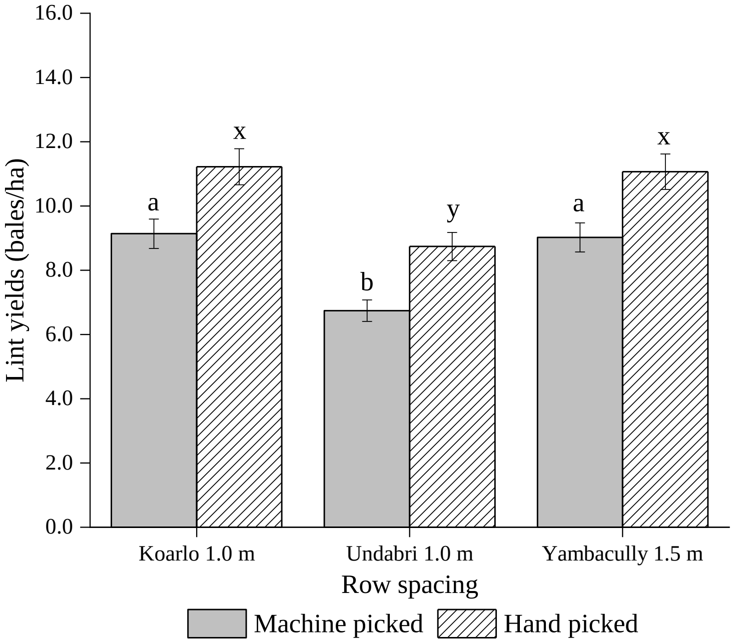


Figure 7.10: Overall cotton lint yields by machine-picked (using CAN-BUS) method and by hand-picked method from cotton grown on 1.0 m and 1.5 m row spacing in 2016/17

7.4.2. Discussion

In general, row spacing has a major effect on the potential yield as it affects the number of plants per hectare (Bartimote et al., 2017). The yield normally decreases with increased row-spacing. However, when comparing RTF and CTF, reducing soil compaction can result in an increase in yield per row (Bartimote et al., 2017). The standard and CTF JD7760 harvesters induce comparable compaction, however, the standard system affects 17% more land due to the dual wheel system (Bennett et al., 2017). Adoption of CTF using commercially available machinery reduces the cropped regions affected by traffic by more than 50% comparing RTF systems (Galambosova et al., 2017).

The current study (Figure 7.10) showed that the CTF site at Yambacully achieved a higher total yield than the RTF site at Undabri, by approximately 34% and 27% for the machine and hand-picked methods, respectively. There was only a small difference in overall cotton yield per hectare between Koarlo and Yambacully. This result demonstrates that the CTF system can achieve at least a comparative cotton yield with RTF, because compaction due to the JD7760 standard configuration under RTF with 1.0 m row spacing can decrease yield on a single row by 15%–30% (CFI, 2016). This was more obvious in Undabri than in Koarlo when compared to the CTF site at Yambacully. With CTF, wider row spacing such as a 1.5 m row can significantly improve water use efficiency, soil health and minimise energy requirements (Antille et al., 2016; Bennett et al., 2019). Furthermore, plants can access a larger amount of soil water since lower plant densities per hectare can assist in reducing water input requirements (Bartimote et al., 2017; Bennett et al., 2017).

7.5. Harvest losses

This section presents the results of: (1) harvest losses row by row for each field; and (2) harvest losses calculated in percentages as affected by the JD7760 standard and the CTF modified harvester.

7.5.1. Harvest losses within individual cotton rows of each field

7.5.1.1. Results

As mentioned above, two field trials were conducted in two different cotton fields at Koarlo in 2016 and 2017. The Koarlo data in Table 7.1 shows that harvest loss was significantly lower in Row 1 than in Row 2, by 33% and 53% in 2016 and 2017, respectively. There was no significant difference in harvest loss between Row 1 and Row 3 in 2016, while the results show a significantly lower yield in Row 1, by 39% in 2017 relative to Row 3. Furthermore, Row 2 had higher losses than Row 3 by 21% in 2016. In contrast, Row 2 had a lower loss than Row 3 by 8% in 2017.

Undabri showed a similar trend to that of Koarlo, where Row 1 had 49.9% and 40.6% lower losses than Row 2 and Row 3. No significant difference in harvest loss was found between Row 2 and Row 3. The results of the CTF site at Yambacully reveal that losses were significantly higher in Row 1 than in Row 2 and Row 3, by 33% and 36%, respectively, while Row 2 showed lower harvest losses than Row 3, by 11% (Table 7.1). These results might be because of the complex interaction between the picking unit (row units not centred on the row), travel speed and operator skill, which directly affected harvest efficiency.

Table 7.1: Harvest losses in individual cotton rows for the study sites

Site	Harvest losses (%)		
	Row1	Row2	Row3
Koarlo 2016	8.53a	11.36b	8.94a
Koarlo 2017	4.54a	6.98b	7.56c
Undabri 2017	8.05a	12.07b	11.32b
Yambacully 2017	3.72a	2.70b	2.38c

7.5.1.2. Discussion

Serious yield losses at harvest reduce the profitability of crops. However, compaction due to harvester traffic is not the only factor that affects cotton productivity. Factors that can affect picker harvesting efficiency include harvester operation and adjustment, boll distribution along the height of the plants, height above ground surface to lowest bolls, plant and seed cotton moisture content, boll type and crop maturity (Wanjura et al., 2013). In general, both delayed harvesting after cotton defoliation and harvester's condition are key reasons for increased harvest losses, which may add up to more than 20% (Khalilian et al., 1999). Harvest efficiency is considered as an important factor when evaluating the harvester's performance (Faulkner et al., 2011). Ground and plant losses and qualitative losses are not affected by increased harvesters' speed (Kazama et al., 2018). Harvest losses may be in the form of cotton left on the plants by the harvester or cotton dropped by the harvester (Kepner et al., 1972; Khalilian et al., 1999).

The current study has demonstrated that the efficiency of the JD7760, in terms of the cottonseed left, varies between the individual cotton rows. The losses were significantly lower in Row 1 than in Row 2 (for both Koarlo and Undabri) by approximately 40% and 45%. By contrast, the CTF site at Yambacully showed a higher loss in Row 1 than in Row 2 and Row 3, by 33%. However, the JD7760 harvester is capable of harvesting 95–98% of the cottonseed. This suggests that the harvester's condition and technical issues might have played a role in increasing yield losses. Another possible explanation is the harvesting of immature plants, when bolls did not open due to early frost, which also results in an increase in lost harvest (Muthamilselvan et al., 2007). The key finding were:

- At both Koarlo and Undabri, Row 1 had lower losses than Row 2, by 40% and 45%
- The CTF site at Yambacully showed a higher loss in Row 1 than in Row 2 and Row 3, by 33%.

7.5.2. Comparison between the JD7760 standard configuration and the CTF7760 modified harvester

7.5.2.1. Results

In this study, the Koarlo and Undabri study sites were harvested using the JD7760 standard with 1.0 m cotton row spacing, whilst the Yambacully site was harvested using the CTF7760 modified harvester with 1.5 m row spacing. The harvesters' efficiencies were determined based on yield losses. Figure 7.11 shows that there was a poor correlation (R^2= 0.10) between row-by-row harvest losses of the two harvesters used at Koarlo and Yambacully.

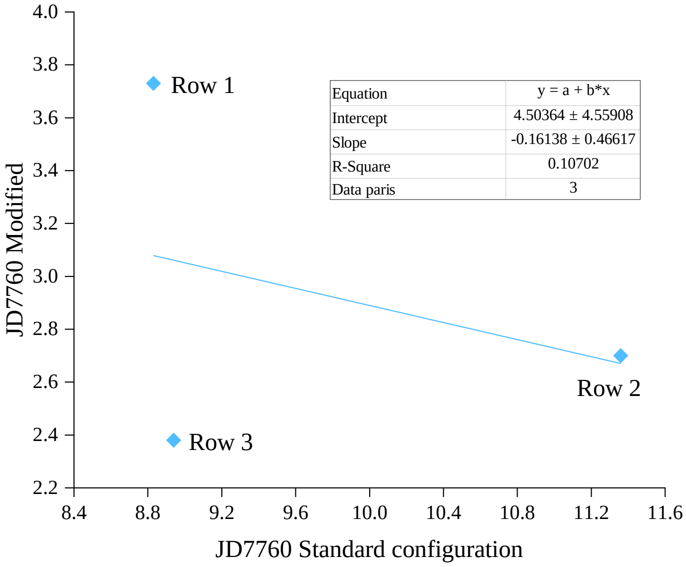


Figure 7.11: The relationship between harvest losses of the JD7760 standard (Koarlo) and the CTF7760 (Yambacully) in individual cotton rows

As shown in Table 7.2, the CTF7760 harvester showed a lower loss than the JD7760 standard at Koarlo and Undabri, by 47%, 72% and 74% for Row 1, Row 2, and Row 3, respectively. This suggests that RTF (Koarlo and Undabri) with 1.0 m row spacing might have had a higher plant density. The 1.5 m row spacing at the CTF site Yambacully played a significant role in decreasing the amount of cotton left on the field. This was because the space between the spindles of the CTF7760 harvester and cotton rows was sufficient to reduce the influence of the overlap between plants (Willcutt et al., 2010; Faulkner et al., 2011).

Table 7.2: Table 7.2: Harvest losses in individual cotton rows for the study areas. The symbol (*) represents a significant difference between the harvesters ($P \leq 0.05$)

Cotton rows	The JD7760 standard 1.0 m row spacing	The CTF JD7760 1.5 m row spacing	Sig[b]
	Koarlo 2016	Yambacully 2017	
Row1	8.53	3.72	*
Row2	11.36	2.70	*
Row3	8.94	2.38	*
	Koarlo 2017	Yambacully 2017	
Row1	4.54	3.72	*
Row2	6.98	2.70	*
Row3	7.56	2.38	*
	Undabri 2017	Yambacully 2017	
Row1	8.05	3.72	*
Row2	12.07	2.70	*
Row3	11.32	2.38	*

7.5.2.2. Discussion

Harvest efficiency is an important factor for evaluating harvester performance because it is a measure of the amount of cotton in the field that is harvested and subsequently cleaned, ginned, and made available for marketing (Faulkner et al., 2011). However, cotton pickers have lower harvest efficiencies comparing stripper harvesters, but the gains in labour efficiency have far surpassed the losses in harvest efficiency, resulting in high interest in the conversion of the global cotton industry to mechanical harvesters (Willcutt et al., 2010).

In this study, harvest efficiency of the CTF7760 and the JD7760 standard harvesters was investigated by comparing harvest losses across individual cotton rows at all sites. The results show that the CTF7760 harvester at Yambacully achieved a lower loss, by approximately 47%, 72% and 74% for Row 1, Row 2, and Row 3, when compared to the JD7760 standard at Koarlo and Undabri. Table 7.2 shows that the CTF7760 harvester had the lowest loss in Row 3 of approximately 2.3%, whilst the JD7760 standard showed the highest loss, which was 12% in Row 2 at Undabri. This indicates that the JD7760 has the ability to harvest about 95–98% of the cottonseed with high efficiency assuming no losses due to harvesters and field conditions. The 1.5 m row spacing had significantly less cottonseed left on the field because the gap between spindles of the CTF7760 harvester and cotton rows was sufficient to reduce the impact of the crop buildup between individual rows when compared to the JD7760 standard configuration (Batey, 2009; Willcutt et al., 2010). Overall, the CTF7760 harvester was superior to the JD7760 standard and showed the lowest losses by 47%, 72% and 74% for Row 1, Row 2, and Row 3 respectively.

7.6. Conclusion

Two novel methodologies (mechanically in 2016 and by CAN-BUS in 2017) have been adopted in this study to estimate cotton yields row by row. The results demonstrate that they could give accurate results for the individual row yield data of both the JD7760 standard and the CTF7760 harvester, showing a very similar trend to that of the hand-picked method.

The yields in individual rows have been compared. Significant compaction occurred after harvester traffic, particularly in the root region. This resulted in reduced cotton yield between and neighbouring the wheel track of the harvester. In particular, it has been found that Row 1 had the highest yield under both RTF and CTF. It was also found that Row 2 under RTF was most sensitive to harvester traffic which showed the lowest yield when compared to Row 1 and Row 3. Furthermore, under both systems, Row 2 and Row 3 were influenced by harvester traffic which led to a significantly lower yield than Row 1.

The measured results for the CTF site at Yambacully also achieved a higher total yield per hectare than the RTF at Undabri site, by 33%. There was only a small difference in overall cotton yield per hectare between Koarlo and Yambacully. This result demonstrates that CTF system can at least achieve a comparative cotton yield with RTF because compaction due to the JD7760 standard configuration under RTF with 1.0 m row spacing can decrease yield on a single row by 15%–30%.

Finally, it was observed that the CTF7760 modified harvester showed a lower yield loss than the JD7760 standard configuration on all cotton rows. Overall, this chapter has answered the Research Questions 2 and 3, and achieved Objectives 2 and 3. Research Question 4 and Objective 4 will be investigated in the next chapter.

Chapter 8. Soil compaction and stress modelling

8.1. Introduction

The experimental results obtained from the fieldwork in 2016 and 2017 have been discussed in Chapters 4, 5, 6 and 7. This chapter presents the results related to the simulation of soil vertical stress distribution under the wheels of both the JD7760 standard configuration and the CTF7760 cotton picker using the SoilFlex model. The chapter begins with a review of some existing soil compaction models and highlights the SoilFlex model (Keller et al., 2007), justifies the use of SoilFlex in this study, and presents the model validation and simulation method. Finally, there is a discussion of the model output and conclusion.

8.2. Soil compaction model

Compaction of the agricultural soil due to machinery is a major concern for both researchers and growers as it results in the decline of crop productivity (Rodríguez et al., 2012; Nawaz et al., 2013). In general, soil compaction models are vital for the successful management of soil properties (Schafer et al., 1991). They present the advantage of being able to assess the potential impact of traffic on production before resources and time are allocated (Reddy & Zhao, 2003). Simulation models are often improved and validated by comparing them to fieldwork data (Carberry et al., 2009). Existing compaction simulation models were reviewed in Chapter 2 (Table 2.6).

According to Defossez and Richard (2002), the framework of compaction models usually consist of two parts: (1) quantification of the propagation of loading stress due to farm machinery; and (2) validation of the modelled stress and strain behaviour. A simplified model was proposed by O'Sullivan et al. (1999), which allows for the estimation of dry bulk density along the centreline of a wheel path. This approach usually includes three key aspects: (1) the load applied by the machinery at the surface layer is simulated; (2) an analytical approach is utilised to predict how the stress is distributed in the soil profile; and (3) a set of proper soil parameters are chosen to describe the influence of compaction on soil deformation. However, this model is not recommended for specialists and researchers (O'Sullivan et al., 1999).

Terranimo® is an online computer model that can predict the risk of soil compaction by farm machinery. This software is particularly designed for growers and consultants (Stettler et al., 2014). Terranimo® is appropriate for simulating the compaction induced by a single pass of machinery. SOCOMO is another soil compaction model that was developed by Van den Akker (2004). This model is analytical, based on the hypothesis of Boussinesq (1885) that analyses the vertical stress distribution in a homogeneous, isotropic, linear-elastic and semi-infinite robust soil block, resulting from a force which is applied at a specific point on the surface of the same block. Overall, SOCOMO is weak in the valuation of stress propagation over the footprint of machinery (Van den Akker, 2004). Figure 8.1 shows the pressure distribution over a soil medium according to Defossez and Richard (2002).

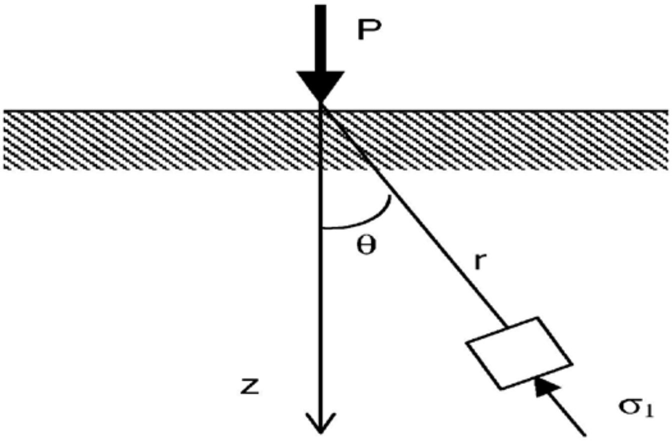


Figure 8.1: Stress distribution in a layer parallel to the surface contact area. According to Defossez and Richard (2002), equation $\sigma z = (\upsilon P/\text{л}\, r^2)\; co\overset{v}{s}$ Θ, where P= Load under a point, σ1 = Principal stress, z= depth, Θ = Internal friction angle, and r = Polar co-ordinate

Source: Adopted by the researcher from (Defossez & Richard, 2002).

SoilFlex is an analytical model, proposed and developed by Keller et al. (2007) to simulate soil compaction due to agricultural machinery traffic. It is a flexible model suitable for predicting tyre stress on the surface layer, and it can provide an accurate simulation of the contact area and the stress distribution in the contact surface from readily obtainable tyre parameters. In SoilFlex, two-dimensional models are coupled to calculate soil stresses, changes in *Pb* and the soil's vertical displacements resulting from farm machinery traffic. The model has the following three major features: (1)

describes stress in the contact area; (2) stress distribution over the soil is computed analytically; (3) allows for the calculation of soil deformation as a function of stress (Figure 8.2). Keller et al. (2007) reported that the calculation of vertical stress in SoilFlex is based on the equations of Boussinesq (1885) and Fröhlich (1934) who introduced the concentration factor. The vertical soil stress at a certain depth is calculated by summation (Söhne, 1953) as shown in Equation (1). The horizontal stress is calculated according to Janosi (1962) as given in Equation (2):

$$\sigma_{z}= \sum_{i=0}^{i=n} (\sigma_{z})_{\mathrm{i}} = \sum_{i=0}^{i=n} \frac{vPi}{2\pi r_{i}^{2}} cos^{v}\, \theta_{i}$$

Where:

σ_z = The vertical stress

P_i = Carrying the load

Z= The profile depth

V = Concentration factor

r = The space between point load and the desired point

θ = Angle between normal load and placement of the desired point

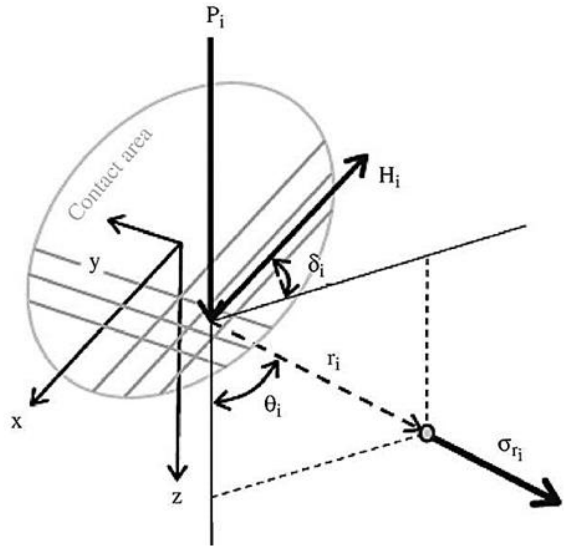


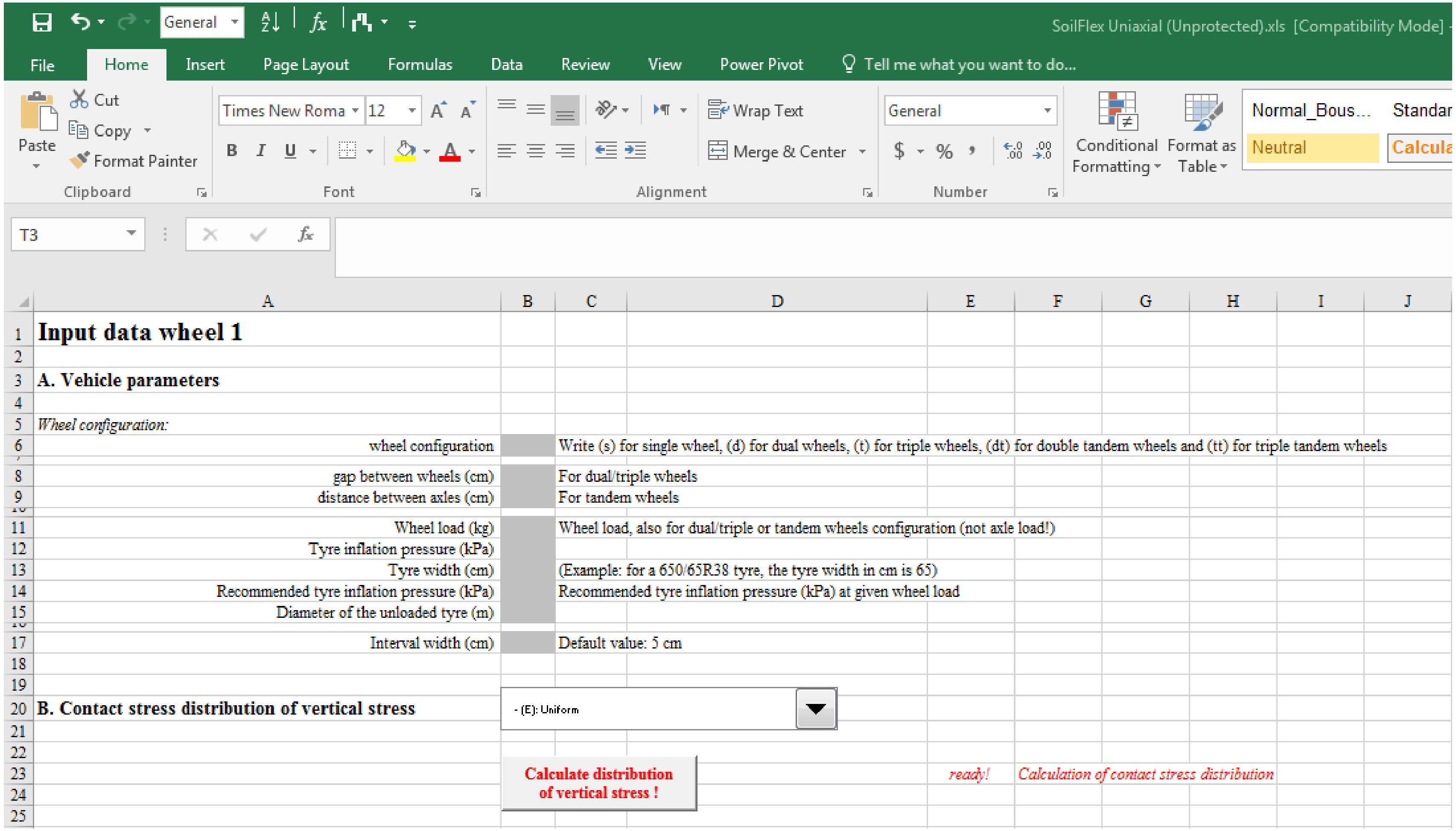
Figure 8.2: A geometric relationship for the stress computation at a required point in the soil mass, where P_i represents vertical load, and H_i represents horizontal load

Source: Adopted by the researcher from (Keller et al., 2007).

Overall, it can be seen that many models have been employed to simulate the influence of machinery traffic on soil properties and compaction state. In this study, SoilFlex was used to predict vertical stress distribution under the wheels of the JD7760 harvester under two different cotton farming systems.

8.3. Justification of SoilFlex model adopting

Several studies (Keller et al., 2007; Braunack & Johnston, 2014; de Lima et al., 2017; Bennett et al., 2019) have employed SoilFlex model to calculate the vertical stress (σz) under the wheels of harvesters. It was found that, overall, SoilFlex provides a realistic simulation of the contact area and the stress distribution in the contact area from readily available tyre parameters (Keller et al., 2007). It also allows researchers and agricultural specialists to calculate the stresses of a machine which has dual or tandem wheels which is an important aspect and an omission in other models (Keller et al., 2007; Nawaz et al., 2013). In addition, SoilFlex is a useful tool which has the ability to simulate stress distribution under the wheel of the JD7760 harvester with tyre size of 520/85R42 and 20.8-38 and an inflation tyre pressure of 270 kPa as input parameters (Braunack & Johnston, 2014). Nevertheless, the model assumes that the soil profile is isotropic throughout, which is considered a limitation in regards to modelling subsequent expected compaction without adequate calibration. But, this does not affect stress state simulation, which is a property of the machine rather than the soil (Keller et al., 2007; Bennett et al., 2016). Figure 8.3 presents the SoilFlex model interface in an Excel spreadsheet.



SoilFlex Uniaxial (Unprotected).xls [Compatibility Mode]

	A	B	C	D	E	F
1	**Input data wheel 1**					
2						
3	**A. Vehicle parameters**					
4						
5	*Wheel configuration:*					
6	wheel configuration		Write (s) for single wheel, (d) for dual wheels, (t) for triple wheels, (dt) for double tandem wheels and (tt) for triple tandem wheels			
8	gap between wheels (cm)		For dual/triple wheels			
9	distance between axles (cm)		For tandem wheels			
11	Wheel load (kg)		Wheel load, also for dual/triple or tandem wheels configuration (not axle load!)			
12	Tyre inflation pressure (kPa)					
13	Tyre width (cm)		(Example: for a 650/65R38 tyre, the tyre width in cm is 65)			
14	Recommended tyre inflation pressure (kPa)		Recommended tyre inflation pressure (kPa) at given wheel load			
15	Diameter of the unloaded tyre (m)					
17	Interval width (cm)		Default value: 5 cm			
18						
19						
20	**B. Contact stress distribution of vertical stress**	- (E): Uniform				
21						
22						
23		**Calculate distribution of vertical stress !**			*ready!*	*Calculation of contact stress distribution*
24						
25						

Figure 8.3: SoilFlex model in an Excel spreadsheet

8.4. Model validation

The model was previously validated by Keller et al. (2007), by calculating 'the vertical stress and vertical displacement of the soil' after one pass of a sugar beet harvester. The wheel load of the harvester was 86 kN with an inflation pressure of 100 kPa on soils (loam and silty clay loam) at different soil depths. The simulated stress was further compared to the measured soil stress obtained from fieldwork (Bennett et al., 2013). Keller et al. (2007) found that simulated results agreed quite well with the measured stresses.

8.5. Simulation method

In this study, SoilFlex was used to simulate the vertical stress under the wheels track of the JD7760 standard configuration and the CTF7760 modified harvester using wheel load and tyre parameters. Simulations were carried out assuming an elliptical contact area, and standard tyres with manufacturer's recommended inflation pressures (Keller et al., 2007; Bennett et al., 2019). The model was set up to calculate soil stresses for three different scenarios. The first simulated the front dual-wheel of the JD7760, the second simulated the front single wheel of the CTF7760, and the third simulated the rear tyre for both harvesters. The JD7760 standard harvester had a dual-wheel at the front, namely 520/85R42 (R1, R2) with inflation pressure of 248 kPa. The wheel load was 5430 Kg. The gap between the dual-wheels was 40 cm. The CTF7760 was modified by replacing the front dual-wheels with a single wheel of specification 620/70R42 with an inflation pressure of 340 kPa. The single wheel load was 10860 kg. Both harvesters had a similar rear wheel load (8250 kg) and tyres, namely IF580/80R34 (R1W), with an inflation pressure of 324 kPa. The wheels data for both harvesters were obtained from Wattonville (2008), Bennett et al. (2015), Antille et al. (2016) and Zimbatu (2016). Table 8.1 shows the parameters of the harvesters used to simulate vertical stress in the SoilFlex model.

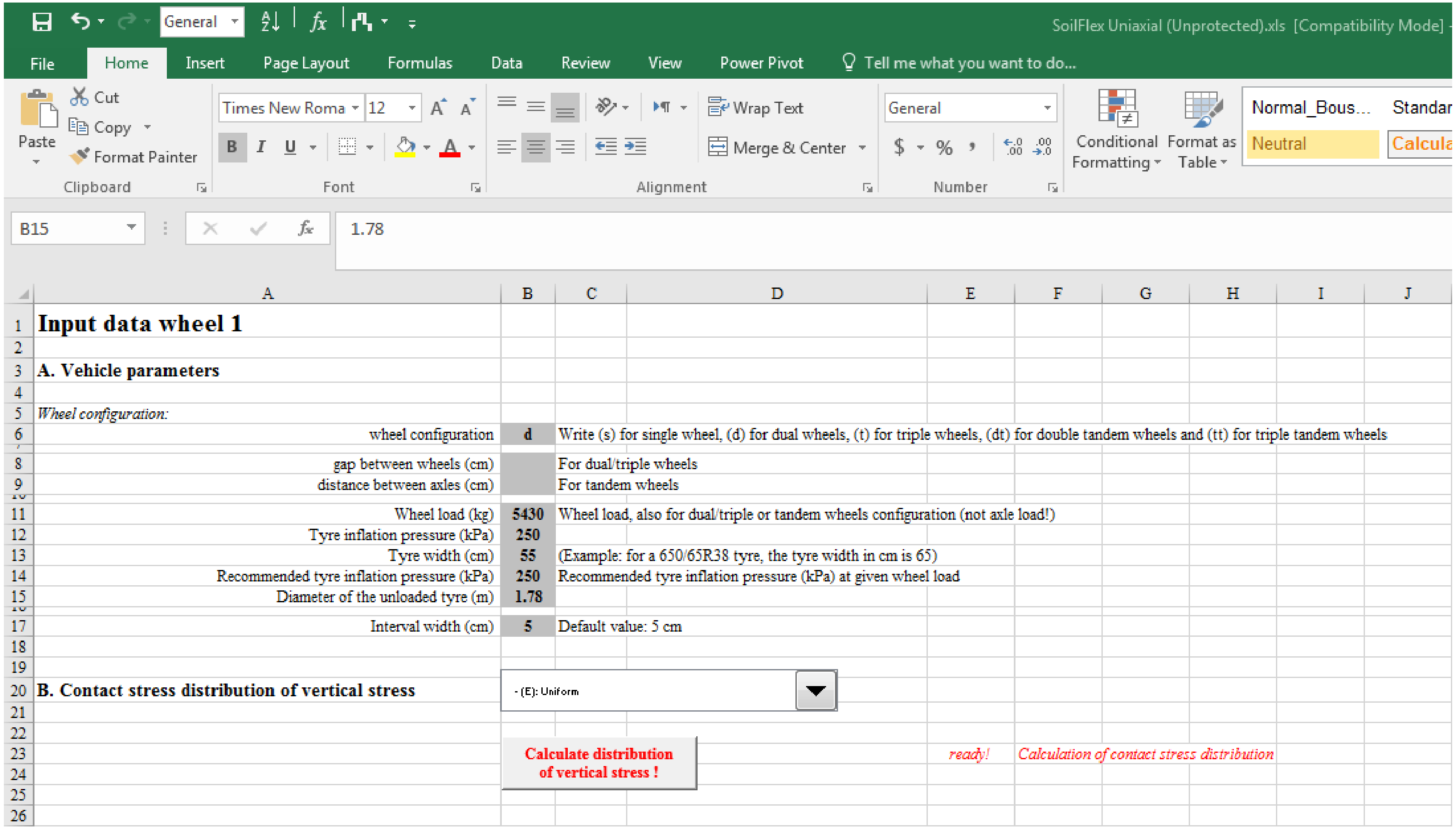
Table 8.1: The input parameters for the SoilFlex model

Parameter	Details	
John Deere 7760	Standard configuration	The CTF modified
Tyre Configuration	Dual wheel	Single wheel
The gap between wheels (cm)	40	-
Wheel load (kg)	5430	10860
Front dual drive tyres	520/85R42 (R1, R2)	620/ 70R42
Tyre infiltration pressure (kPa)	248	340
Tyre width (cm)	55	65
Unloaded tyre diameter (cm)	178	190
Rear guide wheel tyres	IF580/80R34 (R1W)	IF580/80R34 (R1W)
Rear wheel load (kg)	8250	8250
Tyre infiltration pressure (kPa)	324	324

The simulation processes were carried out after consultation with the SoilFlex's author (Keller 2016, Pers comm). The following steps show the process of calculating the soil vertical stress by SoilFlex (Keller et al., 2007):

- Entering tyre parameters and wheel configuration (tyre inflation pressure, single or dual wheel, wheel load, etc.)
- Selecting vertical stress distribution
- Choosing an elliptical contact area (E uniform)
- Confirming the command 'Calculate vertical stress distribution'
- The vertical soil stress distribution was presented in a separate Excel sheet.

Figure 8.4 shows the input data of the dual-wheel in SoilFlex.



	A	B	D	E	F
1	**Input data wheel 1**				
2					
3	**A. Vehicle parameters**				
4					
5	*Wheel configuration:*				
6	wheel configuration	**d**	Write (s) for single wheel, (d) for dual wheels, (t) for triple wheels, (dt) for double tandem wheels and (tt) for triple tandem wheels		
8	gap between wheels (cm)		For dual/triple wheels		
9	distance between axles (cm)		For tandem wheels		
11	Wheel load (kg)	**5430**	Wheel load, also for dual/triple or tandem wheels configuration (not axle load!)		
12	Tyre inflation pressure (kPa)	**250**			
13	Tyre width (cm)	**55**	(Example: for a 650/65R38 tyre, the tyre width in cm is 65)		
14	Recommended tyre inflation pressure (kPa)	**250**	Recommended tyre inflation pressure (kPa) at given wheel load		
15	Diameter of the unloaded tyre (m)	**1.78**			
17	Interval width (cm)	**5**	Default value: 5 cm		
18					
19					
20	**B. Contact stress distribution of vertical stress**	- (E): Uniform			
23		**Calculate distribution of vertical stress !**		*ready!*	*Calculation of contact stress distribution*

Figure 8.4: Input parameters of the dual wheel (JD7760 standard configuration) into SoilFlex

8.6. Simulation outcomes

8.6.1. Model validation

SoilFlex has been evaluated by Keller et al. (2007) who compared predicted and measured soil stress values and demonstrated reasonable agreement. To verify the model in this study, the trend of the simulated soil stress was compared to the pattern of soil penetration resistance (SPR) results after harvester traffic for Koarlo and Yambacully in 2017.

Figure 8.5A shows that vertical stress was higher beneath the loaded area (Furrow 2 and Furrow 3) than Furrow 1. The intersection of the stresses beneath the dual-wheels resulted in greater stress in Row 2 than Row 1 and Row 3 down to 70 cm depth. Figure 8.5B shows that the measured SPR had a similar trend to the simulated vertical stress. Furrow 2 and Furrow 3 showed a higher SPR than Furrow 1, by 73% throughout the 0–60 cm depth after one pass of the dual-wheel. Row 2 had a higher SPR than Row 1 and Row 3 at the surface layer. This indicates that Row 2 was compressed by the inner and outer wheels of the front dual-wheel, which led to significantly higher soil strength.

A similar trend between experimental and simulation results was found at the CTF site at Yambacully. The simulated vertical stress was higher in Furrow 3 (loaded area) than Furrow 1 and Furrow 2 (Figure 8.5A). Vertical stress caused by the single wheel of the CTF7760 harvester was higher in Row 2 and Row 3 than Row 1. Similarly, Figure 8.6B shows that SPR was significantly higher in the wheel track (Furrow 3) of the CTF7760 harvester than the un-trafficked furrows (Furrow 1 and Furrow 2) throughout the 0–70 cm depth. Soil penetration resistance was significantly higher in both Row 2 and Row 3 at the surface layer than in Row 1. Overall, it can be said that the simulated soil stress agreed well with the trends in the SPR values.

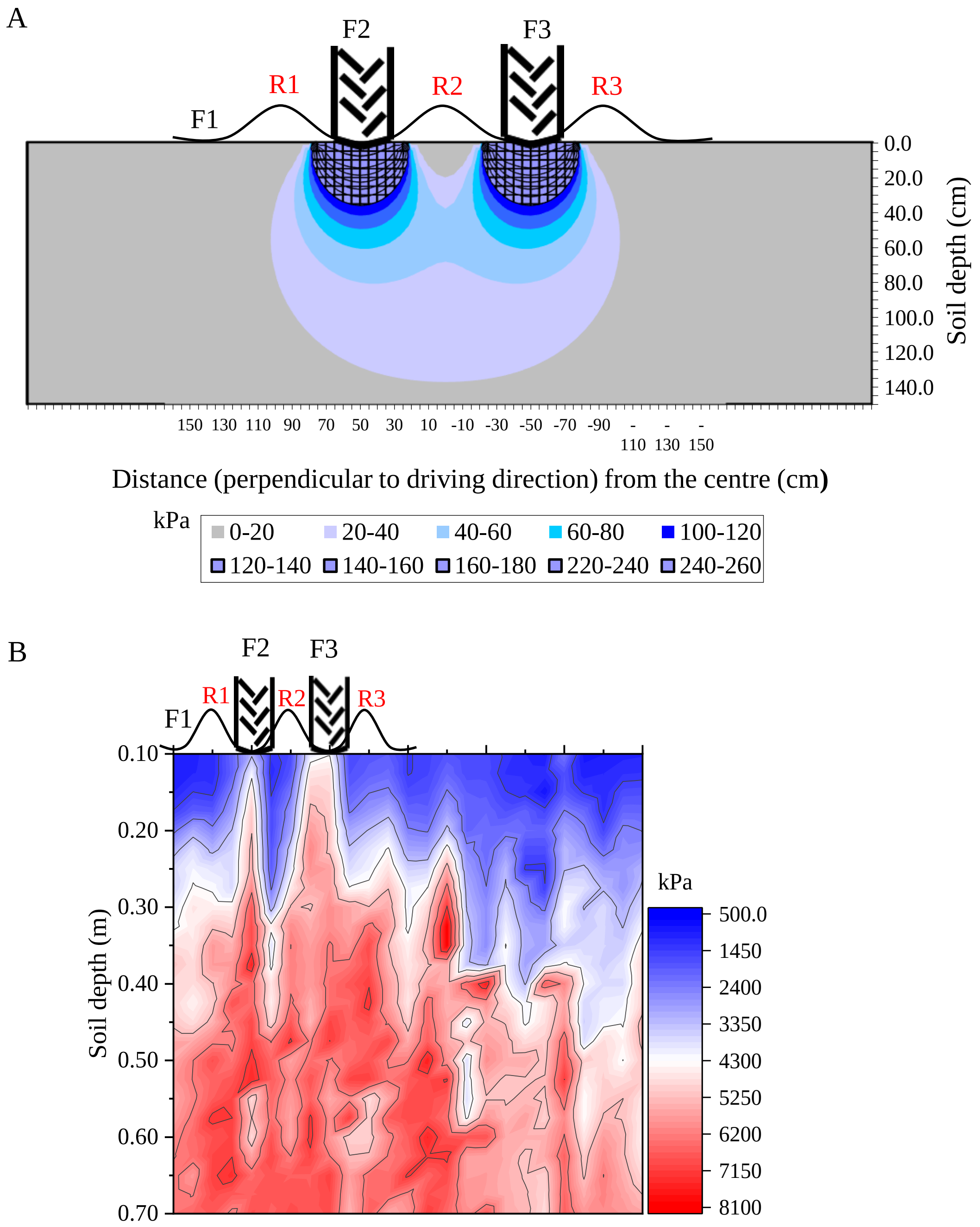


Figure 8.5: Comparison of the trend between the simulated vertical stress and soil penetration resistance results after harvester traffic (JD7760 standard). A represents the simulated vertical stress. B represents the measured soil penetration resistance at Koarlo during 2017

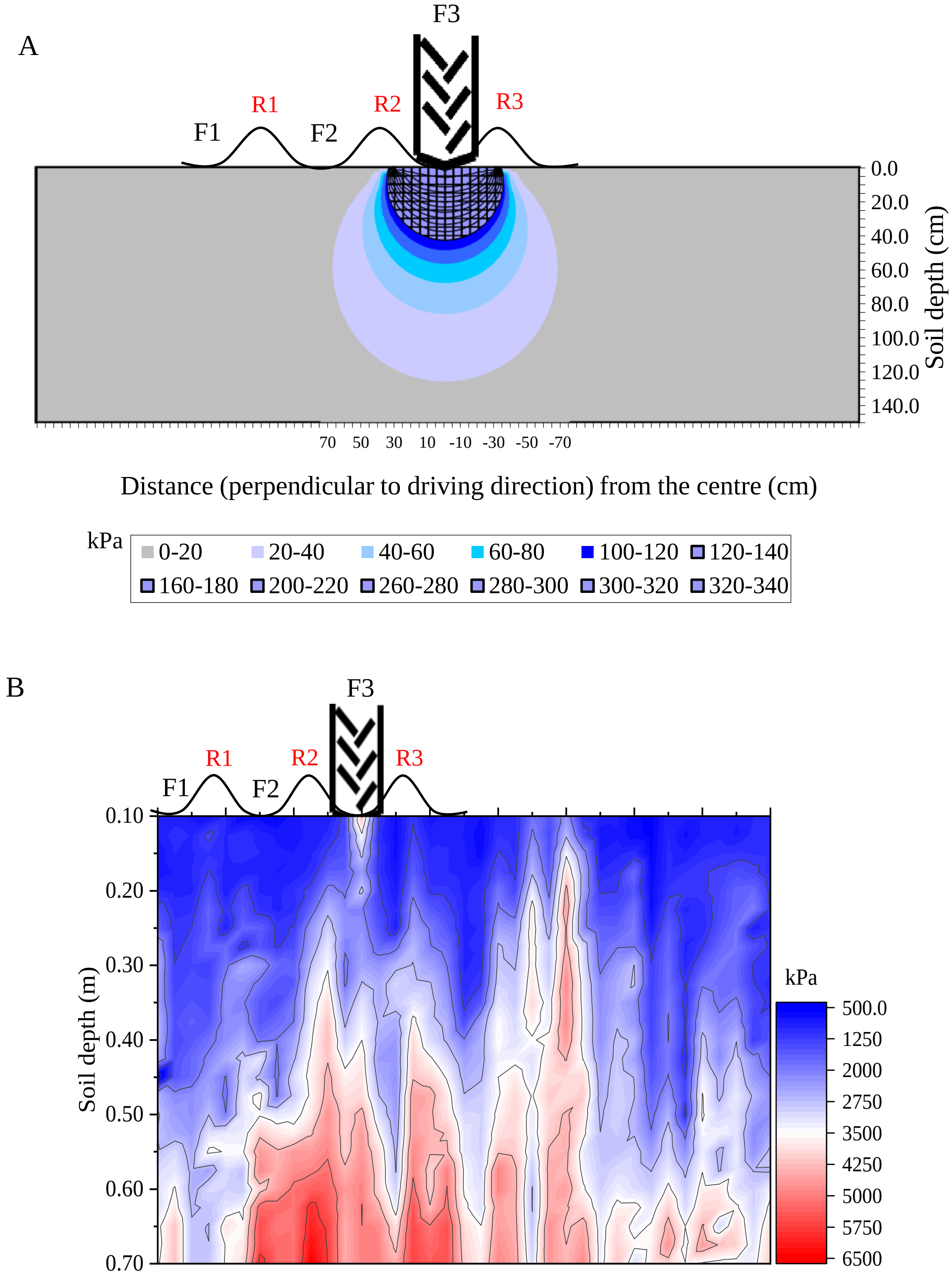


Figure 8.6: Comparison of the trend between the simulated vertical stress and soil penetration resistance results after harvester traffic (CTF modified). A represents the simulated vertical stress. B represents the measured soil penetration resistance at Yambacully during 2017

8.6.2. Stress state simulation

8.6.2.1. Front dual-wheel loading (JD7760 standard configuration)

Figure 8.7 shows that vertical stresses induced by the front dual-wheel of the JD7760 had a similar magnitude (370 kPa) in both Furrow 2 and Furrow 3, at the depth of 75 cm compared to Furrow 1. This reveals that stress distribution and magnitude were higher under the loaded area. Row 2 had higher vertical stress than Row 1 and Row 3 by 10% in the surface soil. This was due to the stress interaction from the front dual-wheels. Furthermore, Figure 8.8 shows that the surface loads applied generated significant stress at the centreline of the trafficked area, which ranged from 350 to 400 kPa and decreased gradually below the contact area with the increasing depth.

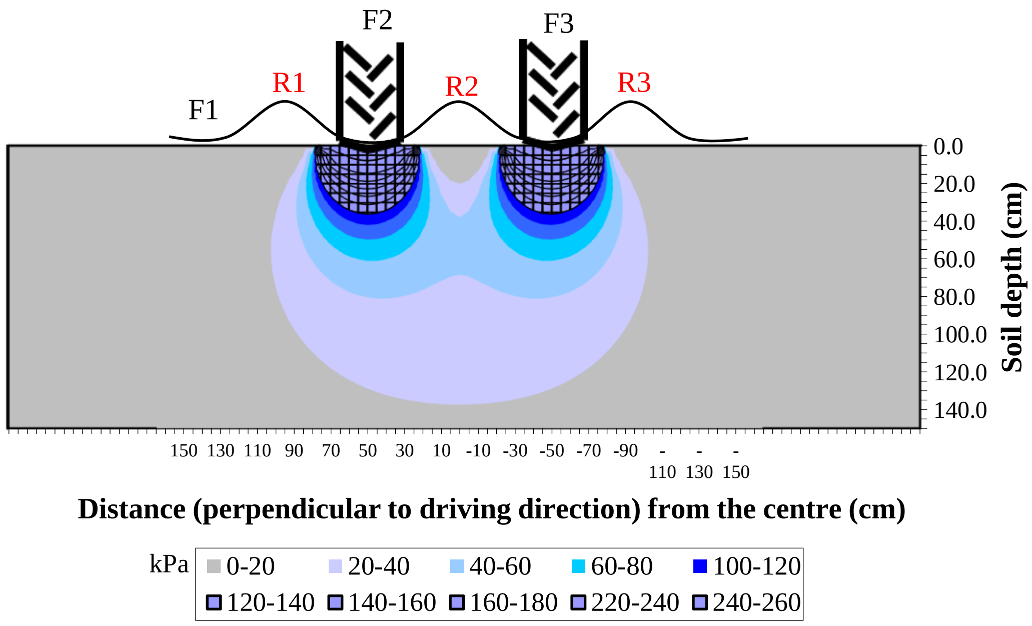


Figure 8.7: The vertical stress distribution beneath the dual-wheel of the JD7760

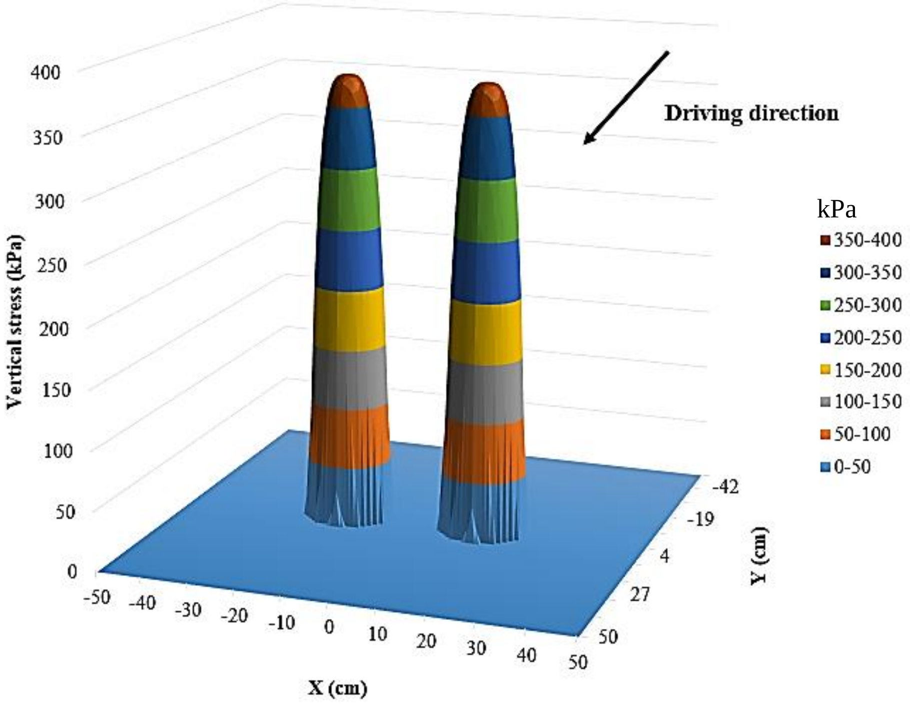


Figure 8.8: The vertical stress generated beneath the front dual-wheel of JD7760

8.6.2.2. Front single wheel load (CTF7760 modified harvester)

Figure 8.9 shows that the vertical stress distribution caused by the single wheel of the CTF7760 harvester was higher (355 kPa) in Furrow 3 at the 75 cm depth when compared to Furrow 1 and Furrow 2. This is because, Furrow 3 was the traffic lane of the harvester under CTF. The stress distribution was higher in both Row 2 and Row 3 in the topsoil compared to Row 1. This was due to the wheel load distribution by a single tyre (front axle) which was between Row 2 and Row 3. Moreover, Figure 8.10 shows that vertical stresses ranged between 500 to 600 kPa at the centreline of the single wheel of the harvester, and then declined gradually below the contact area with the increase in profile depth. This suggests that, in general, the SoilFlex simulations overestimated the effect in the surface layers and underestimated it in the deep layers.

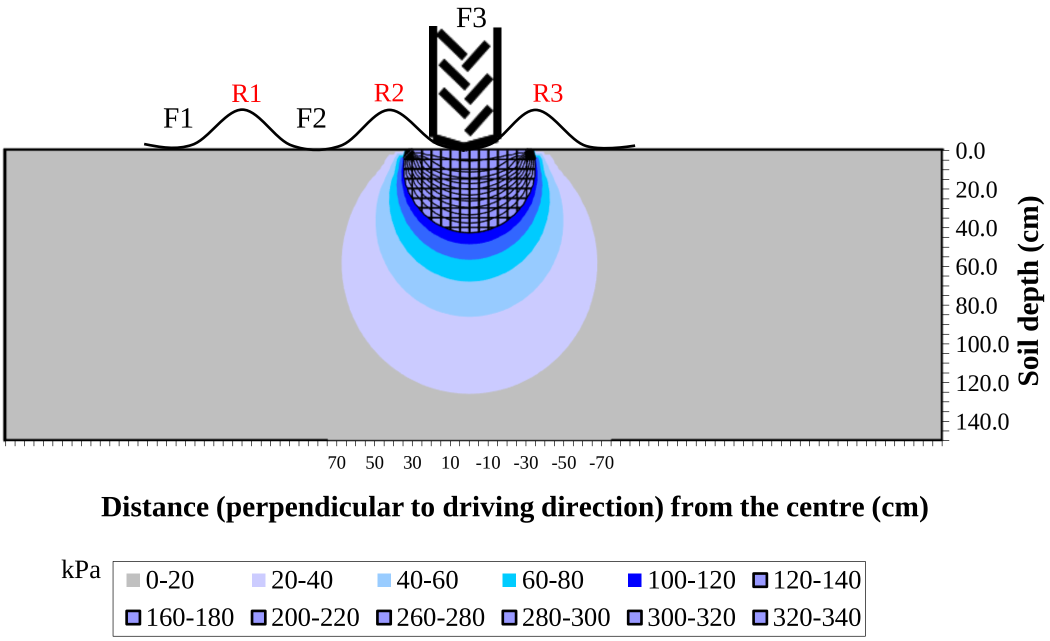


Figure 8.9: The vertical stress caused by the single wheel of the JD7760 modified

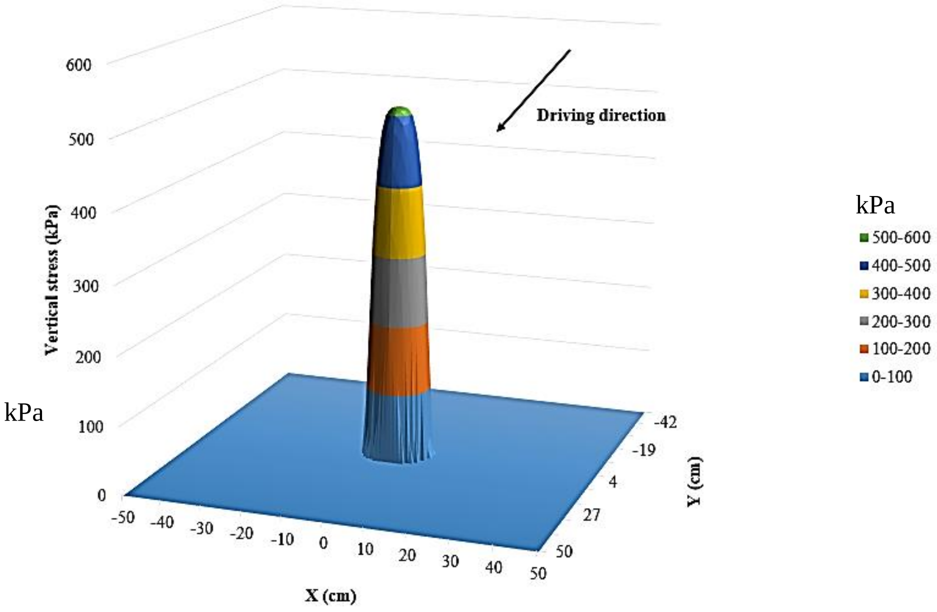


Figure 8.10: The vertical stress generated beneath the front single wheel of the JD7760 modified

8.6.2.3. Rear tyre loading

Figure 8.11 shows that the vertical stress caused by the rear tyre for the J7760 standard and the CTF7760 modified harvesters had a similar magnitude (300 kPa) at the depth of 70 cm. This was because both harvesters had the same rear wheel load and tyre size. Figure 8.12 also reveals that the vertical stress peaked at about 475 kPa in the centre, and decreased radially outward.

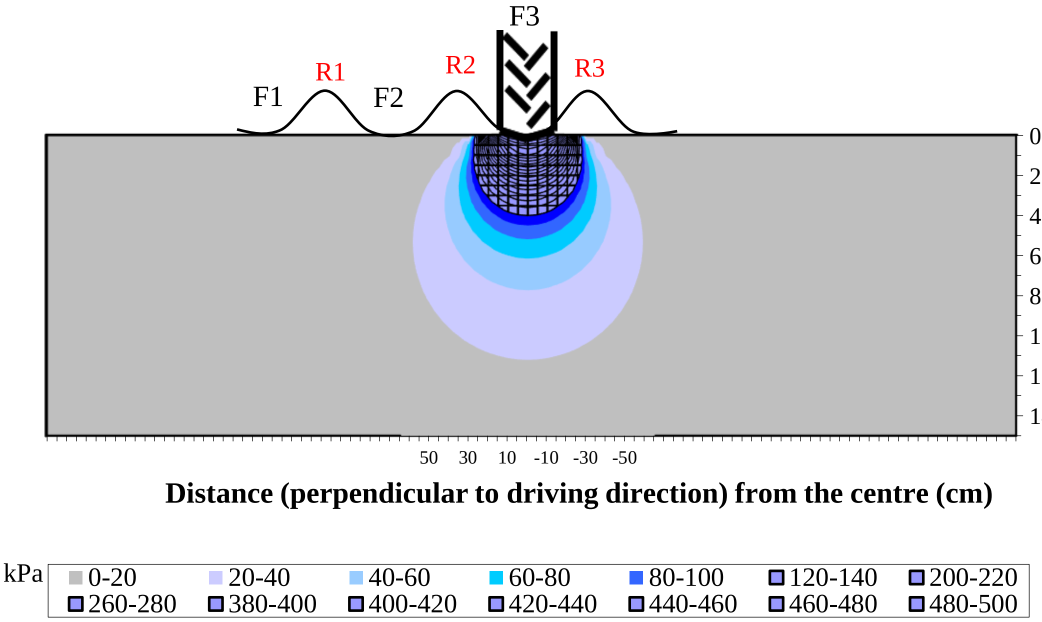


Figure 8.11: The vertical stress distribution underneath the rear tyre of the JD7760 standard and the CTF7760 modified

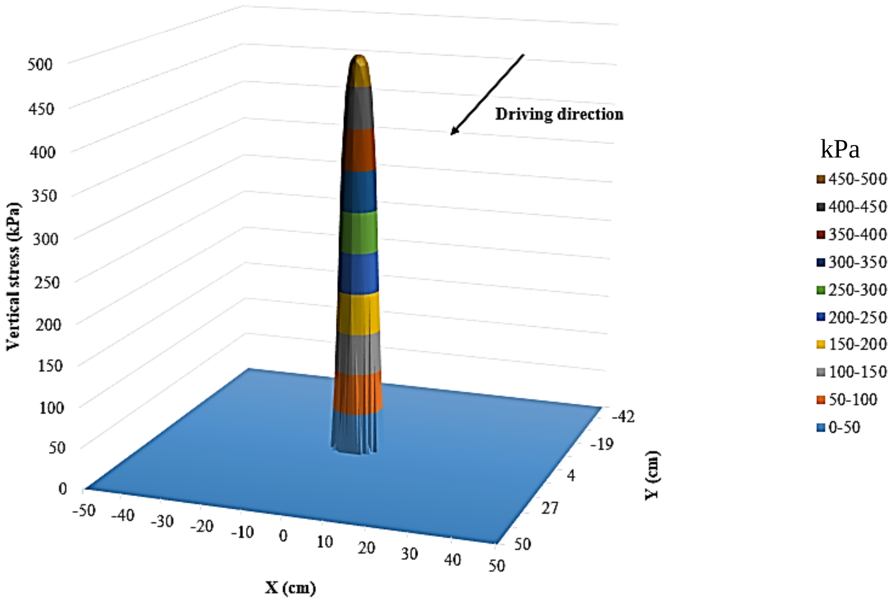


Figure 8.12: The vertical stress distribution beneath the rear tyre of the JD7760 standard and the CTF7760 modified

8.7. Discussion

Agricultural machinery imposes considerable mechanical stresses on soil and can cause soil compaction (Schjønning et al., 2008). Soil compaction models represent an important instrument for controlling traffic-induced soil compaction in agriculture (Keller et al., 2007). The models play an important role in the effective management of soil properties and in the improvement of production (Schafer et al., 1991). In particular, they can be used help to explain the susceptibility of soil to compaction (Nawaz et al., 2013).

The comparison between the JD7760 standard and the CTF7760 modified harvester shows that the wheel load of both the inner and outer dual-wheels traffic had a similar influence on Furrow 2 and Furrow 3 causing vertical stresses of 370 kPa at the depth of 75 cm. Vertical stress caused by the single tyre (front axle) of the CTF7760 harvester in Furrow 3 was 355 kPa at the 75 cm depth. This demonstrates that the heavy wheel load applied with higher tyre inflation pressure underneath the loaded area led to higher soil stresses in the topsoil and subsoil irrespective of single or the dual configuration (Keller & Arvidsson, 2004; Schjønning et al., 2008).

The interaction of the stresses from the inner and outer wheels of the dual configuration led to higher stresses in Row 2 than in Row 1 and Row 3, by 10% in the topsoil (Figure 8.7). In the CTF, both Row 2 and Row 3 showed higher soil stresses in the surface layer compared to Row 1. This indicates that the stress interaction from the two wheels of the dual configuration led to higher stresses compared to the stresses neighbouring to the wheel path (Keller & Arvidsson, 2004; Braunack & Johnston, 2014). Furthermore, vertical stress caused by the rear tyre showed a similar magnitude for both harvesters which was 300 kPa at the 70 cm depth. This was because the wheel load and tyre were the same sizes in both systems.

8.8. Conclusion

This chapter has presented a simulation of vertical stresses under the wheel tracks of the JD7760 standard configuration and the CTF7760 modified harvester. It was found that the simulated vertical stress showed a similar trend to the measured soil penetration resistance. Vertical soil stress underneath the loaded area was related to wheel load and tyre infiltration pressure. The stress distribution in the contact area affected stresses in the topsoil and the subsoil. The vertical stress caused by the inner and outer dual-wheels of the conventional harvester had a similar magnitude at all depths. Both Furrow 2 and Furrow 3 under RTF had higher stresses compared to Furrow 1 in the topsoil and subsoil. The stress interaction from the two wheels of the dual-wheel configuration induced higher stresses in Row 2 when compared to Row 1 and Row 3 in the topsoil.

For the CTF7760, the vertical soil stress at all depths was higher in Furrow 3 (loaded area) than Furrow 1 and Furrow 2 throughout profile depth. Row 2 and Row 3 also showed higher soil stress at the topsoil due to the influence of the single tyre (front axle) when compared to Row 1. Vertical stress induced by the rear tyre under the JD7760 standard configuration was of similar magnitude to that of the rear tyre of the CTF7760 harvester at the 70 cm soil depth. Overall, this chapter has answered the Research Question 4 and achieved Objective 4. Research Question 5 and Objective 5 will be addressed in Chapter 9.

Chapter 9. Modelling of crop performance

9.1. Introduction

The results of the modelling of vertical stresses induced in the soil by the wheels of the JD7760 harvester under two traffic farming systems using SoilFlex was discussed in the previous chapter. This chapter presents and discusses the results of the prediction of the impact of the harvester traffic on cotton yield, row by row, for the Koarlo, Undabri, and Yambacully sites using OZCOT-APSIM model (Keating et al., 2003). It starts with an overview of the model, and the addresses the model validation, simulation methodology and model outputs. Finally, there is a discussion of the findings and chapter conclusion.

9.2. OZCOT model

In Australia, the OZCOT model, which is part of APSIM software is widely used to predict cotton yield in order to make proper decisions and forecasting of crop growth and development (Thorp et al., 2014). The Agricultural Production Systems Simulator (APSIM) is an agronomy software model developed by the Agricultural Production Systems Research Unit in Australia (Keating et al., 2003). This model involves a number of modules that are capable of predicting agricultural practices that cover a range of crops, soils, weather, irrigation, etc. Its improvement and maintenance are based on accurate science and engineering software standards (APSIM Group, 2013).

The OZCOT-APSIM has the ability to predict the theoretical yield by employing historical climate and field data (CRCD, 2013). OZCOT adopts a ‘top-down’ strategy (Hearn 1994; Bange 2012). The OZCOT-APSIM model has been calibrated by the model developers (APSIM Group, 2013). In addition, the model has been validated against six collections of data from agronomic field trials over the past 30 years by covering a range of Australian cotton growing areas (Hearn, 1994). However, the OZCOT-APSIM is not capable of predicting factors such as insects’ impacts, harvest loss, and other effects of plant management (Hearn, 1994; Richards et al., 2001; Keating et al., 2003).

Past examination of the model has shown that the OZCOT model achieved an accurate prediction of commercial irrigated cotton yield (Rechards & Bange, 2003). The OZCOT model can be used for:

(1) Calculating potential yield before sowing by providing the amount of water required

(2) Determining the amount of irrigation and fertiliser that is required during the season

(3) Estimating cotton yield at the end of the season (Rechards & Bange 2003).

The key input parameters of OZCOT are soil properties, the plant index and climate variables (e.g. daily temperature, rainfall and radiation) (McCarthy, 2010). With OZCOT, it is possible to simulate different factors that can directly affect potential yields such as weather, irrigation, and soil fertility. The basic data required to set up the model are soil type, agronomy, climate, crop variety, and irrigation (Rechards & Bange, 2003). The framework of the APSIM is shown in Figure 9.1.

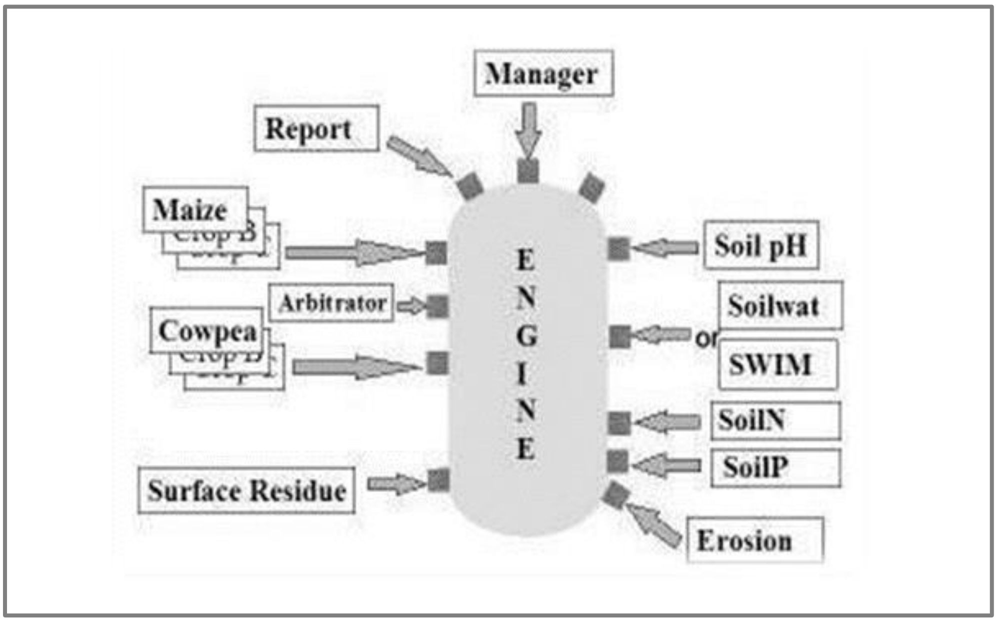


Figure 9.1: Schematic of the OZCOT-APSIM framework

Source: Adopted by the researcher from (Keating et al., 2003).

9.3. OZCOT-APSIM model validation

Validation is an important approach for assessing a model's performance by comparing the model's outputs to experimental results (Ahmed et al., 2016). The OZCOT model has been extensively calibrated against field experiment data. It has also been demonstrated to be able to accurately simulate potential yield under a wide variety of Australian growing conditions (CRDC, 1994). Hearn (1994) reported that the agreement between actual and simulation results was reasonably valid with 70% of the variation in the observed yield captured in the simulation. The OZOCT model provides an accurate simulation as the range between the yield predicted and yield observed is about 0.16–0.7 bales/ha (Richards et al., 2001). In this study, the measured yield data was used to validate the OZCOT model, row by row, at the three study areas.

9.4. Modelling of the study sites

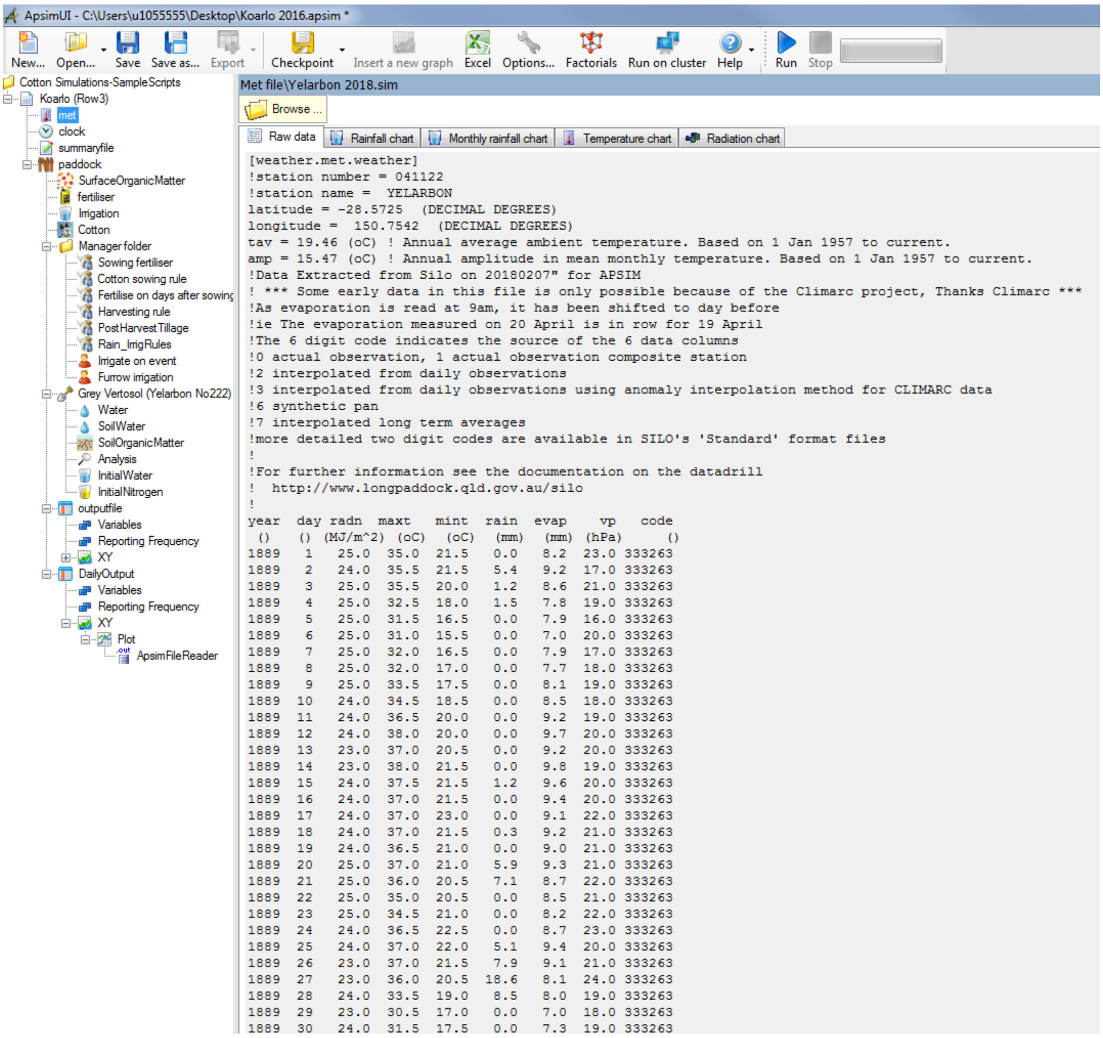
As mentioned above, OZCOT is a part of the APSIM model (Keating et al., 2003). In this study, version (7.9) of APSIM was employed to simulate the row by row effect of the JD7760 and CTF7760 traffic on irrigated cotton yield in order to provide another evidence of soil compaction effect on individual cotton yield and support the findings of the field experiments. Also, this work validated the APSIM model at the single cotton row level by comparing the predicted data and observed yield. This model was used to predict the yield towards the end of the season at Koarlo, Undabri, and Yambacully. In this simulation, the cotton crop cultivar used was S71BR. Daily weather profiles for GPS positions -28.69°N and 150.37°E (Koarlo-Yelarbon), -28.69°N and 150.37°E (Undabri- Goondiwindi) and -28.78°N and 150.54°E (Yambacully- Goondiwindi) were collected from the Australian Bureau of Meteorology SILO data (Queensland Government, 2018) for 2015/2016 and 2016/2017. Table 9.1 shows soil classifications that were chosen from APSIM's APsoil at each site.

Table 9.1: Soil classification of the study sites

Location	APSIM's APsoil file
Koarlo -Yelarbon, QLD	Grey Vertosol (Yelarbon No. 222)
Undabri - Goondiwindi, QLD	Grey Vertosol (Goondiwindi No. 856)
Yambacully - Goondiwindi, QLD	Grey Vertosol (Goondiwindi No. 856)

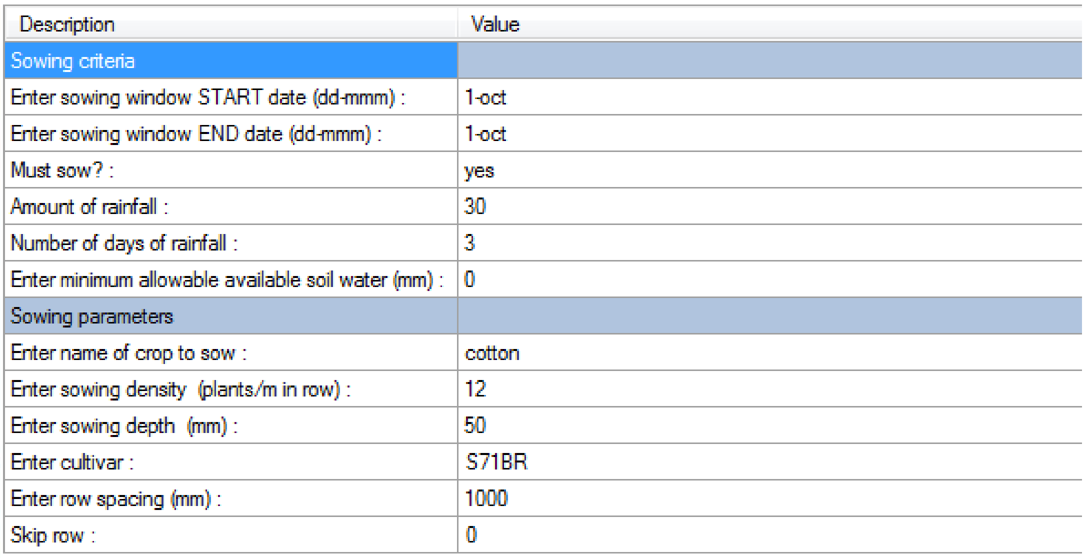
9.5. Simulation methodology

In line with www.apsim.info (2016), the following steps were followed to predict cotton yield at Koarlo for the 2015/2016 season. First, weather data obtained from the SILO data was inserted into the OZCOT-APSIM (Figure 9.2). The simulation period was adjusted to run for one season from 1 October 2015 to 1 July 2016. Next, APsoil was added (Grey Vertosol Yelarbon No. 222) to the simulation tree. Figure 9.3 illustrates the sowing period, which started and ended on the 1 October 2015. Plant density was 12 plants per metre in a row, according to the planter adjustment. The 1.0 m row spacing was used for RTF in this scenario.



```
[weather.met.weather]
!station number = 041122
!station name =  YELARBON
latitude = -28.5725  (DECIMAL DEGREES)
longitude =  150.7542  (DECIMAL DEGREES)
tav = 19.46 (oC) ! Annual average ambient temperature. Based on 1 Jan 1957 to current.
amp = 15.47 (oC) ! Annual amplitude in mean monthly temperature. Based on 1 Jan 1957 to current.
!Data Extracted from Silo on 20180207" for APSIM
! *** Some early data in this file is only possible because of the Climarc project, Thanks Climarc ***
!As evaporation is read at 9am, it has been shifted to day before
!ie The evaporation measured on 20 April is in row for 19 April
!The 6 digit code indicates the source of the 6 data columns
!0 actual observation, 1 actual observation composite station
!2 interpolated from daily observations
!3 interpolated from daily observations using anomaly interpolation method for CLIMARC data
!6 synthetic pan
!7 interpolated long term averages
!more detailed two digit codes are available in SILO's 'Standard' format files
!
!For further information see the documentation on the datadrill
!  http://www.longpaddock.qld.gov.au/silo
!
year  day radn  maxt   mint  rain  evap    vp   code
 ()    () (MJ/m^2) (oC)  (oC)  (mm)  (mm) (hPa)      ()
1889   1   25.0  35.0  21.5   0.0   8.2  23.0 333263
1889   2   24.0  35.5  21.5   5.4   9.2  17.0 333263
1889   3   25.0  35.5  20.0   1.2   8.6  21.0 333263
1889   4   25.0  32.5  18.0   1.5   7.8  19.0 333263
1889   5   25.0  31.5  16.5   0.0   7.9  16.0 333263
1889   6   25.0  31.0  15.5   0.0   7.0  20.0 333263
1889   7   25.0  32.0  16.5   0.0   7.9  17.0 333263
1889   8   25.0  32.0  17.0   0.0   7.7  18.0 333263
1889   9   25.0  33.5  17.5   0.0   8.1  19.0 333263
1889  10   24.0  34.5  18.5   0.0   8.5  18.0 333263
1889  11   24.0  36.5  20.0   0.0   9.2  19.0 333263
1889  12   24.0  38.0  20.0   0.0   9.7  20.0 333263
1889  13   23.0  37.0  20.5   0.0   9.2  20.0 333263
1889  14   23.0  38.0  21.5   0.0   9.8  19.0 333263
1889  15   24.0  37.5  21.5   1.2   9.6  20.0 333263
1889  16   24.0  37.0  21.5   0.0   9.4  20.0 333263
1889  17   24.0  37.0  23.0   0.0   9.1  22.0 333263
1889  18   24.0  37.0  21.5   0.3   9.2  21.0 333263
1889  19   24.0  36.5  21.0   0.0   9.0  21.0 333263
1889  20   25.0  37.0  21.0   5.9   9.3  21.0 333263
1889  21   25.0  36.0  20.5   7.1   8.7  22.0 333263
1889  22   25.0  35.0  20.5   0.0   8.5  21.0 333263
1889  23   25.0  34.5  21.0   0.0   8.2  22.0 333263
1889  24   24.0  36.5  22.5   0.0   8.7  23.0 333263
1889  25   24.0  37.0  22.0   5.1   9.4  20.0 333263
1889  26   23.0  37.0  21.5   7.9   9.1  21.0 333263
1889  27   23.0  36.0  20.5  18.6   8.1  24.0 333263
1889  28   24.0  33.5  19.0   8.5   8.0  19.0 333263
1889  29   23.0  30.5  17.0   0.0   7.0  18.0 333263
1889  30   24.0  31.5  17.5   0.0   7.3  19.0 333263
```

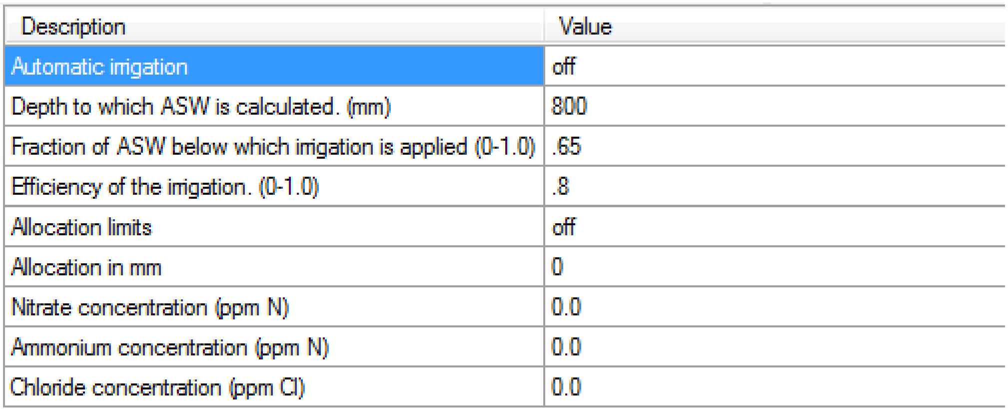
Figure 9.2: APSIM entered weather data (Grey Vertosol Yelarbon No 222)



Description	Value
Sowing criteria	
Enter sowing window START date (dd-mmm) :	1-oct
Enter sowing window END date (dd-mmm) :	1-oct
Must sow? :	yes
Amount of rainfall :	30
Number of days of rainfall :	3
Enter minimum allowable available soil water (mm) :	0
Sowing parameters	
Enter name of crop to sow :	cotton
Enter sowing density (plants/m in row) :	12
Enter sowing depth (mm) :	50
Enter cultivar :	S71BR
Enter row spacing (mm) :	1000
Skip row :	0

Figure 9.3: Inputs of sowing criteria in APSIM

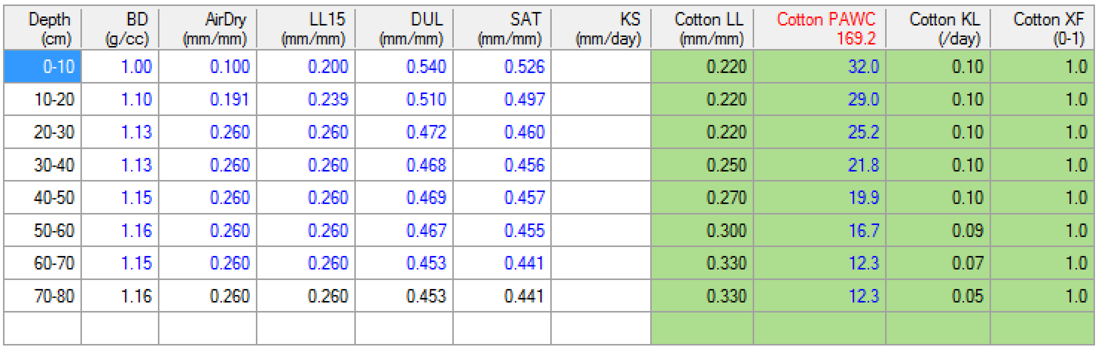
A furrow irrigation system was used at this site. Irrigation inputs were added to the simulation and adjusted to the depth of 800 mm to be matched with the soil profile depth used in the field experiment (Figure 9.4).



Description	Value
Automatic irrigation	off
Depth to which ASW is calculated. (mm)	800
Fraction of ASW below which irrigation is applied (0-1.0)	.65
Efficiency of the irrigation. (0-1.0)	.8
Allocation limits	off
Allocation in mm	0
Nitrate concentration (ppm N)	0.0
Ammonium concentration (ppm N)	0.0
Chloride concentration (ppm Cl)	0.0

Figure 9.4: APSIM entered irrigation components

The harvest rule was also added. When adjusting the water criteria, the profile depth was divided into eight layers (0–10, 10–20, 20–30, 30–40, 40–50, 50–60, 60–70 and 70–80 cm) to match the soil layers in the field trial (Figure 9.5). The *Pb* values obtained from the field experiment for Row 1 of Koarlo were entered into the APSIM. The soil depths of SoilWater, SoilOrgaincMatter, Analysis, and InitialNitrogen criteria were also adjusted to be the same those in the field experiment.

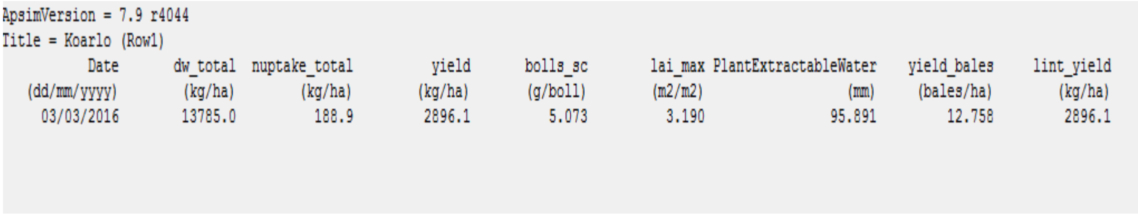


Depth (cm)	BD (g/cc)	AirDry (mm/mm)	LL15 (mm/mm)	DUL (mm/mm)	SAT (mm/mm)	KS (mm/day)	Cotton LL (mm/mm)	Cotton PAWC 169.2	Cotton KL (/day)	Cotton XF (0-1)
0-10	1.00	0.100	0.200	0.540	0.526		0.220	32.0	0.10	1.0
10-20	1.10	0.191	0.239	0.510	0.497		0.220	29.0	0.10	1.0
20-30	1.13	0.260	0.260	0.472	0.460		0.220	25.2	0.10	1.0
30-40	1.13	0.260	0.260	0.468	0.456		0.250	21.8	0.10	1.0
40-50	1.15	0.260	0.260	0.469	0.457		0.270	19.9	0.10	1.0
50-60	1.16	0.260	0.260	0.467	0.455		0.300	16.7	0.09	1.0
60-70	1.15	0.260	0.260	0.453	0.441		0.330	12.3	0.07	1.0
70-80	1.16	0.260	0.260	0.453	0.441		0.330	12.3	0.05	1.0

Figure 9.5: The measured *Pb* of Row 1 entered into APSIM water criteria

When all the inputs and adjustments were completed, the OZCOT-APSIM model was run to simulate the potential yield of Row 1, and then Row 2 and Row 3 separately. The outputs of the model were dry mass (kg/ha), bolls square(g/boll), leaf index (m^2/m^2) and yield (bales/ha) as shown in Table 9.2. The same processes as above were also carried out for Koarlo, Undabri, and Yambacully for 2016/2017. Weather data and APsoil were changed for each field according to GPS locations. Furthermore, the 1.5 m row spacing was entered in relation to the sowing criteria under CTF. The simulation processes were carried out after consultation with CSIRO researchers (Johnston 2018, Pers comm). The attached file (CD), Part IV includes the inputs data that were used to run APSIM. Appendices 9.1, 9.2 and 9.3 show the simulation outputs of the individual rows of each site.

Table 9.2: The simulation output for Row 1 in Koarlo 2016



```
ApsimVersion = 7.9 r4044
Title = Koarlo (Row1)
        Date    dw_total  nuptake_total        yield      bolls_sc      lai_max PlantExtractableWater   yield_bales    lint_yield
  (dd/mm/yyyy)    (kg/ha)        (kg/ha)       (kg/ha)      (g/boll)      (m2/m2)                  (mm)   (bales/ha)       (kg/ha)
    03/03/2016    13785.0          188.9        2896.1         5.073        3.190                95.891        12.758        2896.1
```

9.6. Simulation results

9.6.1. OZCOT-APSIM validation

Figure 9.5 shows the trend between predicted yield against measured yield in individual rows. There was a very strong correlation between the simulated and actual yield (R^2 = 0.99) for Koarlo in 2016 and 2017 (Figure 9.6A and B). The correlation between predicted and measured yield was also very strong at both Undabri (R^2 = 0.99) and Yambacully (R^2 = 0.91) as shown in Figure 9.5C and D. The linear trends for both observed and predicted yield showed a good agreement. However, the regression equation was based on 3 data pairs which considered as a limitation in this study. But the regression line was valid in the sense that at least supplied a strong idea about the relationship between the predicted and observed yield.

Table 9.3 that the predicted yield was close to the measured yield for Row 1, Row 2 and Row 3 for Koarlo in 2016 and 2017. With a similar trend, predicted and measured yield were close for Row 1, Row 2 and Row 3 at both Undabri and Yambacully. However, there was a slight variation because the model was not able to predict factors such as biophysical influences and other influences of plant management (Hearn, 1994; Richards et al., 2001; Keating et al., 2003). Overall, the OZCOT-APSIM model showed a reasonable simulation of the yield at all the study sites.

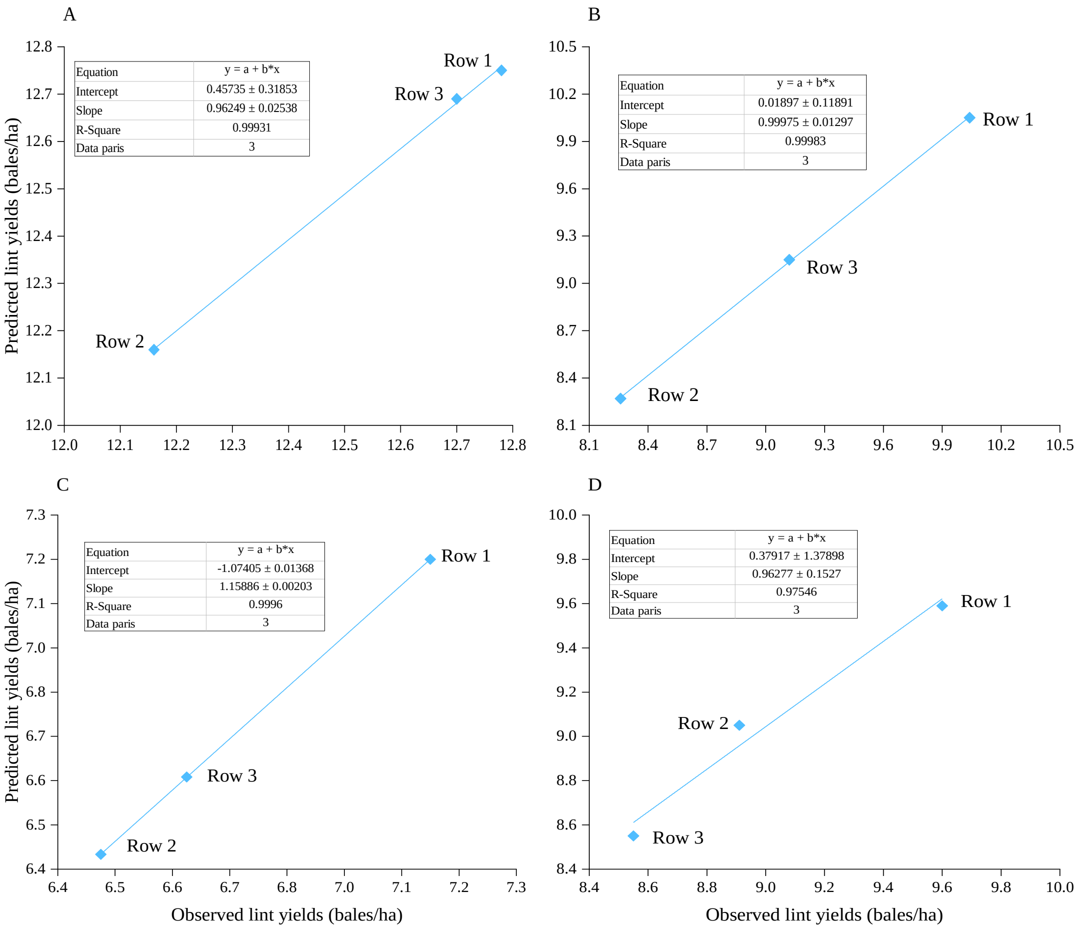


Figure 9.6: Validation simulation results: the measured versus predicted yield. A and B represent Koarlo in 2016 and 2017. C and D represent Undabri and Yambacully in 2017

Table 9.3: The observed and simulated yield of the study areas

Site	Treatment	Observed yield (bales/ha)	Predicted yield (bales/ha)
Koarlo 2016	Row 1	12.78	12.75
	Row 2	12.16	12.16
	Row 3	12.70	12.69
Koarlo 2017	Row 1	10.04	10.05
	Row 2	8.26	8.27
	Row 3	9.12	9.15
Undabri	Row 1	7.14	7.20
	Row 2	6.45	6.40
	Row 3	6.63	6.61
Yambacully	Row 1	9.60	9.59
	Row 2	8.91	9.05
	Row 3	8.55	8.55

9.6.2. Results of simulation for individual cotton rows

9.6.2.1. Koarlo site

As mentioned previously, two field experiments were carried out on two different cotton sites at Koarlo. The first trial was conducted in the harvest season of 2016, while the second was done in 2017, therefore, lint yields were simulated in both 2016 and 2017. Based on the OZCOT-APSIM simulations, lint yields were significantly higher in Row 1 than in Row 2, by approximately 4% and 17% for 2016 and 2017, respectively (Figures 9.7 and 9.8). For both periods, there was no significant difference in the predicted yield between Row 1 and Row 3. Row 2 had a lower lint yield than Row 3, by approximately 4% and 9%, respectively, for 2016 and 2017. These outputs suggest that the model was highly sensitive to variation in the soil density values inserted. The measured *Pb* of Row 2 was higher than Row 1 and Row 3 due to the impact of the dual-wheel traffic of the harvester, as mentioned in previous chapters. Therefore, this effect was negatively reflected in the predicted yield.

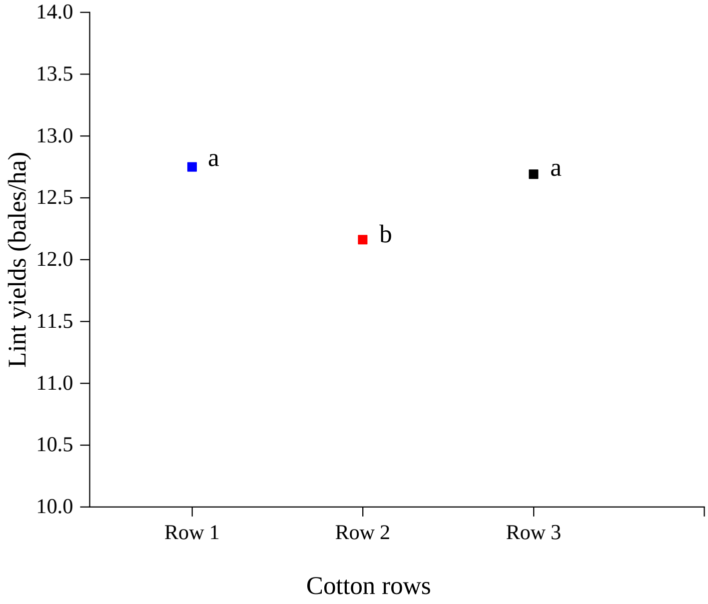


Figure 9.7: Predicted lint yields (bales/ha) for individual cotton rows at the Koarlo site during 2016

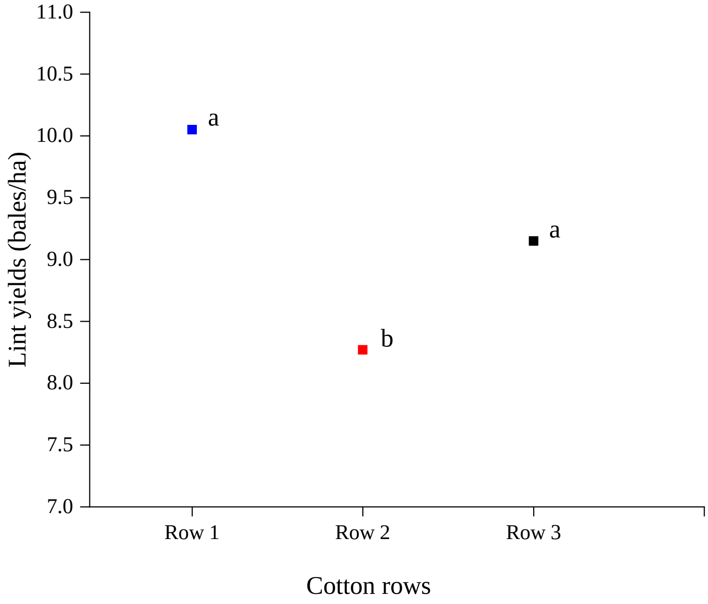


Figure 9.8: Predicted lint yields (bales/ha) for individual cotton rows at the Koarlo site during 2017

9.6.2.2. Undabri site

Row 1 had a significantly higher lint yield (11%) than Row 2, while no significant difference was found between Row 1 and Row 3 (Figure 9.9). The comparison between Row 2 and Row 3 did not show any significant difference in lint yield at $P \leq 0.05$ level. The reason was similar to that highlighted for the Koarlo site (above).

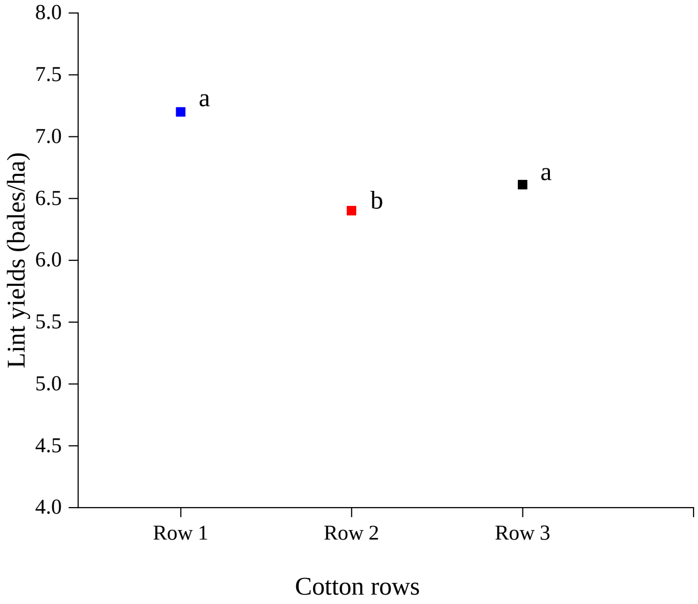


Figure 9.9: Predicted lint yields (bales/ ha) for individual cotton rows at the Undabri site during 2017

9.6.2.3. Yambacully site

Figure 9.10 shows that the lint yield was significantly higher in Row 1 than in Row 2 and Row 3, by approximately 6% and 12%, respectively. There was no significant difference in the predicted yield between Row 2 and Row 3. This was because the measured *Pb* was lower in Row 1 than in Row 2 and Row 3 due to the space between Row 1 and traffic lane under CTF, which was sufficient to protect the soil's structural arrangement. This required that a lower *Pb* be entered into the model, which reflected positively in increased predicted yield for Row 1 than Row 2 and Row 3.

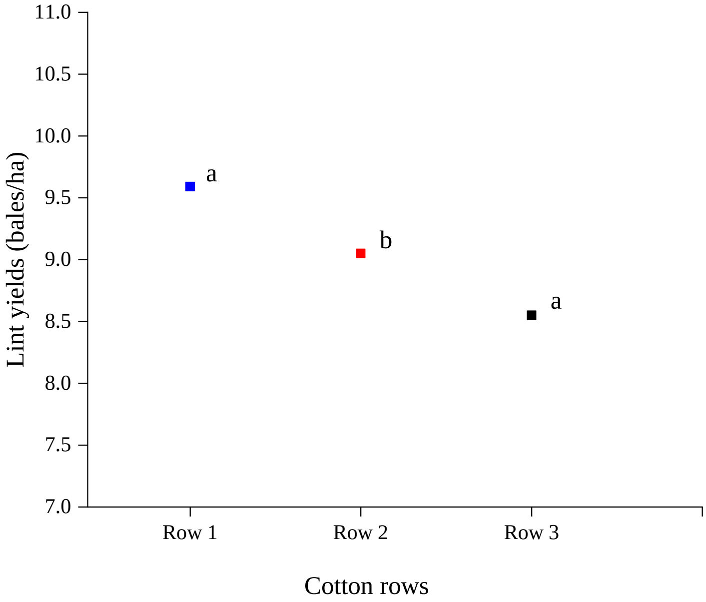


Figure 9.10: Predicted lint yields (bales/ha) for individual cotton rows at the Yambacully site during 2017

9.7. Discussion

APSIM is an agronomic model that was proposed by (Hearn, 1994) and developed by the CSIRO in Australia as a modelling instrument to accurately predict the influence of weather, genetics, soil, irrigation and farm management factors on cotton production (Yang et al., 2014). In this study, the comparison between simulated and measured yield revealed that the model performed well in terms of yield prediction. In addition, there was a very strong linear correlation between the predicted and actual yield for the Koarlo, Undabri and Yambacully sites.

In Koarlo, the simulated yield was significantly higher in Row 1 than in Row 2, by approximately 4% and 17% for both 2016 and 2017, while Row 2 showed a lower yield than Row 3, by 4% and 9%, respectively, for 2016 and 2017. A similar trend was found in Undabri. It showed a significantly higher yield (11%) for Row 1 than Row 2, while no significant difference was found between Row 1 and Row 3. This suggests that the APSIM was sensitive to variations in *Pb*. Measured *Pb* of Row 2, which was entered into the model, was higher than those of Row 1 and Row 3, and this was reflected in the predicted results which showed the lowest yield in Row 2. This was because Row 2 was compressed by the inner and outer dual-wheels of the JD7760.

Furthermore, for the CTF site at Yambacully, lint yield was significantly higher in Row 1 than in Row 2 and Row 3, by approximately 6% and 12%, respectively. There was no statistical difference in potential yield between Row 2 and Row 3. This was because the measured *Pb* was the lowest in Row 1, as the space between Row 1 and the traffic lane was sufficient to protect the soil's structural arrangement. At the same time, the permanent traffic lane was between Row 2 and Row 3, which resulted in increased soil strength in the wheel track which spread to the adjacent rows, and thus the *Pb* increased (Braunack & Johnston, 2014). This led to a decrease in predicted yield because OZCOT-APSIM is sensitive to changes in *Pb* (Hearn, 1994). In summary, the key findings of this simulation are:

- The model outputs demonstrated that predicted yield was close to measured yield from the field experiments which showed a very strong correlation for all the study sites

- Row 2 under RTF (Koarlo and Undabri) had the lowest yield, being 4% and 14% lower than Row 1 and Row 3

- At the CTF site at Yambacully, lint yield was significantly higher in Row 1 than in Row 2 and Row 3, by approximately 6% and 12%, respectively

- The simulation results showed no significant difference in potential yield between Row 2 and Row 3 under CTF

- Row 3 under CTF was most sensitive to harvester traffic with the lowest yield prediction about 12% lower than Row 1 and Row 2.

9.8. Conclusion

Simulation of row by row cotton yield under two traffic systems (RTF and CTF) was carried out using OZCOT-APSIM and results have been presented in this chapter. The model performed, well showing a good agreement between predicted and measured cotton yield for all study sites which is considered another confirmation of compaction impact on individual cotton yield in line with the experimental results. Under both CTF and RTF, Row 1 achieved the highest yield compared to Row 2 and Row 3. Row 2, which was located between the front dual-wheels of the JD7760 standard configuration, was most sensitive to harvester traffic. It showed a lower yield than the rows (Row 1 and Row 3) adjacent to the wheel track of the harvester. Under CTF, traffic by the single wheel of the harvester affected Row 2 and Row 3 which showed a lower potential yield than Row 1. The model outputs revealed that cotton rows between the dual-wheels of the JD7760 standard were influenced by harvester traffic and had a lower yield than those neighbouring to the wheel track of the harvester. In summary, this chapter has addressed the Objective 5 and answered the Research Question 5.

The OZCOT-APSIM has been used for predicting the impact of JD7760 and CTF7760 traffic on row by row cotton yield under different levels of soil compaction in order to confirm and support the results of the experimentations. Also, to validate the model at the single cotton row level by comparing the predicted data and observed yield row by row.

Chapter 10. Conclusions and recommendations

10.1. Overview

Row by row Vertosol soil compaction due to JD7760 cotton picker traffic and its impact on cotton yield under two farming systems (RTF and CTF) has been investigated and presented in this thesis. The response of Vertosol to rainfall, seasonal climatic variability and harvester traffic was monitored during the period from October 2016 to May 2017. Field trials and simulation models were employed to investigate soil compaction and cotton yield. The results of this investigation have contributed to the creation of new knowledge that is relevant to both cotton farmers and researchers across the world. It has also provided important information for farmers intending to grow crops in Vertosol soils in both Australia and around the world.

10.2. Achievement of the research objectives

This section provides a summary of the achievements of each objective in this thesis:

10.2.1. Summary related to Objective 1

"To obtain and compare the parameters of soil compaction due to JD7760 traffic at a single row scale in different fields under RTF and CTF"

The impact of soil compaction due to JD7760 cotton picker traffic at the single row level under two different traffic farming systems (RTF and CTF) was examined. Additionally, the response of Australian Vertosol soil to rainfall, seasonal variability and harvester traffic across the overall field was investigated. Soil water content (Swc), dry bulk density (*Pb*) and soil penetration resistance (SPR) were measured to assess the degree of compaction in the 0–80 cm depth of cotton rows and furrows. The measurements were carried out in October 2016, January 2017 and May 2017 (before and after harvester traffic).

It was found that over an entire field, Vertosol soil was significantly influenced by the wet-dry cycles of the soil. This resulted in the activation of the shrink-swell property in the topsoil. Heavy rainfall in early October 2016 was particularly important for compaction alleviation due to swelling of the Vertosol. Increased temperature in January 2017 also resulted in increased drying and shrinking of the soil that resulted in increased soil strength in the topsoil. It was further found that traffic from the JD7760 harvester induced significant compaction in the 0–30 cm depth, irrespective of RTF or CTF. Overall, about 75% of the fields were compacted due to trafficking with the JD7760 standard under RTF as compared to 50% with the CTF7760 harvester.

Soil properties (Swc, *Pb* and SPR) were significantly affected by harvester traffic across the individual cotton rows and furrows under both RTF and CTF. Wheeled traffic over the furrows induced both topsoil and subsoil compaction. This effect expanded to neighbouring cotton rows, directly affecting cotton yield. In RTF, Row 2 was most influenced by harvester traffic as indicated by a higher *Pb* and SPR in the topsoil when compared to Row 1 and Row 3. Row 2 was located between the front dual-wheels and experienced compaction from both wheels. There was no traffic impact on Row 1 with the CTF7760 harvester throughout the 0–80 cm depth, unlike Row 2 and Row 3. Overall, regardless of traffic system, significant compaction was found in rows and furrows between, neighbouring and beneath the wheel tracks. With these results, Objective 1 is achieved and Research Question 1 is answered. These results provide the international cotton industry with important practical information on the impact of JD7760 traffic on Vertosols at the single row level and the entire field.

10.2.2. Summary related to Objective 2

"To develop and evaluate different methods for estimating row by row cotton yield data"

The influence of soil compaction due to harvester traffic on cotton yield at the single row level under RTF and CTF was investigated. Two novel approaches for collecting row by row yield data were adopted at the three study sites. The first method was designed to gather cotton yield from the existing machine (See Figure 3.21). The second employed the CAN-BUS and sensors of the harvester to directly extract yield data for individual cotton rows in 2017. Cotton yield was also hand-picked at all three sites in this study.

Yield results obtained using both approaches at the single row level showed significant soil compaction due to JD7760 harvester traffic under both RTF and CTF, particularly for rows between and adjacent to the wheel track. It was found that Row 1 achieved the highest yield under both traffic systems when compared to Row 2 and Row 3. Row 2 under RTF was most influenced by the inner and outer dual-wheel traffic which led to lower yield than Row 1 and Row 3. Under CTF, Row 2 and Row 3 had a lower cotton yield than Row 1 due to the impact of wheel traffic. The measured results for CTF site at Yambacully also achieved a higher total yield per hectare than RTF at Undabri site, by 33%. These results were confirmed through comparison with the hand-picked data. With these results, the feasibility of the two new approaches for estimating cotton yield at the single row level was proven. These approaches can therefore be adopted by both farmers and researchers. Overall, Objective 2 is achieved and Research Question 2 is answered.

10.2.3. Summary related to Objective 3

"To compare the harvest efficiencies (harvest losses) of JD7760 and CTF7760"

Harvester performance and harvest system costs are important considerations when comparing cotton harvesting systems. In this thesis, harvester efficiency was measured as a function of harvest loss. The third objective of this study was to examine the harvest efficiency of both the JD7760 standard configuration and the CTF7760 modified harvester at the single row level. The JD7760 standard harvester (6 m frontage width) was used to harvest the RTF sites at Koarlo and Undabri, while the CTF7760 modified (9 m frontage width) was employed to harvest Yambacully.

The results revealed that the CTF7760 harvester was superior and showed lower yield loss than the JD7760 standard configuration for all cotton rows. This indicates that the adoption of the CTF7760 harvester could help farmers to reduce picking costs per hectare and maximise their profits. These results indicate achievement of Objective 3 and answer Research Question 3.

10.2.4. Summary related to Objective 4

“To select and utilise an appropriate soil stress model to simulate soil compaction due to JD7760 and CTF7760 traffic”

This study used SoilFlex to simulate vertical stress distribution under the wheel track of the JD7760 standard (front dual-wheel) and the CTF7760 modified (single wheel). This model is easy to use and applicable for farmers and agricultural advisers to control soil compaction in practice. This model has the ability to simulate the stress distribution underneath the wheel with tyre sizes (520/85R42 and 20.8-38) and inflation tyre pressure of 270 kPa as input parameters.

First, the SoilFlex model was validated. Results obtained from this project agree well with the trend in the measured soil penetration resistance. The simulation results confirmed that vertical soil stress beneath the loaded area was highly related to wheel load and tyre infiltration pressure. In addition, the vertical soil stress caused by the inner and outer dual-wheel of the conventional harvester was of similar magnitude throughout the entire depth. The stress interaction from the two wheels of the dual configuration induced higher topsoil stresses in Row 2 than Row 1 and Row 3. Under CTF, Row 2 and Row 3 also showed higher soil stress in the topsoil due to the load of the single tyre (front axle) compared to Row 1. This was because the tyre was located between Row 2 and Row 3. The results of the study therefore demonstrate that it is possible to predict the impact of wheel traffic of heavier machinery on agricultural soil using SoilFlex. The outputs of SoilFlex demonstrate the achievement of Objective 4 and answer to Research Question 4.

10.2.5. Summary related to Objective 5

“To utilise a crop model to predict the impact of JD7760 and CTF7760 traffic on row by row cotton yield”

The OZCOT-APSIM model was used to predict the impact of harvester traffic on cotton yield, row by row. This model was selected because it was able to simulate the theoretical yield by using historical weather and field data. It can provide a good prediction for the commercial yield of irrigated cotton. In this project, the OZCOT-

APSIM model was first validated by comparing the predicted yield data against the observed yield. This demonstrated a good agreement between them. Importantly, the model outputs showed that cotton rows between the dual-wheels of the JD7760 standard were most sensitive to harvester traffic and had a lower yield than those adjacent to the wheel track of the harvester. Under CTF, traffic from the single wheel of the harvester had an influence on both Row 2 and Row 3 which showed lower yields than Row 1. Results obtained with the model confirmed results obtained from field experiments. This result demonstrates the achievement of Objective 5 and answers Research Question 5.

10.3. Contributions of the research

The literature review of this project revealed that there is currently a paucity of information pertaining to the impact of soil compaction due to JD7760 harvester traffic on cotton yield at the single row level under different farming systems. There is also a lack of studies on the impact of factors such as rainfall, seasonal climatic variability and harvest traffic on Vertosol soil behaviour. Thus, this study has been successful in identifying research gaps that need to be addressed (theoretical contribution) and in developing of new measurement methods, collection of field data, and computer simulation (practical contribution). Details of these contributions are highlighted below.

10.3.1. Theoretical contributions of this thesis

Through a comprehensive review of literature, this thesis has brought together and contextualised a range of issues relating to soil compaction and highlighted the research gaps. It has also offered a thorough review of the relationship between soil compaction and agricultural field traffic and their impacts on crop performance. In addition, this thesis has presented a comprehensive review of approaches used to reduce the level of soil compaction, including the best management strategies for avoiding and alleviating topsoil and subsoil compaction. This thesis has further delivered a comprehensive review of existing soil compaction and agronomy models. This knowledge can help future research in selecting an appropriate model for controlling traffic-induced soil compaction in agriculture and support to sound decision making and forecasting of crop growth and development. Overall, the findings of this thesis have made an important scholarly contribution to the growing body of literature related to soil compaction and cotton yield.

10.3.2. Practical contributions of this thesis

The Australian cotton industry has made considerable advances in cotton production by adopting improved management strategies. With the widespread uptake of the JD7760 cotton picker, evaluation of its impacts under different farming systems has become critical. Previous researchers have studied the effect of this cotton picker on soil compaction and cotton yield. But, these studies provided overall field results rather than results at individual row level. This thesis has, therefore, made an important contribution to the global knowledge by delivering new findings in regards to the impact of JD7760 traffic on soil compaction and cotton yield at the single row level under different farming systems. The behaviour of Vertosol in response to factors such as rainfall, seasonal variability and harvester traffic under RTF and CTF was also monitored and investigated within the short-term (between October 2016 and May 2017).

Another significant contribution of this thesis is its development of two new methodologies for estimating cotton yield at the single row level (discussed in Chapter 3). Use of these methods revealed that, for both systems, individual row yield data was significantly influenced by JD7760 traffic compaction. The yield was much lower in the rows between the dual-wheel than the yield in those adjacent to the wheel track. Overall, it has been demonstrated that the results of these methods are valid because they show a similar trend to the findings of hand-picked method which was also used in this study.

This thesis further examined the efficiency of the harvesters under RTF and CTF. Previous studies had only compared the efficiencies of cotton pickers and strippers based on overall yield loss, while the efficiencies of the JD7760 standard configuration and the CTF7760 modified version had not been investigated, particularly within Australian cotton industry. This project has, for the first time, shown that the CTF7760 harvester was superior and showed lower yield loss than the JD7760 standard configuration in all cotton rows.

Finally, this study has simulated the impact of JD7760 harvester traffic on soil compaction and cotton yield for both RTF and CTF. Validation of soil compaction (SoilFlex) and biophysical (APSIM) models was again performed at the single row level. This was done by comparing the model outputs against field data to increase the reliability of the results of this study. Thus, this thesis has provided new insights and information to Australian and international cotton farmers in terms of the influence of John Deere 7760 traffic on cotton yield and enables the adoption of better strategic management and the development of aids for better production decision making under different levels of soil compaction.

10.4. Recommendations for further research

This thesis has achieved the main aim and objectives outlined in Chapter 1. However, it has some limitations due to limited harvest seasons and limited availability of equipment. Therefore, the following recommendations are made for future work:

- The findings reported in this thesis were based on fieldwork conducted in Yelarbon and Goondiwindi, Queensland. In the future, the field work will need to be extended to different locations and soils, and to multiple harvest seasons to provide further verification of the impact of compaction due to JD7760 picker traffic on cotton production, row by row. Particularly, field trials should be undertaken in Australia (Narrabri, Moree, Warren, etc.) and other cotton growing regions around the globe.

- Soil compaction was identified within individual rows due to the JD7760, regardless of random or controlled traffic, and this resulted in cotton yield decline. DI practices the costs of removal of such compaction and how it can affect crop returns or net profit.

- The results of this study have quantified the impact of JD7760 traffic on soil compaction. However, this study did not attempt to employ methods and models developed by civil engineers for measuring compaction in agricultural soils. Thus, it is recommended that civil engineering methods and models should be explored for compaction measurement of agricultural soils.

- The experiments undertaken in this thesis were carried out to investigate the impact of JD7760 traffic in changing the soil's physical properties and cotton production row by row. The soil's chemical properties were not investigated in this study. Thus, further research into the effect of compaction, due to JD7760 traffic on soil chemical properties is also recommended.

- The current thesis has highlighted the influence of compaction by a specific cotton picker model (JD7760) on row by row cotton yield. Further studies will need to compare the John Deere round baler and other brands of round bale harvesters or the conventional basket pickers, in terms of soil compaction and its influence on row by row cotton performance.

- This study has successfully employed the JOHN DEERE-DATALOGGER and the JD7760 cotton picker CAN-BUS to extract yield data at the single row level. Thus, for future work, it is recommended that this approach could be repeated or used with a different crop, such as sugarcane.

- Harvesting is expensive for many cotton growers and requires a significant investment to achieve a high yield and profitability. This thesis has compared the harvest efficiency between the JD7760 standard and the CTF7760 modified based on harvest loss for only one harvest season. Hence, it is recommended that harvest loss measurements be repeated under both systems across different sites and multiple seasons for more accuracy.

- This thesis has investigated the influence of soil compaction due to trafficking on cotton yield. However, this study did not attempt to calculate total operating costs for the JD7760 standard and the CTF7760 modified. Therefore, it is recommended that investigating of the operating costs for both systems be undertaken and these be compared.

- The current thesis has employed the SoilFlex model to simulate vertical stress distribution in Australian Vertosol soil underneath the wheels of the JD7760 standard configuration and CTF7760 modified harvester at the single row level. However, this study did not attempt to calculate soil deformation under the wheels of both the JD7760 standard and the CTF7760 modified. Therefore, it is recommended that soil deformation simulations be undertaken.

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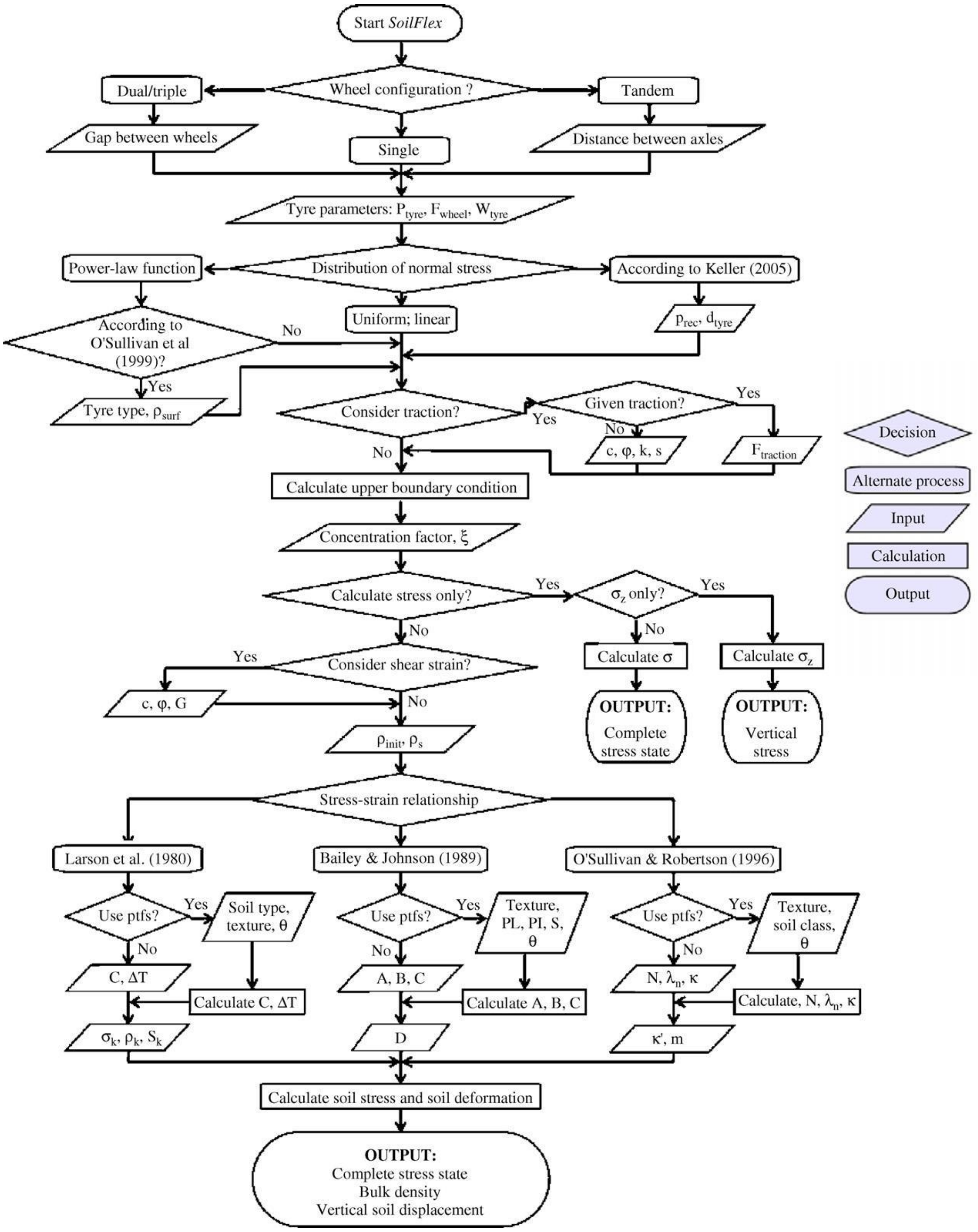
Appendix

Appendix 2.1: Classification of mechanism soil compaction model

Model	Pseudo-analytical	Finite element method (FEM)
Propagation sub- model	Pseudo-analytical calculus of stress propagation.	Numeral calculus of displacement propagation.
Surface- applied force sub-model.	Inhomogeneous stress propagation through an elliptical contact region.	Uniform stress propagation through an elliptical contact region.
Stress-strain behaviour sub-model.	Empirical models.	Pseudo-elastic models, Cam clay type models Combined models.



Appendix 2.2: Flowchart-Inputs and outputs of SoilFlex model

Appendix 3.1: Soil cores collected during the study period

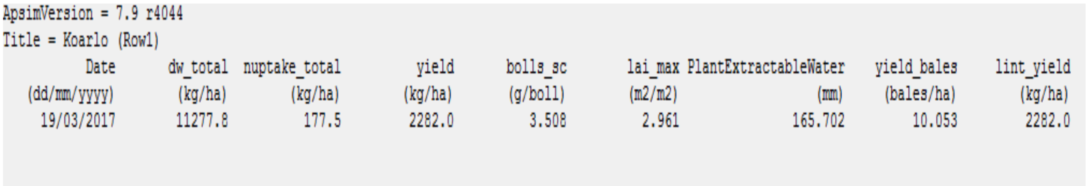
Appendix 3.2: Soil penetration resistance measurement in situ

Appendix 3.3: General specifications of the JD7760 cotton picker

Engine:		
Manufacturer		John Deere 7760
Tier III compliant		Yes
Horsepower		373 kW (500 hp) @ 2100RPM
Displacement		13.5 L
Number of cylinders		6
Aspiration		Turbocharged/air to air
Air filter		Dry air cleaner w/Safety Element
Alternator		200 Amp
Batteries		Three batteries (925 CCA) 12V
Fuel Capacity		1136 L (300 Gallon)
Drive Train:		
Transmission		Electronic controlled hydrostatic ProDrive™ Automatic Shift
		(AST), full time 4WD
Picking mode		6.8 kph (4.2 mph)
Scrapping mode		8.1 kph (5.0 mph)
Field transport mode		14.5 kph (9.0 mph)
Road transport mode		27.4 kph (17.0 mph)
Final drives		Super Heavy Duty (SHFD), dual wheels standard
Brakes		Independent hydraulic assist wet disk
Parking brake		Electronically activated (spring-applied - hydraulic release)
Tyres:		
Guide wheels	Standard	520/85R34 R1 (20.8R34 R1)
	Optional	520/85R34 R2 (20.8R34 R2)
Drive tyres (duals)	Standard	520/85R42 R1 (20.8R42 R1)
	Optional	520/85R42 R2 (20.8R42 R2)
Module Builder:		
Shape		Round (Cylindrical)
Round Module Size		90 in DIA. * 94 in W (max)
Weight		2041 to 2722 kg (4,500 to 6,000 lbs)

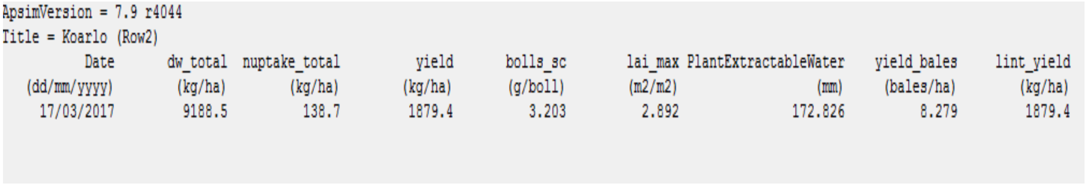
Appendix 9.1: The OZCOT-APSIM outputs for Koarlo 2017. A, B and C represent Row 1, Row 2 and Row 3 respectively

A



```
ApsimVersion = 7.9 r4044
Title = Koarlo (Row1)
           Date    dw_total  nuptake_total          yield       bolls_sc        lai_max PlantExtractableWater    yield_bales     lint_yield
   (dd/mm/yyyy)     (kg/ha)        (kg/ha)        (kg/ha)       (g/boll)        (m2/m2)                  (mm)     (bales/ha)        (kg/ha)
     19/03/2017     11277.8          177.5         2282.0          3.508          2.961               165.702         10.053         2282.0
```

B



```
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Title = Koarlo (Row2)
           Date    dw_total  nuptake_total          yield       bolls_sc        lai_max PlantExtractableWater    yield_bales     lint_yield
   (dd/mm/yyyy)     (kg/ha)        (kg/ha)        (kg/ha)       (g/boll)        (m2/m2)                  (mm)     (bales/ha)        (kg/ha)
     17/03/2017      9188.5          138.7         1879.4          3.203          2.892               172.826          8.279         1879.4
```
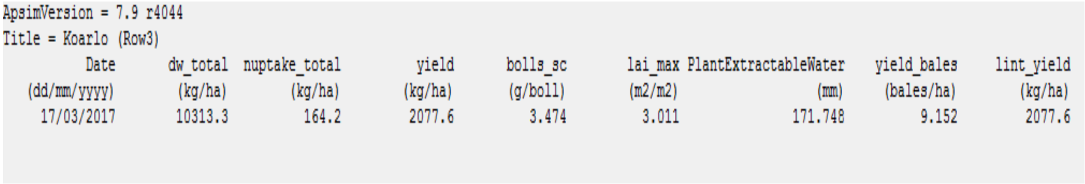

C



```
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Title = Koarlo (Row3)
           Date    dw_total  nuptake_total          yield       bolls_sc        lai_max PlantExtractableWater    yield_bales     lint_yield
   (dd/mm/yyyy)     (kg/ha)        (kg/ha)        (kg/ha)       (g/boll)        (m2/m2)                  (mm)     (bales/ha)        (kg/ha)
     17/03/2017     10313.3          164.2         2077.6          3.474          3.011               171.748          9.152         2077.6
```
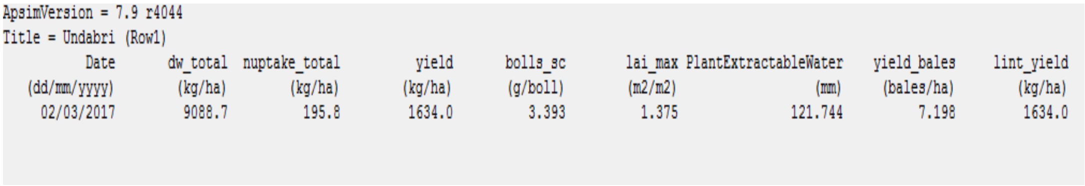
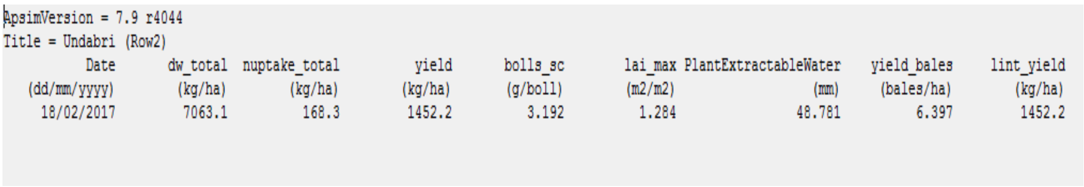

Appendix 9.2: The OZCOT-APSIM outputs for Undabri. A, B and C represent Row 1, Row 2 and Row 3 respectively

A



```
ApsimVersion = 7.9 r4044
Title = Undabri (Row1)
           Date    dw_total  nuptake_total          yield       bolls_sc        lai_max PlantExtractableWater    yield_bales     lint_yield
   (dd/mm/yyyy)     (kg/ha)        (kg/ha)        (kg/ha)       (g/boll)        (m2/m2)                  (mm)     (bales/ha)        (kg/ha)
     02/03/2017      9088.7          195.8         1634.0          3.393          1.375               121.744          7.198         1634.0
```

B



```
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   (dd/mm/yyyy)     (kg/ha)        (kg/ha)        (kg/ha)       (g/boll)        (m2/m2)                  (mm)     (bales/ha)        (kg/ha)
     18/02/2017      7063.1          168.3         1452.2          3.192          1.284                48.781          6.397         1452.2
```
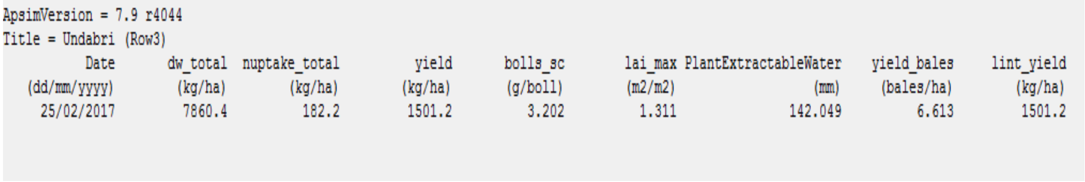
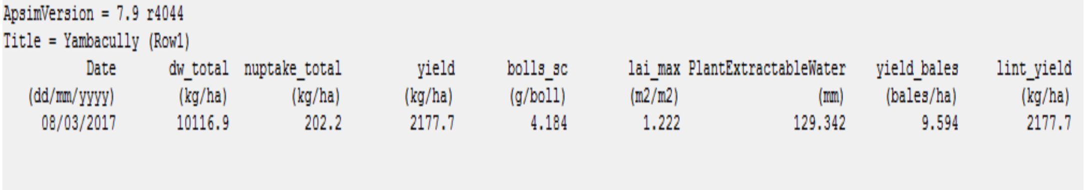

C



```
ApsimVersion = 7.9 r4044
Title = Undabri (Row3)
           Date    dw_total  nuptake_total          yield       bolls_sc        lai_max PlantExtractableWater    yield_bales     lint_yield
   (dd/mm/yyyy)     (kg/ha)        (kg/ha)        (kg/ha)       (g/boll)        (m2/m2)                  (mm)     (bales/ha)        (kg/ha)
     25/02/2017      7860.4          182.2         1501.2          3.202          1.311               142.049          6.613         1501.2
```

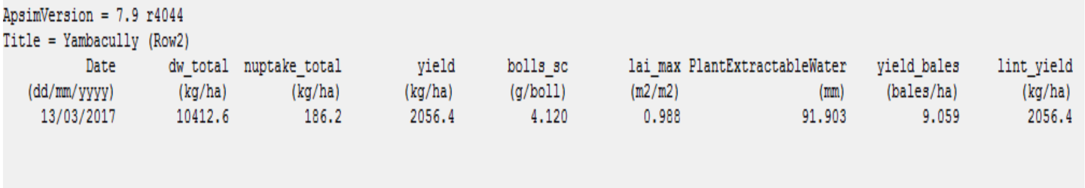
Appendix 9.3: The OZCOT-APSIM outputs for Yambacully. A, B and C represent Row 1, Row 2 and Row 3 respectively

A



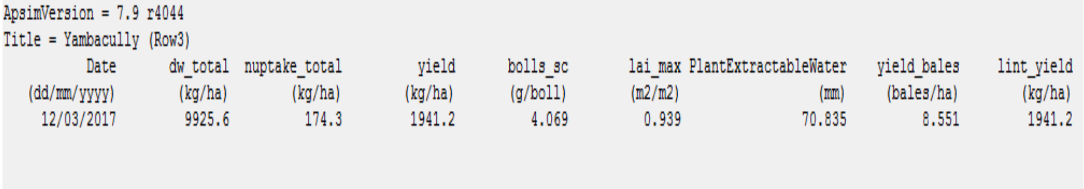
```
ApsimVersion = 7.9 r4044
Title = Yambacully (Row1)
           Date       dw_total  nuptake_total          yield       bolls_sc        lai_max PlantExtractableWater    yield_bales     lint_yield
   (dd/mm/yyyy)        (kg/ha)        (kg/ha)        (kg/ha)       (g/boll)        (m2/m2)                  (mm)     (bales/ha)        (kg/ha)
     08/03/2017        10116.9          202.2         2177.7          4.184          1.222               129.342          9.594         2177.7
```

B



```
ApsimVersion = 7.9 r4044
Title = Yambacully (Row2)
           Date       dw_total  nuptake_total          yield       bolls_sc        lai_max PlantExtractableWater    yield_bales     lint_yield
   (dd/mm/yyyy)        (kg/ha)        (kg/ha)        (kg/ha)       (g/boll)        (m2/m2)                  (mm)     (bales/ha)        (kg/ha)
     13/03/2017        10412.6          186.2         2056.4          4.120          0.988                91.903          9.059         2056.4
```

C



```
ApsimVersion = 7.9 r4044
Title = Yambacully (Row3)
           Date       dw_total  nuptake_total          yield       bolls_sc        lai_max PlantExtractableWater    yield_bales     lint_yield
   (dd/mm/yyyy)        (kg/ha)        (kg/ha)        (kg/ha)       (g/boll)        (m2/m2)                  (mm)     (bales/ha)        (kg/ha)
     12/03/2017         9925.6          174.3         1941.2          4.069          0.939                70.835          8.551         1941.2
```