THE IMPACT OF CONTROLLED TRAFFIC FARMING ON ENERGY USE AND TIMELINESS OF FIELD OPERATIONS

A Thesis submitted by

Adnan Abed Ahmed Luhaib

B.Sc., M.Sc.

For the award of

Doctor of Philosophy

2019

ABSTRACT

Over past few decades, farm machinery has simultaneously become more powerful, efficient and heavy. This increasing heaviness however, has increased the risk of deep soil compaction. Deep compaction may be rectified by deep tillage, but this is an energy-intensive process and therefore expensive. It is also often temporary as subsequent field traffic causes new compaction problems. Consequently, compaction avoidance is the best management strategy.

Controlled traffic farming (CTF) systems achieve this by confining all load-bearing wheels to the smallest possible area of permanent traffic lanes. Whilst up to 80% of cereal crops area can be wheeled in non-CTF systems each time a cereal crop is produced, the permanent traffic lanes of CTF typically occupy less than 15% of the field cropped area in well-designed grain-cropping systems.

Controlled traffic farming systems eliminate the need to disturb the compacted soil of wheel-tracks when tilling and seeding; they also minimise or eliminate the need to re-compact soft, disturbed soil for traffic and traction associated with field operations. Both aspects of CTF reduce the energy requirement of grain cropping activities. The main objectives of this work are, therefore to quantify:

- The effect of CTF on the draught requirements and soil impact (soil surface roughness and soil physical properties) of tillage and seeding operations
- The effect of driving a farm vehicle on permanent traffic lanes on the motion resistance encountered during field operations
- The implications of CTF for timeliness of field operations as motion resistance is related to trafficability and field access.

Field work was conducted during three years (2015-2017) on farms located in two Australian grain cropping regions with contrasting soils: heavy clays in the Northern region sites and lighter sands and loams in the Southern region sites. Four sites were used within each region and, where possible, experimental sites were on broadacre grain farms in long-term CTF. Northern region sites were all in Queensland, and Southern region sites were in Victoria and South Australia.

The field work was designed to assess wheel traffic effects on draught force and soil surface roughness, with replicated measurements on sweep, chisel and narrow opener

tines at three depths for wheeled traffic lanes and non-wheeled traffic lanes (adjacent crop beds). Motion resistance was assessed by replicated runs towing tractors on permanent traffic lanes, adjacent crop beds and the nearest available hard surface at three different speeds. In all cases, soil textural, physical and mechanical properties were determined together with tine parameters of width of foot (tip) and rake angle, and tyre parameters including tyre inflation pressure, wheel load, tyre section width, overall unloaded tyre diameter, tyre section height and tyre deflection.

Results derived from field studies showed that wheel traffic had a significant effect on draught force for all tines and depths in CTF sites, but was non-significant in most cases in non-CTF sites. This showed that the soil of non-CTF sites was affected by historic traffic compaction therefore, in non-CTF sites there were no differences in draught forces measured in wheeled soil and non-wheeled soil. This observation confirmed that most of the compaction damage to the soil likely occurred after the first wheel traffic.

At the Northern region sites established with CTF on clay soils, draught force measurements showed that wheel traffic increased draught by up 74% and 47% for conservation tillage system (CTS) (sweep and chisel tines) and no-tillage (NT) (seeder opener tines) respectively, compared with draught forces measured on non-wheeled soil (≈2.21 vs. 3.85 kN, and 2.7 vs. 3.18 kN for CTS and NT for non-wheeled and wheeled soil, respectively). While at the Southern region sites, the draught force increased by up to 28% and 25% respectively for CTS and NT at the Swan Hill site (loam soil), compared to draught forces measured on non-wheeled soil (≈ 0.95 vs. 1.22 kN and 1.09 vs. 1.36 kN for CTS and NT for non-wheeled and wheeled soil, respectively). At the Loxton site (sand soil), the draught force increased by up 22% and 9% for CTS and NT, respectively, compared to draught forces measured on non-wheeled soil (≈ 0.94 vs. 1.18 kN, and 0.97 vs. 1.06 kN, for CTS and NT for non-wheeled and wheeled soil, respectively).

Wheeled traffic also resulted in greater soil surface roughness. The results showed that the Northern sites had 37% for NT systems and 59% for CTS and the Southern sites had 23% for NT systems and 27% for CTS.

At Northern region sites, Controlled traffic farming resulted in improved soil physical properties. The results showed that soil penetration resistance (PR), bulk density of soil (BD), soil moisture content (MC) and shear strength (SS) at depth 0-150 mm were higher (1.58 MPa, 1.19 Mg m^{-3}, 38 % (w/w) and 0.19 MPa, respectively) and (2.18 MPa, 1.6 Mg m^{-3}, 22% (w/w) and 0.31 MPa,) on Permanent Traffic Lanes (PTL) for the Felton and Pittsworth sites respectively, compared with Permanent Crop Lanes (PCB), where the results were lower (1.04 MPa, 1.08 Mg m^{-3}, 36% (w/w) and 0.06 MPa, respectively) and (0.93 MPa, 1.17 Mg m^{-3}, 22% (ww), and 0.08 MPa, respectively), for Felton and Pittsworth sites, respectively.

At the Southern region sites of Hopetoun (VIC), Swan Hill (VIC) and Loxton (SA) respectively, results also showed that PR, BD, MC and SS were higher (3.4 MPa, 1.66 Mg m^{-3}, 11% (w/w) and 0.21 MPa, respectively), (3.68 MPa, 1.75 Mg m^{-3}, 13% (w/w) and 0.28 MPa, respectively) and (2.44 MPa, 1.67 Mg m^{-3}, 6% (w/w) and 0 MPa, respectively), with PTL, compared with PCB where the results were lower (1.91 MPa, 1.44 Mg m^{-3}, 10%(w/w) and 0.09 MPa, respectively),(2.3 MPa, 1.32 Mg m^{-3}, 8%(w/w) and 0.13 MPa, respectively) and (1.20 MPa, 1.54 Mg m^{-3}, 5% and 0 MPa, respectively).

Motion resistance (MR) results showed that wheeled traffic and ground speed both had significant effects on MR, and that traffic on permanent wheel tracks reduced MR at all CTF sites. Mean energy input to permanent traffic lane soil, that is MR on soil-motion resistance on a hard surface, was up to 23% lower in Northern region clay soils (≈9.22 vs. 11.92 kN for PTL (CTF) and non-wheeled soil (non-CTF), respectively), and up to 20% lower in Southern region sands and loams (≈10.26 vs. 12.81 kN for PTL (CTF) and non-wheeled soil (non-CTF), respectively), compared with non-wheeled soil.

Modelling of draught force and motion resistance, based on soil, tine and tyre parameters was used to validate and extend the usefulness of the field results of draught force and motion resistance. The integrated tillage force prediction model of Godwin and O’Dogherty (2007) was used to predict the draught required by the implements employed in this study. Regression analyses showed a reasonably good agreement between predicted and observed draught for the range of different tines and soil types investigated, with the exception of the Hopetoun (Victoria) site. This was because the soil of the Hopetoun site was affected by non-homogeneous compaction as a result of using different track width of equipment (incomplete CTF).

In the Northern region CTF sites, which are dominated by clay soils, model predictions of draught were within an error range between 3% and 5%, -17% and 2%, and -12% and 1% for sweep, chisel and opener tines, respectively. In the Southern region CTF sites, which are dominated by medium and light-textured soils, model prediction of draught was in the range of 5% to 26%, -13% to -8%, and -21% to -15% for sweep, chisel and opener tines, respectively.

Prediction of motion resistance was conducted with the Gee-Clough and Brixius models. Linear regression analyses showed that measured and predicted data did not correlate well, and this was observed for all soil types. But, predictions of Brixius's model was better corresponding with most experimental data of motion resistance compared with the Gee-Clough's model.

For timeliness implications, the results derived from this study showed that the improvement in trafficability for CTF can be up to 50% and 80% for NT and CT (conventional tillage), respectively at Northern region sites on clay soil, while at Southern region sites on medium and light textured soils, the improvement in trafficability was 38%.

The results of this study clearly demonstrate the potential of CTF to significantly reduce the energy requirements of cropping operations. The results demonstrate the validity and usefulness of the Godwin and O'Dogherty (2007) model. This study also demonstrates that permanent traffic lanes can significantly improve the trafficability of soil. These findings also confirm that CTF resultes in improved soil physical properties, which reduce the energy requirements of cropping operations including draught force and motion resistance, and improve trafficability and timeliness. These are expected to increase the sustainability of soil and enhance crop and environmental performance.

CERTIFICATION OF THESIS

This Thesis is entirely the work of Adnan Abed Ahmed Luhaib except where otherwise acknowledged. The work is original and has not previously been submitted for any other award, except where acknowledged.

Guangnan Chen

Principal Supervisor: ____________________

Diogenes L. Antille

Associate Supervisor: ____________________

Jeff N. Tullberg

Associate Supervisor: ____________________

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

STATEMENT OF CONTRIBUTION

This is the first study looking at the estimation of energy requirements of soil engaging implements and motion resistance of farm equipment in the context of controlled and non-controlled traffic farming systems in a wide range of Australian soils and climatic conditions. Based on the findings of this study, the following contributions to theory and practice are made to this field of research and the practice of Australian broadacre grain farmers:

- The determination and quantification of the benefits of CTF in terms of on-farm energy requirements through the estimation of total draught force from compacted and non-compacted zones. Such estimations of draught were conducted for different soils types, on- and off-wheel tracks, and for different tillage systems. Differences in energy requirements for soil engaging implements have been quantified for both CTF and non-CTF systems
- The Godwin and O'Dogherty (2007) model was used to predict draught force for a range of tine designs, soil types and soil conditions. Draught force prediction derived from this model was in close agreement (±20) with data derived from the present field experimentation. Therefore, this modelling approach may be used to assist decision-making for operators and designers of soil engaging implements
- This work also estimated the motion resistance of farm equipment travelling over compacted (wheel tracks) and non-compacted (crop beds) zones in different soils, soil conditions, and tillage systems. This work enabled differences in motion resistance to be quantified for both CTF and non-CTF systems
- Based on the field experiments and modelling work, the research indicated up to 74% reduction in the energy requirements due to non-compacted (crop beds) zone effects in CTF system compared to non-CTF systems. CTF system was able to reduce motion resistance by up to 23% compared to non-CTF systems. The CTF system also resulted in improvement in trafficability of soils (up to 80%) and timeliness of field operations due to the tramline effects compared to non-CTF systems. The research undertaken also draws a set of recommendations to further promote the adoption of CTF by Australian farmers. Areas that merit further research are presented and discussed.

ACKNOWLEDGEMENTS

I wish to express my sincere appreciation to those who have contributed to this thesis and supported me in one way or the other during this amazing journey. Without them, this research work would not have been possible.

First and foremost, I wish to place on records my heartfelt and sincere thanks to my supervisors Assoc. Prof. Guangnan Chen, Dr Diogenes L. Antille, and Assoc. Prof. Jeff N. Tullberg for their advice, guidance and continuous encouragement throughout this work. In particular, Assoc. Prof. Jeff N. Tullberg helped with the organisation of experimental fieldwork and the editing of the draft of the present thesis. Dr Diogenes L. Antille helped with the data analyses and had a major impact on the thesis. Their help and support in the past five years went far beyond the academic and technical aspects of this research, *thank you!*

This research was made possible through the financial assistance of the Iraqi Government (the Ministry of Higher Education and Scientific Research), Australian Commonwealth Government contribution through the Research Training Program (RTP), and the Grains Research and Development Corporation Project on CTF in the Low Rainfall Zone led by the Australian Controlled Traffic Farming Association. This is much appreciated.

Sincere thanks are extended to Mr Mahmood Hussein for his significant contribution and permanent assistance at all stages of the experimental work. Technical assistance from Mr Kasem Al-Halfi, Mr Sombat Khawprateep, Mr Chris Galligan, Mr Daniel Eising, Mr Bruen Smith and Mr Brian Aston (USQ, Toowoomba, QLD), Mr Brett Jahnke (UQ, Gatton, QLD) and Mr Luke Hogan and Mr Christopher Johnstone (Rimik, Toowoomba, QLD) is greatly appreciated.

I would also like to extend my special appreciation and gratitude to Mr John Piper (Felton site, QLD), Mr Peter Black (Pittsworth site, QLD), Mr Julian (Kingaroy site, QLD) Mr Alistair Murdock (Swan Hill site, VIC), Mr Darrel Boxall (Hopetoun site, VIC), Mr Robin Schaeffer (Loxton site, SA) and Mr Allen Buckley (Waikerie site, SA) for the generosity of contributing their equipment, cropping area and time to this study.

I also wish to acknowledge the proofreading support provided by Sandra Cochrane and the contribution of my supervisory team who reviewed the early versions of this thesis.

Many thanks must go to all my colleagues and friends at USQ; especially: Dr Saddam H. Al-Lwayzy, Dr Raed Al-Juboori, Mr Mohammed Haraz, Mr Mohammed Al-Azzawi and Mr Redha Al-Rekabe for their support and assistance.

My acknowledgement would be incomplete without thanking the biggest source of my strength, my father, brothers and sisters, for their love and sincere encouragement through my entire life.

Finally, this thesis is heartily dedicated to my late mother and my late nephew (Mr **Taha Luhaib**) who sacrificed his soul to liberate our city (Mousl) from ISIS.

This one is for you all!

LIST OF RELATED PUBLICATIONS

CONFERENCE PROCEEDINGS

Aikins, K. A, **Luhaib, A. A. A.**, Antille, D. L., Jensen, T., Barr, J. B. (2019). Discrete element method (DEM) for simulating draft and soil movement with a winged narrow point opener in Vertisols, (**Abstract accepted**) ASABE Paper No.: 1900038.

Antille, D. L., Nguyen-Ky, T., Aikins, K. A., Hussein, M. A. H., Singh, S., **Luhaib, A. A. A.**, Singh, A. (2018). Evaluation of NEXEN™ stabilized nitrogen applied to overhead irrigated cotton (Gossypium hirsutum L.). ASABE Paper No.: 1800252. St. Joseph, MI.: ASABE. DOI: 10.13031/aim.201800252.

Luhaib, A. A. A., Antille, D. L., Tullberg, J. N., Hussein, M. A. H**.,** Chen, G. 2017. Effect of controlled traffic farming on energy savings in Australian grain cropping systems. ASABE Paper No.: 1700583. St. Joseph, Mich.: ASABE. DOI: 1013031/aim.201700583.

Hussein, M. A. H., Antille, D. L., Chen, G., **Luhaib, A. A. A.,** Kodur, S., Tullberg, J. N. 2017. Agronomic performance of wheat (*Triticum aestivum* L.) and fertiliser use efficiency as affected by controlled and non-controlled traffic of farm machinery. ASABE Paper No.: 1700586. St. Joseph, Mich.: ASABE. DOI: 1013031/aim.201700586.

Luhaib, A. A. A., Chen, G, Tullberg, J. N, Hussein, M. A. H. 2017. Controlled traffic farming reduces energy requirements in Australian cropping systems. *The First MoHESR and HCED Iraqi Scholars Conference in Australasia 2017*, pp 360-367. http://www.iraqischolarsisca2017.org/files/proceedings_ISCA2017.pdf

Hussein, M. A. H., Antille, DL, Chen, G, **Luhaib, A. A. A.,** Kodur, S, Tullberg, JN 2017. Agronomic response of sorghum (*Sorghum bicolor* L.) to different nitrogen fertiliser rates under controlled and non-controlled traffic farming systems in Red Ferrosol. *The First MoHESR and HCED Iraqi Scholars Conference in Australasia 2017*, pp 353-359. http://www.iraqischolars-isca2017.org/files/proceedings_ISCA2017.pdf

CONFERENCE POSTERS

Luhaib, A. A. A., Tullberg, J. N., Chen, G. Antille, D. L. 2016. Effect of controlled traffic farming on energy savings in Australian grain cropping systems. ASABE Paper No.: 16-2457743. St. Joseph, Mich.: ASABE. DOI: 1013031/aim.20162456743. Orlando, Florida, USA.

Luhaib, A. A. A., Tullberg, J. N., Chen, G. Hussein, M. A. H., Antille, D. L. 2017. Effect of controlled traffic farming reduces energy requirements of no-tillage cropping systems. National CTF conference, Perth, South Australia, Australia.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

ABS	Australian Bureau of Statistics
ACTFA	Australian Controlled Traffic Farming Association
AGF	Australian Grain and Forage Seeds
ANOVA	Analysis of variance
ASABE	American Society of Agricultural and Biological Engineers
BD	Bulk Density
CA	Conservation agriculture
CI	Cone Index
CMR	Coefficient of motion resistance
C_n	Wheel numeric
CP	Chisel plough
CT	Conventional tillage
CTF	Controlled Traffic Farming
CTS	Conservation tillage system
DEM	Discrete element method
DGPS	Differential global positioning systems
FAO	Food and Agriculture Organisation
GRDC	Grains Research and Development Corporation
LGP	Low ground pressure
M	Mean

MC	Moisture content of soil
Mg	Mega-gram
MR	Motion resistance
MRT	Multiple range test
N	Mobility number
n	Number of observations
NT	No-tillage
PR	Penetration resistance of soil
PCB	Permanent crop beds
PTL	Permanent traffic lanes
QLD	State of Queensland
RTK	Real-time kinematic
SA	State of South Australia
SCTF	Seasonal Controlled Traffic Farming
SD	Standard Deviation
SE	Standard Error
SMD	Soil moisture deficit
SPSS	Statistical Package for the Social Sciences
SS	Shear strength
SSR	Soil surface roughness
ST	Shallow tillage
TMR	Department of Transport and Main Roads

TS	Tilled soil
UEE	Universal Earthmoving Equation
UK	United Kingdom
USA	United States of America
USQ	University of Southern Queensland
VIC	State of Victoria
WS	Wheeled soil
ZT	Zero-Tillage

TERMINOLOGY

Header = harvester = reaper (in South Australia) = combine harvester in UK and USA

Non-wheeled soil = TS or Tilled Soil (Gatton site) = NT or No Tillage (Waikerie site)

Permanent crop bed = non-wheeled traffic = seedbed = NT (in Felton, Pittsworth, Hopetoun, Swan Hill and Loxton sites)

Permanent traffic lane =Wheeled track = tramline (permanent) = wheeled-way

Tramline (UK) = Seasonal wheel track

Seeder = bar (in Western Australia) = air-seeder = planter (in Eastern Australia)

Sprayer = boom-spray

CHAPTER 1: INTRODUCTION

1. INTRODUCTION

1.1. Background

The need to continuously increase farm operating efficiency and reduce the cost of labour motivates the use of larger farm equipment. For instance, the mass of the larger agricultural tractors and harvesters has increased from less than 2 Mg in the 1940s to up to approximately 40 Mg today. When heavy equipment is used on moist, weak soil conditions, the risk of soil compaction increases significantly (Chamen & Longstaff 1995; Horn et al. 2006).

Soil compaction refers to the increase in soil density and consequent reduction in soil porosity, which therefore restricts water and air entry to the soil. This increases the risk of runoff and erosion. Compaction also increases resistance to root penetration, reducing root growth and crop yields (Khan et al. 2012). It is considered to be a serious environmental problem and is responsible for severe physical land degradation (e.g. Iler and Stevenson, 1991; Al-Gaadi 2013).

Often, compaction of arable land in mechanised crop production is caused by vehicular traffic or external loads applied to soil by farm machinery (Hassan et al. 2007; Ahmad et al. 2009). While the first pass by a given machine can create up to 85% of the damage, (Jones et al, 1990), soil deformation increases with the number of subsequent passes (Seker & İşıldar 2000), so compaction is also related to the intensity of traffic or the number of tractor passes.

In cropping systems where controlled traffic is not practiced, the area subject to traffic is often greater than 45%, and traffic may occur in different areas in successive crops. The trafficked area can be as large as 85% in conventional tillage systems (Tullberg et al. 2007). The outcome is widespread compaction throughout cropped fields, with substantial damage to soil structure; sometimes up to a depth of 40 cm or more (Batey 2009). Depending on soil type, rainfall and crop species, this can also prevent crops from reaching yield potential and, in cereal crops, yield losses of 10% to 40% have been reported by Hussein et al. (2017, 2018) in Southern Queensland.

Soil compaction may be rectified by deep tillage (Spoor & Godwin 1978), but deep tillage is energy-intensive, expensive, and often ineffective particularly when soil re-settles very rapidly or has negative effects where an unfriendly subsoil layer is mixed with the topsoil (Tullberg 2018). The cost of soil compaction in Australia is estimated to be AUD $850 million per year (Walsh 2002) and AUD $450 per hectare (White 2007). Controlled traffic farming (CTF) systems offer an effective means of managing soil compaction and saving energy, in addition to other agronomic and environmental benefits (Tullberg 2000; Vermeulen & Mosquera 2009; McPhee et al. 2015). The Australian Controlled Traffic Farming Association Inc. (ACTFA, https://www.actfa.net/) defines Controlled Traffic Farming (CTF) as a system in which:

- All machinery has the same or modular working and track gauge width, which enables establishment of permanent traffic lanes
- All machinery is capable of precise guidance along those permanent traffic lanes
- Farm, paddock and permanent traffic lane layout are arranged to optimise drainage and logistics (**Figure 1.1**).

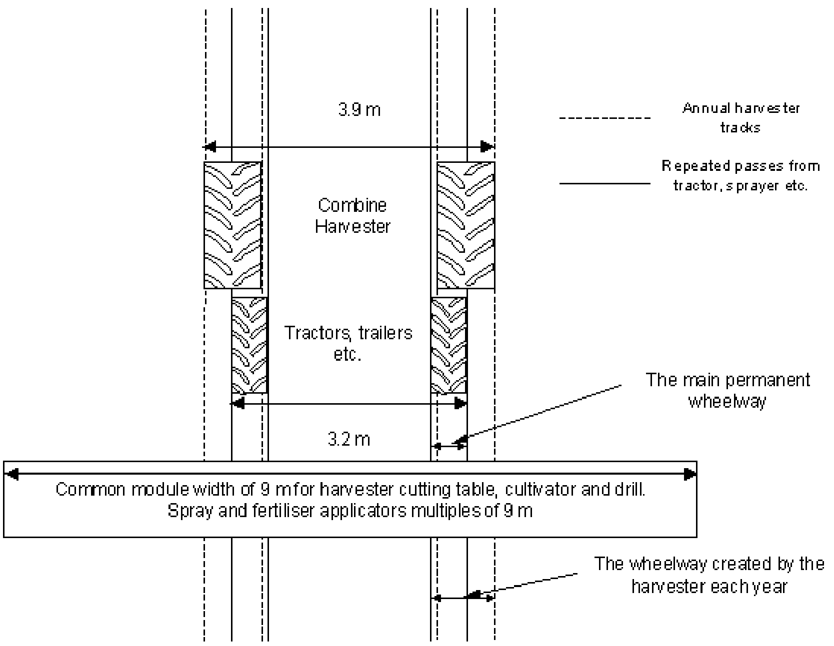


Figure 1.1: Layout of traffic lanes under controlled traffic farming systems (Chamen et al. 2003)

In well-designed CTF grain-cropping systems, permanent traffic lanes typically occupy ≤15% of the total cultivated area, particularly when permanent no-tillage is practised. By contrast, in the absence of CTF, the area subject to traffic is often greater than 45% and can even be as high as 85% in conventional tillage systems that require primary tillage operations prior to crop establishment (Tullberg et al. 2007).

CHAPTER 1: INTRODUCTION

In general, the tyres of agricultural equipment need strong soil for efficient traffic and traction, but agricultural crops need weak, non-compacted soil for plant growth (Tullberg 2008; Botta et al. 2012). Therefore, soil compaction has positive effects on the mobility, trafficability and motion resistance of wheeled vehicles. According to Zoz (1970), the tractive efficiency (TE) of wheeled tractors is greater on firm soils but smaller on soft soils due to the difference in soil strength. Furthermore, soil compaction has a positive impact on the coefficient of motion resistance (Kurjenluoma et al. 2009; Botta et al. 2012).

Terms of trafficability is known as the ability of the soil to support and provide mobility for a vehicle (Muro & O'Brien 2004; Shoop 2009). Mobility is referred to as the ability of a vehicle to establish motion between two designated points over a prescribed course (Yong et al. 1984). Whereas motion resistance is defined as the force opposing the movement of a wheel (or other running gear) on a given surface (Macmillan 2002). Motion resistance is often expressed in terms of the motion resistance coefficient, which is the motion resistance per unit wheel load.

The obvious solution for soil compaction prevention is complete and permanent separation of productive cropping soil (beds) from the permanent traffic lanes to which all heavy wheels track systems are confined. This combination might be expected to largely eliminate compaction from cropping beds, ensuring improved crop performance, while the severely compacted traffic lanes ensure improved trafficability (mobility and motion resistance) and tractive performance for machinery and improved timeliness of cropping operations.

Controlled traffic farming systems restrict compaction to precise permanent traffic lanes and improve wheel performance (enhancing mobility and reducing motion resistance), leaving natural soil processes and productivity, uncompromised by heavy traffic, over most of the field area (Vermeulen et al. 2010). Controlled traffic farming offers an effective means of managing compaction and saving energy by operating agricultural machinery on uncompacted soil (Tullberg 2000) and, more importantly, avoiding structural damage to cropping soil. This usually results in an improvement in the soil structure of cropping paddocks (McHugh et al. 2009) and enhanced crop and environmental performance (Tullberg et al. 2018).

CHAPTER 1: INTRODUCTION

Australian farmers who practice CTF report reduced power and fuel requirements for field operations. While CTF has been the subject of considerable research, most has focused on the agronomic and environmental aspects such as gaseous emissions and loss of crop yield (e.g. Braunack et al. 1995; Braunack & McGarry 2006; Li et al. 2008; McHugh et al. 2009; Antille et al. 2016; Tullberg et al. 2018). Little research has been conducted on the matter of energy requirements in CTF. Therefore, the assessment of CTF is of great importance because of its consequences for soil compaction, and its effect on energy requirements. There appears to be a paucity of information concerning the effects of compaction of wheel tracks on the energy requirements of modern, heavy tractors and harvesters, some of which are more than 40 Mg.

The conclusions derived from the literature review indicate that only two studies in Australia (Tullberg 1986; 2000), have investigated traffic impacts on tillage energy requirements, but the heaviest traffic used in that study was produced by a 6 Mg tractor which was used in only one cropping system. This study also gave no consideration to the detrimental effects of wheel traffic on the motion resistance of equipment. However, Tullberg (2000) did observe that the traffic effect of wheels on the draught of tillage implements increased total draught by 30% or more compared with the same implement operating in non-trafficked soil. Burt et al. (1994) in the USA and Arslan et al. (2015)in the UK however, found that traffic systems had no significant effect on energy requirements but, these studies gave no consideration to the detrimental effects of wheel traffic on the motion resistance of equipment.

Thus, this project study has first investigated the effect of wheel traffic on the energy requirements of soil-engaging implements in a number of cropping environments. This study also assessed the effect of permanent traffic lanes on the motion resistance of farm equipment for crop production. The experimental data was obtained from assessing the textural and physical parameters of the soil in both wheeled and non-wheeled conditions. Modelling and validating were used to extend the usefulness of the results on both draught force and motion resistance. To achieve this, the Godwin and O’Dogherty (2007) model was used to predict draught force, while the Gee-Clough (1980) and Brixius (1987) models were used to predict motion resistance. The latter models were also used to determine impacts of CTF on timeliness by comparing the results of mobility and coefficient of motion resistance under uncontrolled and controlled traffic conditions.

1.2. Project description

1.2.1. Aim

The overall aim of this research is to determine the energy effects of CTF in the context of Australian broadacre grain cropping systems, and using tillage draught and motion resistance models to provide more generalised outcomes.

1.2.2. Hypothesis

The hypothesis of this research is:
The separation of traffic lanes and crop bed under CTF reduces draught (energy) requirements and machinery motion resistance. Reducing machine motion resistance improves trafficability, field access and timeliness of field operations.

1.2.3. Objectives

To achieve the overall aim of this research, the following objectives were defined:

1) To determine the effect of wheel traffic on the draught force of soil-engaging implements (tillage and seeding)
2) To model draught of soil engaging implements operated in controlled and non-controlled traffic systems in Australian soils
3) To determine the effect of permanent traffic lanes on motion resistance
4) To identify the implications of CTF for timeliness of field operations as motion resistance is related to trafficability and field access.

1.3. Outline of methodology

This research tested the hypotheses that the permanent traffic lanes of CTF systems improve the productivity and sustainability of conservation farming by reducing the energy requirements and timeliness of field machinery operations. To achieve a strong conclusion on the outlined objectives, a number of approaches will be used. The research was undertaken in five phases as shown below.

1.3.1. Phase I

Review the relevant literature to assess the current state of knowledge on the impacts of soil compaction by farm machinery traffic on the energy requirements of soil-engaging implements. The following aspects were also taken into account:

- Identification of those parts of the Australian agricultural system using CTF and their cropping environment
- The impact of soil properties on draught force and motion resistance
- Understanding how traffic influences on draught force and motion resistance are important engineering considerations which have a direct effect on energy use-efficiency on-farm
- A critical review of draught force prediction models
- An overview of the motion resistance models with an emphasis on the Gee-Clough and Brixius (ASABE) models.

As a result of these, the draught force objective will be achieved using a special machine called a tillage unit (**Figure 1.2**). It was manufactured to measure the draught force immediately behind the tractor wheel and off wheel.

Figure1.2: Overview of the experimental tillage unit

In addition, the three tine types to be used (chisel, sweep, and seeder opener), are widely used in Australian farming. The three working depths to be used (75, 100, and 125 mm) are those commonly used for planting and fertiliser application: shallow tillage, and deep placement of fertiliser, respectively. This stage will also examine the calibration and testing of experimental devices, such as load cells and pull meter, which will be used in all experiments. Device testing was conducted at the USQ Materials Laboratory. These devices were then tested at the USQ ag-plot before being utilised in a real farm environment.

1.3.2. Phase II

The main task of this stage was to conduct the experimental work on-farm to investigate the effect of traffic-induced compaction on the energy requirements of soil-engaging implements. This experiment is related to Objective 1. The study was done at different sites as follows:

- Queensland:
  - Felton (CTF system)
  - Pittsworth (CTF system)
  - Gatton (non-CTF system)
  - Kingaroy (non-CTF system)
- Victoria:
  - Hopetoun (incomplete CTF system)
  - Swan Hill (CTF system)
- South Australia:
  - Loxton (CTF system)
  - Waikerie (non-CTF system).

These are common areas where CTF is most widely used on larger crop areas in Australia. Furthermore, some soil parameters were measured during these experiments:

- Dry bulk density
- Moisture content
- Shear force
- Soil penetration resistance
- Soil profile.

1.3.3. Phase III

This stage specifies the details of laboratory work conducted in the civil engineering facility at the University of Southern Queensland to measure the soil mechanical properties:

- Cohesion
- Soil friction angle
- Adhesion
- Soil-metal friction.

These measurements were made to feed the Godwin and O'Dogherty (2007) model to predict the draught force. The task of this stage was aimed at achieving Objective 2.

1.3.4. Phase IV

The literature review revealed that variation in soil condition and type can influence machine energy requirements due to differing soil strength and bulk density. Therefore, soil condition was selected as the first factor. Two soil conditions were represented in both CTF and non-CTF systems. Permanent Traffic Lane (PTL) and Permanent Crop Bed (PCB) were used in the CTF systems. In the non-CTF system, the soil condition factor was represented using non-wheeled soil to represent non-compacted traffic lanes and wheeled soil to address compacted traffic lanes. Because of variation in working speed on the farms due to the diversity of agricultural operations, working speed was selected as the second factor. This stage consisted of conducting the experiment in all selected sites, to achieve the Objective 3. The results from this experimental work were compared with results obtained from the Gee-Clough and Brixius (ASABE) models (Objective 3).

1.3.5. Phase V

This stage specifies the details on timeliness, thus the results from the experimental work conducted in **Phase 2 and 4** were brought together to investigate the effect of CTF on timeliness. This stage was designed to achieve the Objective 4 of the research. At the end of the study, findings were summarised and conclusions were drawn. Recommendations for future research in this field were also produced.

1.4. Statistical analyses

Experiments in this study were conducted in a block design. Statistical analyses were undertaken using the Statistical Package for Social Sciences (SPSS) (version 24), and involved the analysis of variance (ANOVA), and Duncan's multiple range test (MRT) to compare the means. A probability level of 5% ($p<0.05$) was used. Nonlinear and linear regression analyses were used to describe the relationships between draught force and operating depth. The relationship between motion resistance and cone index was investigated by regression analyses. This also was used to describe the relationships between predicted and measured values for draught force and motion resistance. The relationship between motion resistance coefficient and mobility number was also investigated by linear regression analyses. The values of analyses are reported as the mean and standard deviation (SD).

1.5. Thesis structure

A summary of the methodological approach and the thesis structure is shown in **Figure 1.3**.

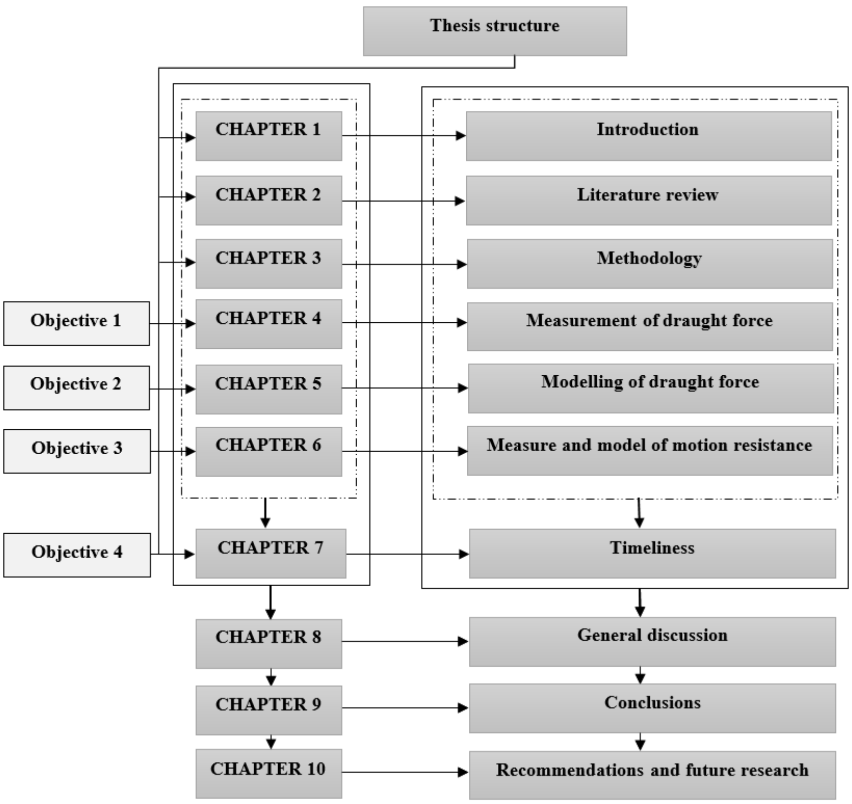


Figure 1.3: Outline of the research methodology and summary of the thesis structure

CHAPTER 1: INTRODUCTION

Chapter 1 presents an introduction to the research and background information which link into the subsequent chapters. **Chapter 2** provides a literature review on soil compaction and its impact on soil properties, yield and energy requirements of agricultural machinery. The focus of the review includes controlled traffic farming (CTF) as a system used to manage soil compaction in field, comparative studies between CTF and conventional practice, and CTF's role in increasing agricultural productivity and reducing energy requirements. This work identifies the scientific and knowledge gaps in the literature.

Chapter 3 introduces the methodologies employed to meet the four research objectives. This chapter includes site locations and layouts, methods and the equipment used at each site, soil descriptions and an overview of instrumentation used in this research. **Chapter 4** presents the research carried out at field scale to examine the effect of wheel traffic on the draught force of soil-engaging implements and soil surface roughness. The outcome of this chapter addresses Objectives 1. **Chapter 5** introduces the modelling aspects of the data in relation to draught force. The results of this chapter refer to Objective 2.

Chapter 6 focuses on the experimental work to assess the benefits of permanent traffic lanes in CTF on the motion resistance characteristics of farm equipment on a range of soil types and conditions. In addition, the chapter also covers the models which have been used to predict motion resistance. The results of this chapter address Objective 3. **Chapter 7** focuses on the role of CTF in the improvement of timeliness of cropping operations. Special emphasis has been placed on the effect of permanent traffic lanes trafficability and field access, which are related to motion resistance. The results of this chapter refer to Objective 4.

Chapter 8 integrates the findings from **Chapters 4**, **5**, **6** and **7** to provide an overall discussion. **Chapter 9** presents the conclusions of this research project, reflecting on the overall findings from each of the previous chapters. A number of recommendations and future research directions are provided **Chapter 10**.

2. LITERATURE REVIEW

2.1. Introduction

This literature review attempts to:

- Summarise the current state of knowledge on soil compaction
- Identify those techniques that can be used to manage the soil compaction
- Understand how CTF influences tillage draught forces and motion resistance
- Properly identify the knowledge gap this research aims to correct.

2.2. Soil compaction

Knowledge on soil compaction has increased remarkably in the past two decades (Sidhu & Duiker 2006; Batey 2009; Nawaz et al. 2013; Antille et al. 2016). Many researchers have defined soil compaction one of these is Craig (1997), who defines it as *"the process of increasing the density of a soil by packing the particles closer together with a reduction in the volume of air but with no change in the volume of water"*. Chancellor and Schmidt (1962) pointed out that soil is compacted when the load applied to the soil is larger than its strength. **Figure 2.1** attempts to illustrate its impact on porosity. Soil compaction is often associated with an increase in soil density and strength, and reduction in soil macro-pores, which decreases the hydraulic conductivity (Schwab et al. 2002), and affects water, air and nutrient availability to plants (Agricultural Training Board 1989).

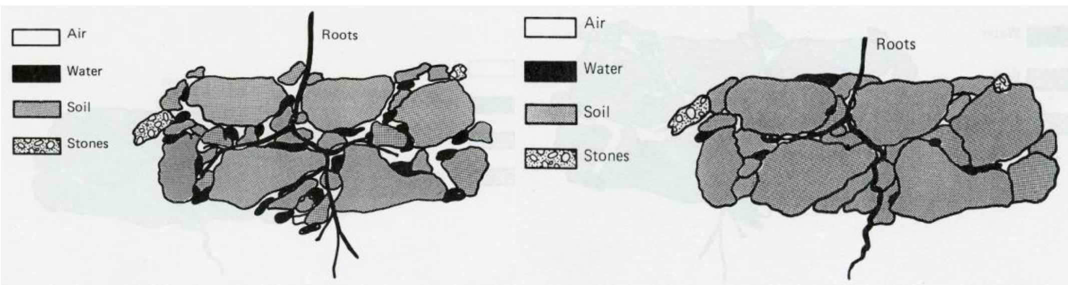


Figure 2.1: Soil compaction causes a reduction in available space for air and water (Agricultural Training Board 1989 quoted by Misiewicz 2010)

Soil compaction can occur at any soil layer and can be caused by a number of factors. Chancellor (1976) classified these as natural soil-forming processes resulting from the impact of animals or human intervention (mechanical farm/forestry operations). The last factor is generally regarded as the primary factor, and clearly within man's control

(Lipiec et al. 2003). Raper (2005), for instance stated that 90 % of soil compaction is caused by machinery traffic, and similar statements were made by Soane et al. (1980b); Soane and van Ouwerkerk (1980).

Soil compaction changes the physical, mechanical, chemical and biological properties of soil which severely inhibits the capability of the soil to supply plants with water and the air. According to Tullberg (1990), traffic from wheeled farm machines is common in most agricultural operations, even in zero tillage systems. Most, if not all, common farm operations require the use of heavy machinery during field operations and Soane et al. (1982), found that >90 % of field area is impacted during traditional UK seedbed preparation. An example of high traffic area in Australia is illustrated **Figure 2.2**.

Figure 2.2: Traffic patterns from non-CTF cropping are illustrated in this photograph taken after flash flooding removed loose surface tilth from a conventionally-tilled, freshly seeded field in Central NSW (McGarry, no date quoted by Tullberg et al. 2007)

Soil compaction has been reviewed by many authors, (e.g. Soane et al. 1980a, 1980b; Soane et al. 1982; Hamza & Anderson 2005; Batey 2009; Nawaz et al. 2013), who have provided a detailed overview of its causes. Compaction is affected by a number of factors such as nature and type of soil, soil moisture content, amount of compaction attainable under field conditions, and type of machinery causing compaction (Whitlow 2001). The susceptibility of the soils to compaction varies with the soil texture. Frictionless clay soils (clay) are the most susceptible to compaction, and silt soils and cohesion-less sand soils the least (Horn et al. 1995) when they are at the optimum water content. The susceptibility of soils to compaction is highly affected by water content (Horn et al. 1995; Hamza & Anderson 2005), and most soils offer more resistance to compaction when dry. As water is added to dry soil; it is absorbed and films are created around the soil particles, providing lubrication as they pack more closely together as illustrated in **Figure 2.3**.

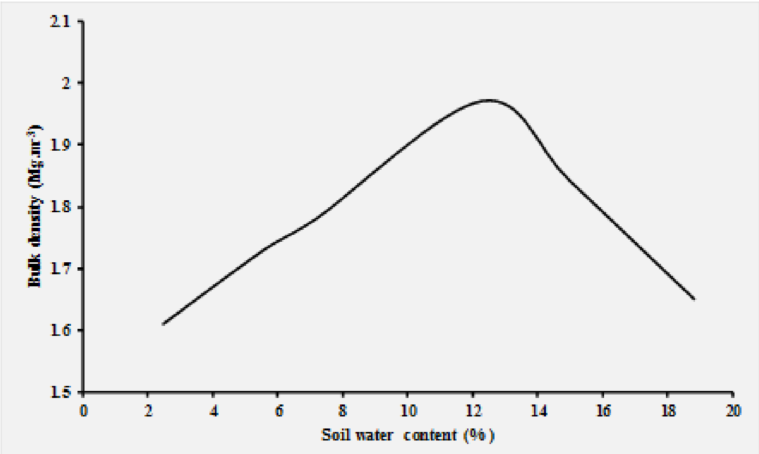


Figure 2.3: Dry bulk density vs. water content relationship (Ishaq et al. 2001)

The primary source of external soil loads is the running gear of tractors and machinery. When these loads produce stresses less than that soil's pre-compression stress, the outcome is largely elastic deformation according to Koolen and Kuipers (1983) and Horn and Lebert (1994). In this case, compaction occurs only under stresses greater than the precompression stress. Subsequent work by Kirby (1991) and Keller (2004) found that some permanent deformation also occurs when measured stress is less than the pre-compression stress. **Figure 2.4** presents the effect of a wheel load on soil.

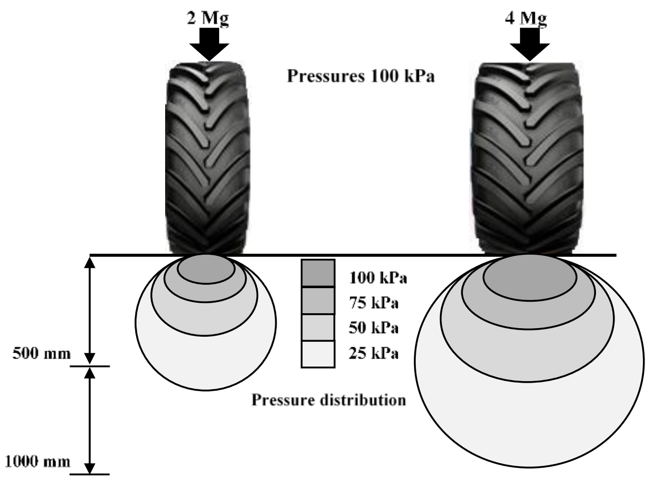


Figure 2.4: Pressure stresses distribution beneath two different tyres and loads at same ground pressures (Forristal 2003)

The soil compaction caused by wheel load at given soil condition depends on tyre carcass stiffness, inflation pressure, diameter and section width (Håkansson et al.

1988; Antille et al. 2013). If the tyre carcass is more flexible, then more load is carried by the rolling surface and less on the edges of the carcass (Misiewicz et al. 2016). Low inflation pressure of the tyre results in an increase in the footprint and tyre flexibility (Ansorge 2007). Raper et al. (1995) found that increased inflation pressure decreased both the total contact length and the total contact area of the tyre, and resulted in the level of soil-tyre interface stresses (**Figure 2.5**). Soil compaction can result from high contact pressure, low soil strength, or both (Soane et al. 1982).

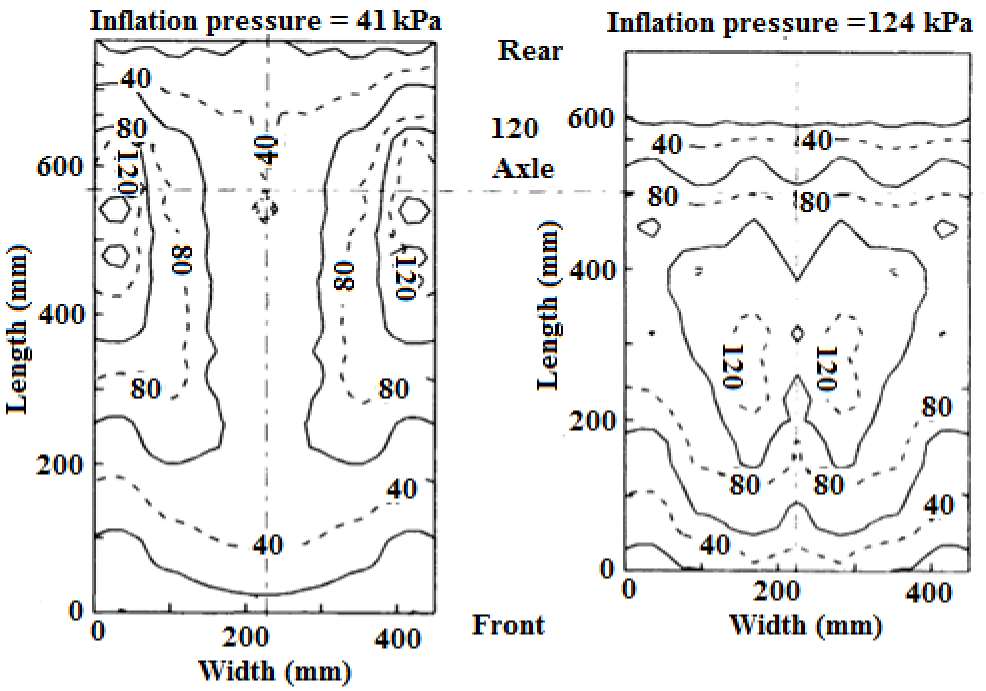


Figure 2.5: Effect of tyre inflation pressure on soil-tyre interface stress (kPa) for 18.4R38 tyre with load 1.34 Mg (Raper et al. 1995)

The effects of tyre size at high axle loads and a range of inflation pressure were investigated by Antille et al. (2013), where soil compaction resulting from loaded tyres was assessed. The study proved that increased tyre size and low inflation pressure reduced both soil deformation and the increase in soil bulk density beneath the tyres. The authors also found the advantage of increasing tyre size (i.e. contact patch area) and lowering inflation pressure where the tyre with the highest inflation pressure gave a significantly higher increase in penetration resistance obtained from drop-cone penetrometer compared with the tyres with lower inflation pressures. In a different study, Ansorge and Godwin (2007) examined the effects of tyres and tracks at high axle loads on soil compaction. Their results show that the TerraTrac system causes less soil damage than tyres (at an overall load of 12 tonne for the tracks and 10.5 tonne for the tyres).

In spite of a great benefits of reducing the pressure of the equipment load on a soil at given condition which could be achieved by increasing the contact area but the total volume of compaction does not necessarily reduce, however, most of the soil receiving most of the compaction will be near the surface (Chancellor 1976). Its alleviation is usually costly in terms of the energy and power required by the soil loosening process.

2.3. Influencing of soil compaction

Soil compaction is considered to be a multi-disciplinary problem in which machines, soil and crop interactions play an essential role. It is also seen as a major cause of physical land degradation worldwide (e.g., Al-Gaadi 2013) and a threat to agricultural productivity. Compaction is responsible for the degradation of an estimated 83 million hectares globally, in Europe (33 million ha), Africa (18 million ha), Asia (10 million ha), Australia (4 million ha), and in some areas of North America (Flowers & Lal 1998; Hamza & Anderson 2005; Nawaz et al. 2013). Mechanical methods such as deep ripping can be used to disturb compacted soil, but these are expensive and consume much energy, as noted by Raper et al. (1995). Lipiec et al. (2003) tried to summarise all the factors influencing of soil compaction in his scheme (**Figure 2.6**).

The effects of soil compaction are not always negative. Appropriate soil compaction may improve the germination of seeds by providing a better soil/seeds contact and might also improve root absorption of nutrients and water (Arvidsson 1999). It has also been said to improve the ability of the soil to withstand further stresses by increasing its (mechanical) strength of the soil and improving mobility and traction (Schafer et al. 1992).

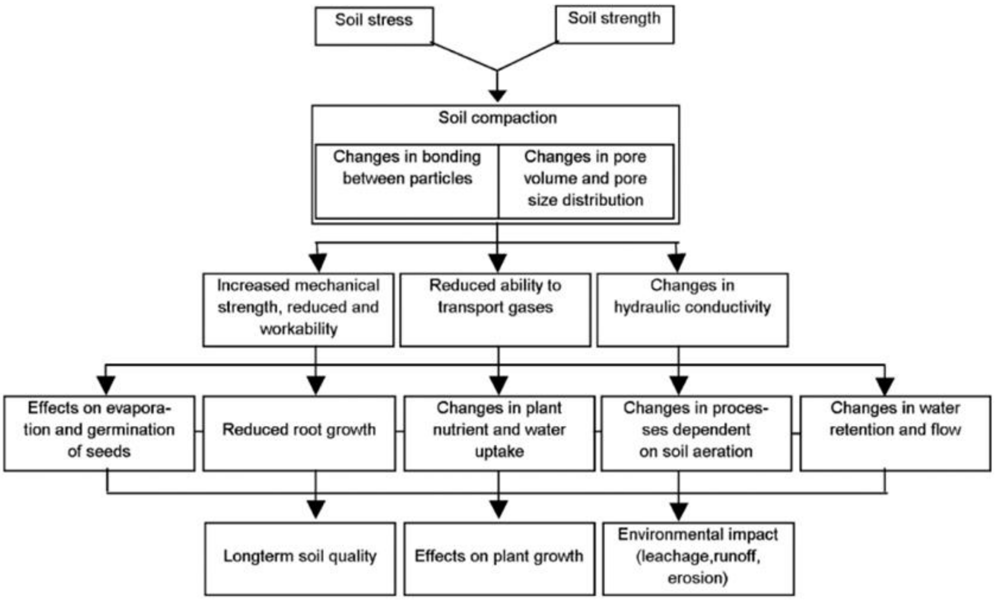


Figure 2.6: Scheme of soil compaction influences (Lipiec et al. 2003)

2.3.1. Influence of soil compaction on soil physical properties

The physical parameters used to quantify soil compactness include bulk density and porosity, soil strength, water infiltration rate, and reduction of aeration(Nawaz et al. 2013).

Bulk density, the dry soil mass per unit volume, is the parameter most commonly used to characterise and quantify the soil compaction (Panayiotopoulos et al. 1994), but in shrink/swell soils, characterisation and quantification of soil compaction should be done at the standard soil moisture content (Håkansson & Lipiec, 2000). For an accurate determination of the influences of the soil compaction on all soil types, the soil bulk density alone is not enough; other soil parameters such as penetration resistance (cone index), soil aeration, and soil moisture content should also be measured (Lipiec & Hatano 2003). Chamen (2006) presented a comprehensive review of soil compaction effects on soil strength and bulk density, and concluded that imposed wheel loads caused an increase in both soil bulk density and penetration resistance.

In an experiment on a silty clay loam, Jorajuria and Draghi (1997) measured the impact of traffic intensity (0, 1, 5 and 10 passes) on bulk density by comparing the impact of tractors with similar contact pressures but different mass (4.2 Mg and 2.3 Mg) on a soil (**Figure 2.7**).

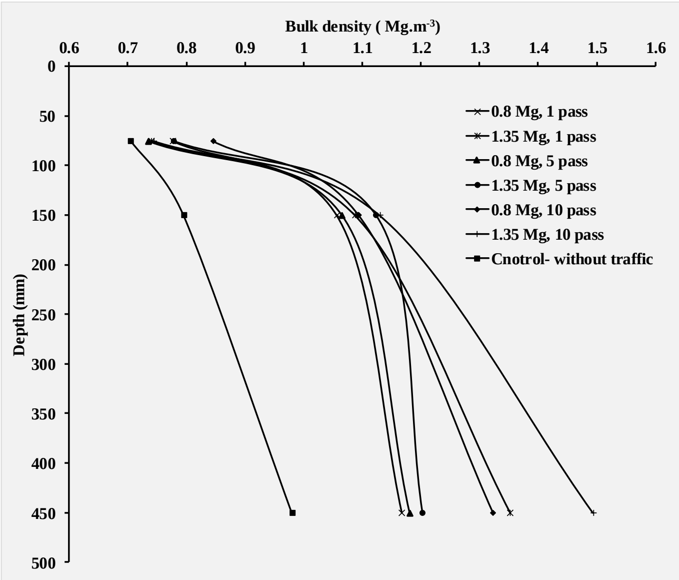


Figure 2.7: The Relative effects of wheel loads and wheel passes on soil bulk density (Jorajuria and Draghi 1997).

They noted that the first pass of both tractors caused a greater increase in soil bulk density (26% and 20%, respectively) than that of five passes (24%, and 19%, receptively); an effect confirmed by Silva et al. (2008). The impact of traffic compaction is nevertheless highly variable in different soils and cropping systems, as demonstrated by Chamen (2006) (**Figure 2.8**).

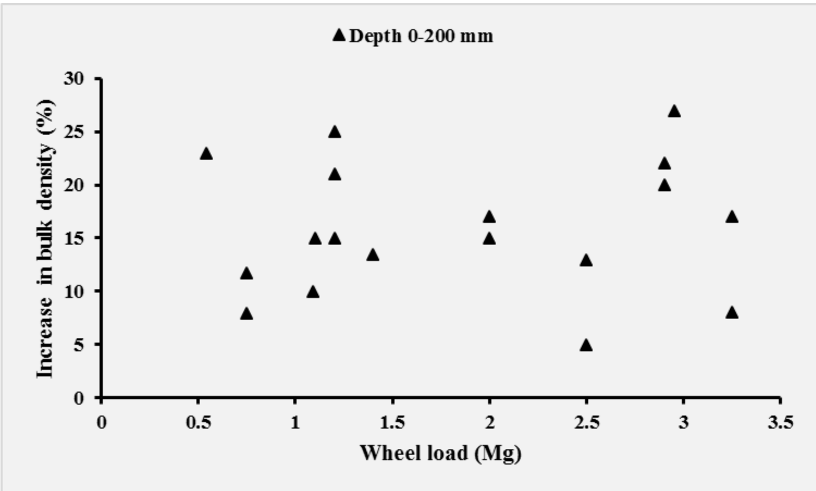


Figure 2.8: Wheel loads effects on bulk density of the surface 200mm in different UK cropping systems and soils

Bulk density increases with a decrease in the number and volume of large soil pores, which in turn alters aeration, infiltration, and hydraulic conductivity. It is normally accompanied by an increase in soil strength and penetration resistance, which is often used as a parameter of soil compaction (e g. Chamen et al. 1990; Botta et al. 2006;

Nawaz et al. 2013). The cone penetrometer is widely employed (ASABE 2013a) to carry out simple measurements of soil strength and indicate soil accessibility for root penetration and exploration (Materechera & Mloza-Banda 1997). Ghildyal and Tripanthi (1987) demonstrated a clear linear relationship between penetration resistance and bulk density for one soil at the same moisture content. Soil strength normally increases with bulk density, but it also decreases with moisture content, so caution is necessary when interpreting penetration resistance measurements when moisture content varies (Bouwman & Arts 2000). Other factors such as clay content and exchangeable cations can also affect soil strength (Mathers et al. 1966).

The literature includes many papers investigating soil compaction in terms of bulk density and penetration resistance (e.g. Chamenet al. 1990; Chamen & Cavalli 1994; Jorajuria et al. 1997; Botta et al. 2002; Pagliai et al. 2003; Radford & Yule 2003; Botta et al. 2006; Nawaz et al. 2013), but the difficulty with using penetration resistance alone to measure compaction effects has been demonstrated by Chamen (2006) who collated data for wheel load impacts on penetration resistance across the depth range 0–500 mm for different UK cropping systems and soils (**Figure 2.9**).

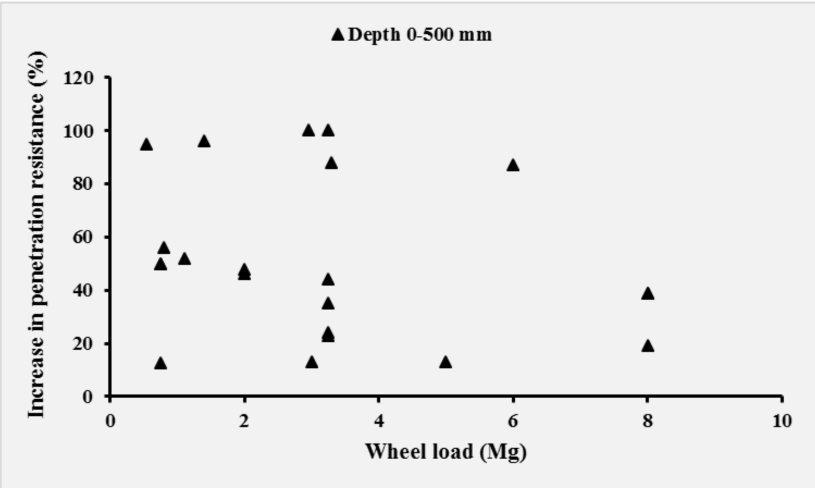


Figure 2.9: Wheel load effects on penetration resistance change across different UK cropping systems and soils

Traffic-induced soil compaction causes deleterious effects on pore space, water holding capacity, infiltration, and drainage characteristics of soil, so hydraulic conductivity and water infiltration rates can also be used as indicators of soil compaction (Silva et al. 2008). This has been demonstrated by many authors, and a review by Chamen (2011) reported infiltration ranging from 84 to 400% in uncompacted versus compacted soil. Australian examples include Hamza and

Anderson (2003), and Li et al. (2001) who reported a 4–5 fold increase in infiltration in the absence of traffic. Another example is illustrated in **Table 2.1**.

Table 2.1: Soil conditions affects by soil compaction at 0-61 mm. (Flocker et al. 1958)

Compaction treatment	Bulk density ($Mg.m^{-3}$)	Air-filled porosity (%)	Water infiltration rate ($mm.h^{-1}$)
Light	1.25	30.8	40.17
Moderate	1.40	22.6	9.7
Severe	1.56	13.6	10

The hydraulic conductivity of soil is defined as "the ratio of water flow rate (flux) to the potential gradient, where flux is normally expressed as volume per unit area per unit time" (Hillel 2007). Chamen and Longstaff (1995) demonstrated the significant effect of 3 Mg wheel load traffic in reducing hydraulic conductivity of 4-year non-trafficked clay soil at 0.8 m depth from 30 to 12 $mm.day^{-1}$. Arvidsson (2001) documented a more extreme case of the conductivity change produced by four passes by a 10 Mg wheel load sugar beet harvester (**Table 2.2**).

Table 2.2: Hydraulic conductivity following four passes of a sugar beet harvester with 10 Mg wheel loads on a loam soil (Arvidsson 2001)

	Hydraulic conductivity, $mm\ h^{-1}$			
Depth	**300-350 mm**		**500-550mm**	
Year	1996	1999	1996	1999
Reduction (%)	825	596	1314	406

Reduced soil aeration is an indicator of soil compaction. This indication can be quantified by different parameters such as the air filled porosity, oxygen diffusion rate, redox potential, and air permeability (Cannell 1977). The data presented in **Table 2.1** indicate how extreme compaction effects can be on the air filled porosity. Soil aeration is also fundamental for the activity of the soil organisms which develop soil structure and fertility through interaction with organic matter and crop residues to supply the soil with humus and nutrients.

Compaction reduces pore size and number, reducing the infiltration capacity of soil, increasing surface runoff and erosion under intense rainfall. Tullberg et al. (2001) demonstrated that tractor traffic produced a consistent annual runoff over 4 years. In this case mean annual run-off from wheeled plots was 44% greater than that from controlled traffic plots, whereas runoff from stubble mulch tillage plots was 24% greater than that from zero tillage plots. Greater run-off is also associated with greater erosive loss of soil and nutrients.

2.3.2. Crop growth and yield affected by soil compaction

The relationship between crop performance and soil compaction has been widely investigated, because compaction often has negative effects. (**Figure 2.10**), and most researchers recognise that soil degradation is likely to diminish the capacity for productive cropping.

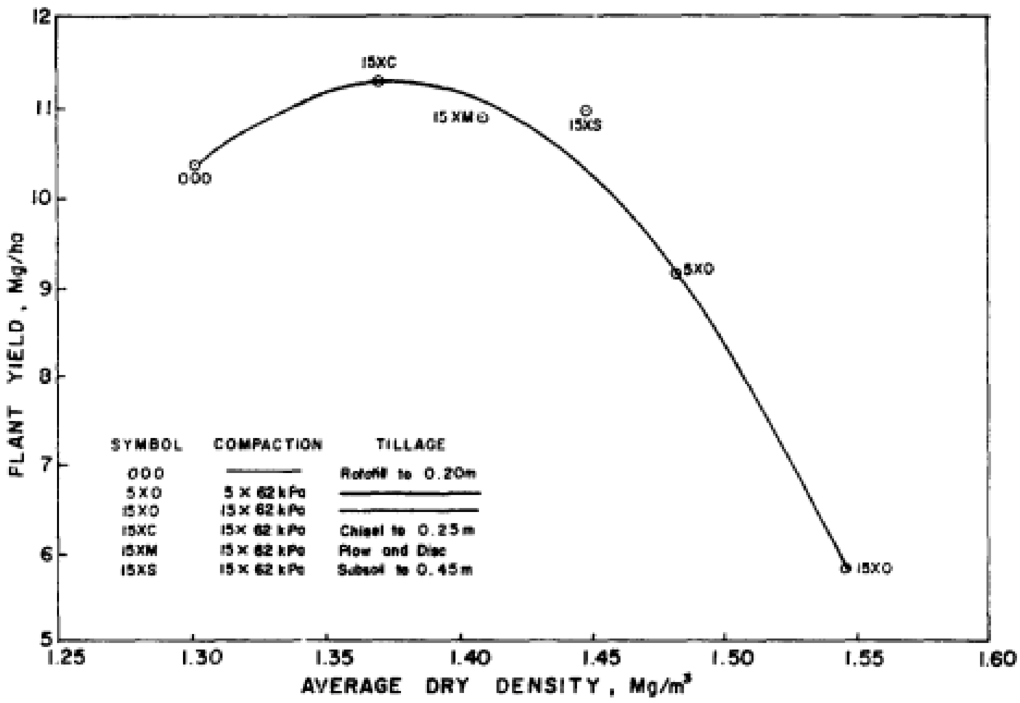


Figure 2.10: Relationship between soil compaction and crop yield in a sandy loam soil (Negi et al. 1981)

Håkansson et al. (1988) reported that crop responses could be directly and indirectly influenced by soil compaction. The direct impact is interference with the crop uptake of water, nutrients and air mentioned by Nawaz et al (2013). The indirect effect is associated with timeliness, and particularly the additional time often required to prepare a seedbed and, the quality of the seedbed, once prepared. Compaction can also increase soil nutrient loss by leaching, runoff, and gaseous losses to atmosphere (Iler & Stevenson 1991), thus reducing fertiliser efficiency (Hussein et al. 2017).

Voorhees (1986) in Minnesota, reported a series field trials demonstrating that axle loads less than 5 Mg could cause compaction to a depth of 300 mm, but with axle loads greater than 10 Mg, compaction would reach a depth of 600mm. This research confirmed that surface layer compaction can significantly influence crop yield depending on soil texture and climatic conditions. A moderate increase in the soil compaction level may increase yields during relatively dry conditions, while yields will be decreased during wet seasons. Subsoil compaction, on the other hand, resulted in a significant yield decrease over several years. (**Figure 2.11**).

These trials covered a range of soil textures and crop species, and showed that soils with high clay content generally experience a greater crop yield response to compaction (negatively or positively) than coarse textured soils. This is consistent with findings of past studies by Negi et al. (1981), and also generally agree withDwyer (1983) in the UK, who found that maximum axle weight should not exceed 6 Mg to avoid subsoil compaction. Voorhees (1986) also noted that deep ripping of compacted soil can be detrimental because subsequent wheel traffic on the loosened soil can recompact the soil to a higher bulk density than its original value.

It is interesting to note that axle loads smaller than 3 Mg were typical for most field operations in 1975, whereas axle loads of harvest and transporting equipment were between 10 and 20 Mg in 1992 (Koolen et al. 1992). These values are substantially smaller than those found now (2018) in Australian grain production, where tractor and harvester axle loads often exceed 10 Mg and 20 Mg respectively.

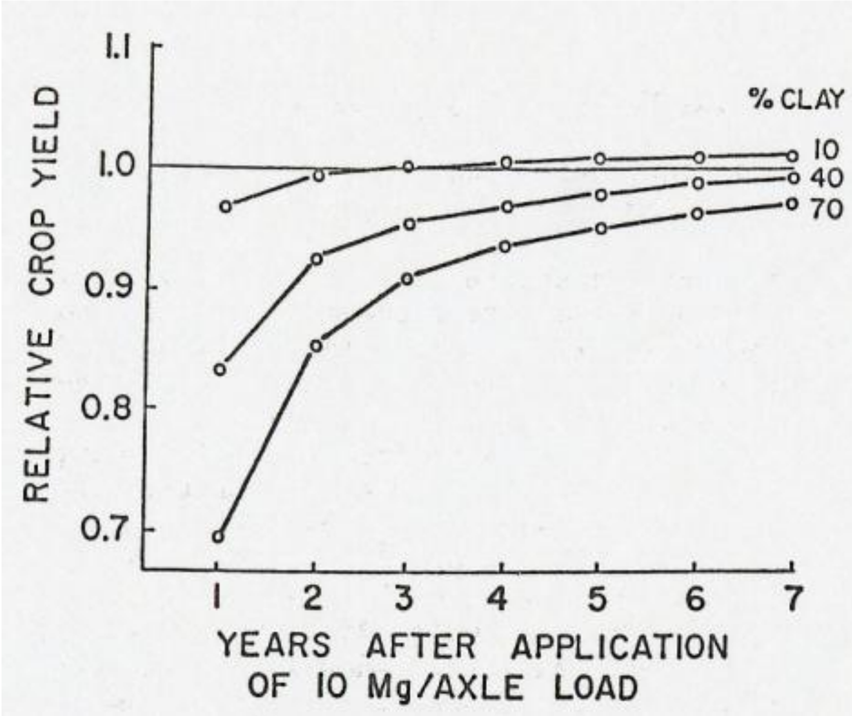


Figure 2.11: Relative crop yield as an effect of 10 tonnes load application (Voorhees 1986)

Douglas et al. (1992) compared the effect of traffic system on crop responses, showing that that total dry matter yield was significantly greater after zero traffic than either conventional traffic or reduced ground traffic systems. Chamen et al. (1990) also looked at the effects of low ground pressure, conventional and zero traffic systems on soil and crop responses. Their tests were conducted on a clay soil with wheeling treatments varying in pressure from 0 to 250 kPa. They found that conventional and low ground pressure systems resulted in the highest values of soil properties including soil bulk density and cone penetration resistance, whereas the zero traffic system returned the lowest. However, there was no significant difference in yield recorded between conventional, low ground pressure and zero traffic direct drilled treatments. Only the combination of the zero traffic and shallow cultivation led to some drop in yield. Therefore, the authors concluded that the crop performance is more likely to be reduced by under-compaction than over-compaction in the wheeling pressure range 0 to 250 kPa. Chamen et al. (2015) argued that low ground pressure systems were a reasonable means of compaction mitigation but were constrained due to their negative impact on topsoils and gradual degradation of subsoils

In conclusion, the relationship between soil compaction and yield is not straightforward. It involves some interactions of soil, water and air as it affects various stages of plant development. In this discussion, it is necessary to remember that that an optimum soil compaction is required for appropriate seed germination. Each species has an optimum soil bulk density which gives maximum yield. The densities lower and higher than the optimum cause yield reduction. In recent years, agricultural equipment has become progressively more powerful but also heavier, therefore, its harmful effect on the soil-plant relationship tends to increase. Here are recent studies on the effect of compaction on crop performance and yield (e.g. Smith et al. 2014; McPhee et al. 2015; Godwin et al. 2017; Hussein et al. 2017, 2018; Hefner et al. 2019).

2.3.3. Effect of soil compaction on draught force and motion resistance

Surface soil compaction is mainly a function of the pressure applied to the soil surface (Plackett 1984), so the amount and type of tillage required to loosen it is closely related to the forces previously applied (Soane 1983). Soil compaction can have both direct and indirect effects on energy requirements. The direct effects are associated with draught force and motion resistance, while the indirect effect is the creation of clods. Energy is dissipated when compacting soil (overcoming motion resistance), which in turn requires significantly greater (usually draught) energy to disturb by subsequent tillage or seeding equipment (Tullberg 2014).

Draught force, defined as the force needed to pull implements, is increased by soil compaction, which increases the strength of the soil mass and the aggregates within that mass (Chamen 2006). For a given soil type, energy levels for cultivation differ widely according to soil moisture content (Chamen et al. 2015). Soil related differences are illustrated in the work of Patterson et al. (1980) who produced data for cereal crop establishment over a number of years from three different soils, the principal components of which are listed in **Table 2.3** together with energy requirements per unit volume of soil moved. Soil strength usually increases with its bulk density (Keller 2004), as does draught force (Mouazen & Ramon 2002). Draught requirements for agricultural operations also increase with soil moisture (Solhjou et al. 2013; Tagar et al. 2014; Chamen et al. 2015), increasing the energy required for tillage; an effect illustrated in **Figure 2.12**, by López Bravo et al. (2016).

Table 2.3: Energy requirements for different cultivation systems in three soils (Patterson et al. 1980).

Description	Site 1			Site 2			Site 3		
Soil texture	**Clay loam**			**Silty loam**			**Clay loam**		
Particle size distribution (%)									
Sand	25			12.1			27.2		
Silt	25.1			51.4			21.4		
Clay	45.9			28.5			51.4		
Energy requirements									
Depth of work, mm	220	130	110	220	145	105	205	130	105
Energy, kJ.m^{-3}	117	103	108	56	75	74	146	108	122

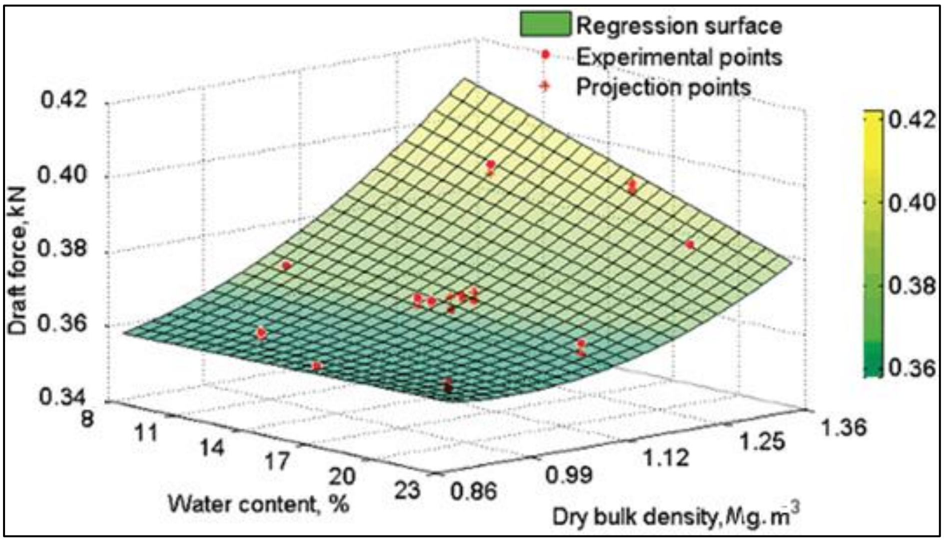


Figure 2.12: Draught force response surface function of moisture and soil dry bulk density (after López Bravo et al. 2016)

Soil compaction is, thus, a major factor contributing to increased draught force (Sahu & Raheman 2006), and the literature provides many examples of this. In the USA for instance, Voorhees (1979) found draught force increases of 25% and 43% respectively from one and five passes of a 7 Mg tractor, and DeJong-Hughes (2015) also found that compaction increased the draught of a narrow chisel from 0.311 kN to 1.55 kN.

In Australia, Tullberg (2000) demonstrated that compaction, due to tractor and/or implement wheels preceding a tillage implement, can increase total implement draught by more than 30%. He labelled this effect the 'traffic penalty' of the operation, pointing out that the energy inefficiencies of traction are responsible for increasing the energy requirements of tillage and seeding.

An indirect effect of soil compaction is the increase in cloddiness of soil after tillage, requiring more intensive tillage to produce a seedbed (Chancellor 1976), and increasing the time required for tillage operations. This cloddiness impact of compaction has also been investigated by Lyles and Woodruff (1961) who found similar patterns to those reported by Flocker et al. (1958) and illustrated in **Table 2.4**.

Table 2.4: Effect of soil compaction on cloddiness and clod strength (Flocker et al. 1958)

Compaction treatment	Bulk density ($Mg.m^{-3}$) 0-61 mm depth	Clod population (grams)	Clod density ($Mg.m^{-3}$)	Clod shear strength ($g.cm^{-2}$)
Light	1.25	8 440	1.49	492.6
Moderate	1.40	21 770	1.50	745.9
Severe	1.56	43 680	1.64	865.6

Motion resistance is the force opposing the movement of a wheel (or other running gear) on a surface (Macmillan 2002). Motion resistance of agricultural equipment includes two components: an internal resistance (due to losses inside wheels or tracks) and external resistance (due to soil deformation)(Lyasko 2010b). Internal resistance is largely related to running gear (tyre or track) type and characteristics, and is relatively small in most field situations. External resistance, which is heavily influenced by soil conditions, is normally the biggest contributor to motion resistance in agriculture. This is clear from the early work of McKibben and Davidson (1940) quoted by McKyes (1985), and Lyasko (2010a) has demonstrated the impact of wheel slip in increasing motion resistance on field surfaces. (F**igure 2.13**).

Soil deformation is the major factor affecting motion resistance, as illustrated in a field experiment on a fine clay by Botta et al. (2012), where motion resistance force was greatest on soft ploughed soil with large plastic deformation and rut depths. Motion resistance was much smaller on soil prepared for no-tillage (NT) (**Figure 2.14**). This is consistent with the results of Zoz & Grisso (2003) and Kurjenluoma et al. (2009).

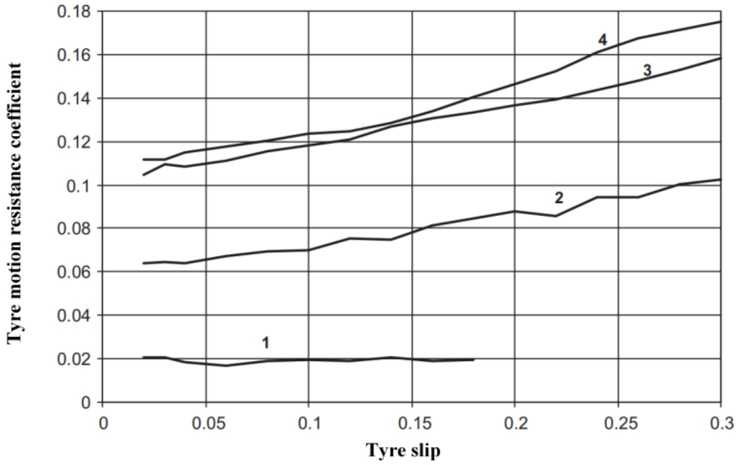


Figure 2.13: Motion resistance coefficient vs. tire slip in four soil conditions: 1 = concrete; 2 = firm soil; 3 = tilled soil; 4 = soft or sandy soil (Lyasko 2010a).

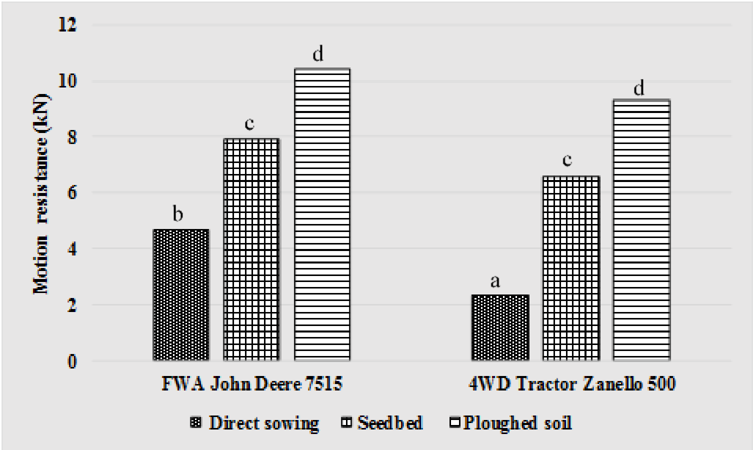


Figure 2.14: Relationship between motion resistance (kN) and soil conditions. Values with different letters within each soil conditions show significant differences between tractors (P < 0.01, Duncan's multiple range test) (Botta et al. 2012).

When one wheel follows precisely in the track of another wheel, compaction by the front wheel will increase soil strength and thus, tractive performance of the rear wheel. This accounts for the commonly observed improvement in tractive efficiency of four-wheel-drive (versus two wheel drive) tractors. Bezborodova et al. (1968), for instance, found that the motion resistance of a wheel with a 12.00-18 tyre on loam soil at 12 to 14% moisture content, decreased by 41%, 36% and 31% respectively in the 2nd, 3rd and 4th passes along the same wheel track.

Guerif (1994) noted that compaction can improve field access for vehicles particularly during wet periods, improving the ability to perform operations such as planting and harvest at the optimum time (timeliness). Field access depends on equipment mobility and trafficability; this in turn is related to motion resistance as pointed out by Saarilahti (2002) who provided mobility/trafficability classes based on motion resistance coefficients (**Table 2.5**).

Table 2.5: Mobility and trafficability classes based on motion resistance coefficient (Saarilahti 2002)

Mobility/ trafficability class	Motion resistance coefficient
Good	< 0.02
Fair	0.20-0.30
Poor	> 0.30

In conclusion, the relation between soil compaction and energy requirements is straightforward. Compaction increases the strength of a soil, and the energy required to disturb or till it. It also increases cloddiness after tillage, which can increase the time required for tillage operations. Meanwhile, the greater strength of compacted soil can also limit deformation and reduce motion resistance, increasing mobility and trafficability.

A question here is: Which system can optimise all these contradicting factors, and, at the same time provide soft soil for high yield and less draught force, and hard soil for good traction, mobility and trafficability with and less motion resistance? Australian farmer experience has been that the strategies that improve soil conditions such as CTF and NT (together or separately) have their largest effects in bad years, which is when prices are highest. Australian farmers also point out that a whole lot of system effects-timeless being the most important (but it only applies with self-draining layouts), but also factors such as greater uniformity of both crop and weed growth (better timing of pesticide applications) and avoiding issues with harvester ruts, which frequency spoil double-cropping opportunities.

2.4. Techniques for overcoming soil compaction

Soil compaction is inevitable, and potentially damaging compaction is unavoidable due to the intensive use of farm machinery in different farm operations (Hamza et al. 2011). Soil compaction is significantly affected by soil moisture, clay content, and bulk density (initial strength), as discussed earlier (Saffih-Hdadi et al. 2009). From the perspective of machine-soil interaction, compaction is influenced by axle load, wheel slip, and contact area, which depends on tyre inflation pressure and, therefore, contact pressure at the tyre-soil interface, and tyre deflection (Soane et al. 1980a, 1980b). To minimise compaction, these parameters can be manipulated in conjunction with soil moisture conditions at the time of traffic. An example is the Schjønning et al. (2013) 50:50 rule proposal, which avoids traffic if soil stresses at 50 cm deep exceed 50 kPa on soils with moisture contents near field capacity. Similar strategies based on critical soil moisture levels for field traffic have been used to determine suitable conditions for traffic with slurry-spreading equipment (Vero et al. 2014), but these strategies can produce yield or financial penalties. Such penalties arise when unsuitable soil moisture conditions result in delay or avoidance of operations such as planting and harvesting.

Potential strategies for eliminating, alleviating or managing compaction are summarised in **Figure 2.15**, from Soane et al. (1979); (1982) (in Antille et al. 2016). Mechanical loosening operations such as deep ripping are sometimes effective for alleviating compaction, as demonstrated by e.g., Bennie & Botha (1986); Varsa et al. (1997); Hamza and Anderson (2003, 2005). This can result in increased crop yield (e.g., Bennie & Botha 1986; Vepraskas & Wagger 1990; Willis et al. 1997), but deep ripping is an energy-intensive activity and subsequent heavy wheeling can result in even worse soil compaction (DeJong-Hughes et al. 2001). Deep ripping can also produce unsatisfactory results, particularly when other subsoil constraints (e.g., sodic subsoil) are present (GRDC 2009), and its beneficial effects are often short lived.

An alternative approach to alleviating compaction is the use of deep-rooted annual crops such as mucuna or pigeon pea (Hulugalle & Lal 1986; Hulugalle et al. 1986) or deep-rooted perennials such as Leucaena leucocephala (Lal 1989; Kang et al. 1990). In Australia, for instance, growers talk about the benefits of tillage radish (Giarola et al. 2013; AGF 2018). These and similar strategies can also improve the soil's physical conditions by enhancing the biological activity of earthworms and through the addition of organic matter (Adem & Tisdall 1984; Derpsch et al. 1986). The beneficial effects of biological loosening are not clear but Hulugalle et al. (1986) indicates they are greater in soils that have been subjected to only low levels of compaction.

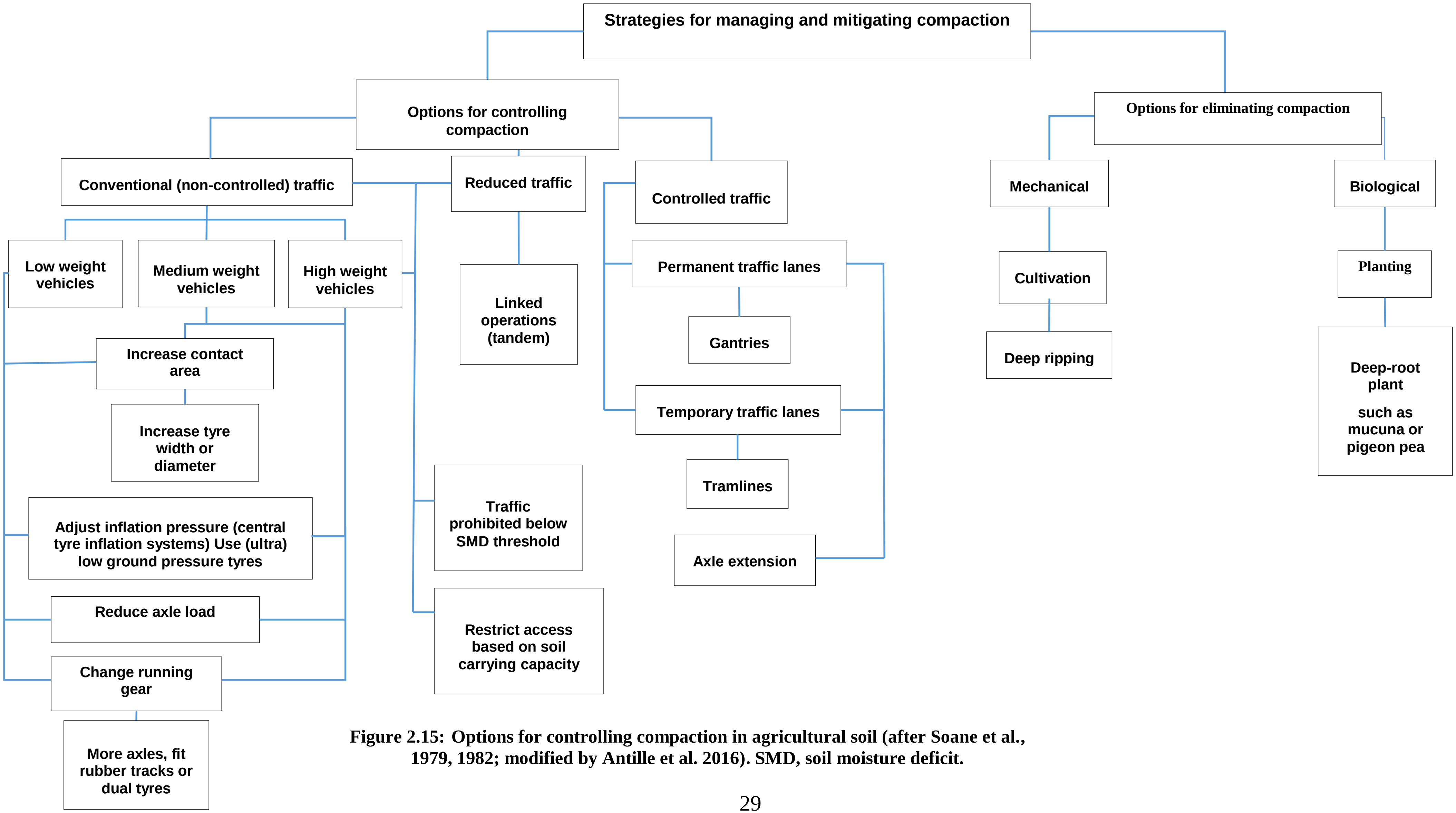


Figure 2.15: Options for controlling compaction in agricultural soil (after Soane et al., 1979, 1982; modified by Antille et al. 2016). SMD, soil moisture deficit.

Avoidance might well be the best strategy for managing compaction (Antille et al. 2016) by restricting all heavy loads to well-defined traffic lanes, whether temporary or permanent (e.g. Soane et al. 1979; 1982; see aslo Godwin 2009; 2016).

In **Figure 2.15**, full adoption of Controlled Traffic Farming (CTF) requires permanent traffic lanes or tramlines, but the term 'seasonal' CTF refers to temporary tracks, where affected areas may be targeted for post-harvest remediation. The latter approach relates to the concept of precision soil management (Godwin 2009). Gantry systems (Chamen et al. 1992b, 1994a, 1994b) are technically feasible, but without large-scale manufacture their development has been limited (Godwin, 2009). These approaches appear to be best management for controlling soil compaction.

The traffic reduction approach can be achieved by combining, in one pass, operations such as cultivation and seeding or certain types of harvesting operations using currently available machinery and common sense attitudes to machinery management (Kayombo & Lal 1993).

Soil compaction caused by a tyre at a given load and soil condition depends on tyre inflation pressure, diameter and section width. Low inflation pressure of the tyre results in an increase in the contact area and tyre flexibility (Ansorge 2005). The effects of tyres and tracks at high axle loads were studied by Ansorge and Godwin (2007), where soil compaction resulting from loaded tyres and tracks was assessed. The study proved that TerraTrac system causes less soil damage than tyres (at an overall load of 12 tonne for the tracks and 10.5 tonne for the tyres). This study concluded that the method of load distribution to the ground is very important.

Antille et al. (2013) also looked at the effects of tyre size on soil compaction and provided an indicator for tyre selection for combine-harvester tyres at high axle load and a range of inflation pressure. Their results show that increased tyre size and low inflation pressure reduced both soil deformation and the increase in soil bulk density beneath the tyres. After one passage of tyres on the soil, the increase in soil bulk density was approximately 25% for the low bulk density soil (1.20 t m^{-3}) and only 2.3 – 5% for the high bulk density soil (1.60 t m^{-3}). The authors also found the advantage of increasing tyre size (i.e. contact patch area) and lowering inflation pressure where the tyre with the highest inflation pressure gave a significantly higher increase in penetration resistance obtained from a drop-cone penetrometer compared with the tyres with lower inflation pressures. Chamen et al. (1990) and Alakukku et al. (2003) state that greater benefits in reducing soil compaction could be achieved by reducing tyre inflation pressure or by using more favourable/suitable tyres.

2.4.1. Relationship between contact area and soil deformation

The options suggested in **Figure 2.15** may be related to Micklethwaite's equation (Micklethwaite 1944 cited by Alcock 1986; Antille et al. 2016) for maximum thrust:

$$S=((c\times A)+(W\times \tan\Phi)) \quad \text{Equation 2.1}$$

where S is thrust, c is cohesion, A is area, W is weight, and **Φ** is angle of internal friction. In clay soils, in order to maximise traction and reduce wheel slip, greater benefits result from increased contact area because of the cohesive component of shear force (Micklethwaite 1944). This can be achieved by increasing tyre diameter, section width or both, whereas for sandy soils, benefits will be from increased weight (Antile et al. 2016). The following are requirements for maximising thrust with minimum motion resistance, slip and compaction (after Wong 2010):

An increase in contact area through increased tyre diameter is preferable to section width because it will minimise rut width and reduce motion resistance (McAllister 1983; Crossley et al. 2001; Kurjenluoma et al. 2009). Increased contact area will also reduce slip and therefore motion resistance (Inns & Kilgour 1978; Komandi 1999). **Figure 2.16** (Antille et al. 2016 quoted from the earlier work Soehne 1958; modified by Godwin (2005)) shows the relative effects of wheel load, inflation pressure and forward speed on pressure distribution beneath a tyre and highlights the relative influence of those parameters on soil compaction. In fact, these approaches can be combined with CTF, which is characterized by a permanent traffic lane, and greater benefits will result from this combination. However, an increase in contact area through the use of dual tyres, has a positive effect on the reduction of soil compaction compared with single tyre use. Meanwhile the single tyre doesn't have always a negative effect, according to Bennett et al. (2017) who demonstrated that a standard cotton picker (JD7760) did not significantly affect penetration resistance when compared with the penetration resistance under a CTF cotton picker (JD7760) (**Figure 2.17**). They also concluded that the CTF approach provides better protection of the soil resource than the conventional system and is likely to result in greater productivity in the long-term.

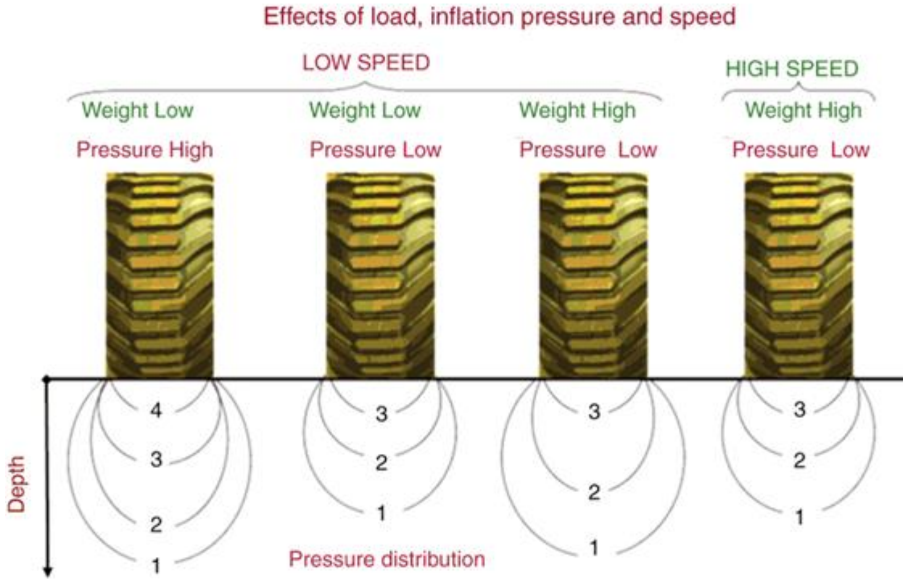


Figure 2.16: Relative effects of tyre load, tyre inflation pressure and forward speed on pressure distribution beneath self-propelled tyres (after Soehne 1958; modified by Godwin 2005; quoted by Antille et al. 2016).

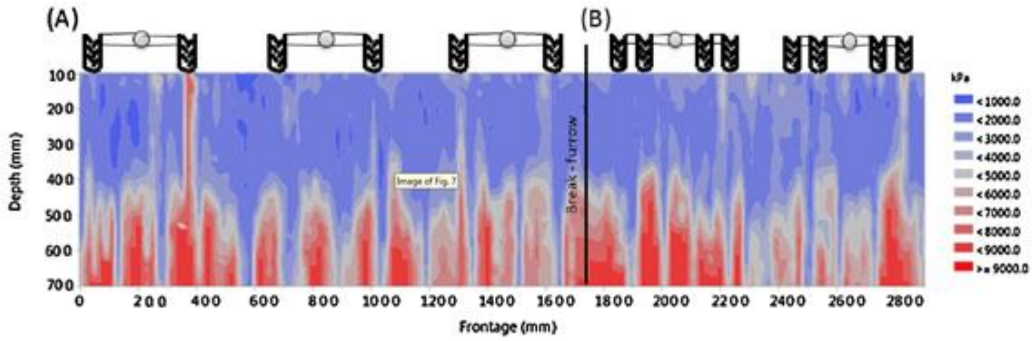


Figure 2.17: Penetration resistance maps for (A) CTF JD7760 system, and (B) standard JD7760 system (Bennett et al. 2017)

In many studies on soil compaction, emphasis has been placed on the need to reduce the high axle loads and the high contact stresses that are imposed by modern vehicles, and to reduce the amount of such traffic involved in crop production (Håkansson et al. 1988; Soane 1990). All of the above approaches could be combined with CTF to achieve their purpose. Researchers in Western Australia found that integrating deep ripping with CTF could increase the benefit and longevity of ripping. In addition, these approaches are working to alleviate and remove soil compaction. The use of CTF in this approach would make soil compaction exploitable. As machinery is getting bigger and soil compaction is getting deeper, CTF is definitely worth considering.

2.5. Controlled traffic farming

CTF is an agricultural system that seeks to isolate cropping zones from the damaging effects of compaction by concentrating traffic in permanent laneways where compaction will improve trafficability. This is achieved by use of the same or modular equipment working widths with all heavy equipment wheels adjusted to a common track gauge to fit the permanent lanes. A multidisciplinary scientific and engineering team working with grain farmers in Central Queensland from 1993 to 1998 developed the Australian CTF system (Tullberg et al. 2007). In these systems the permanent lanes – often referred to as "tramlines" – can occupy less than 15% of field area with precise guidance. This common 3-m track gauge system is illustrated in **Figure 2.18** and operates well with a 9 m seeder and harvester and 27 m sprayer, but use of 12.2 m seeders and harvesters, with 36.6 m sprayers is increasing, and even wider systems are contemplated (Isbister et al. 2013).

Beside this, the rules of road transport must be considered. Generally, in Australia, the maximum road transport limit is 5 m. This layout of CTF (machine width 3 m) requires various combinations of warning signs, lights etc., when equipment travels along public roads in densely populated areas. The vehicles over 3.5 m can only travel in daylight hours. They also require front and rear pilot vehicles during public road transport (TMR 2013). This suggests a track width less than 3.5 m and a maximum tyre width of 0.5 m for unrestricted road travel (McPhee & Aird 2013).

Marker arms and physical measurement have been used to set out CTF systems, but most Australian growers now use real-time kinematic (RTK) differential global positioning systems (DGPS) auto-steer. The current RTK-DGPS system precision is about 2 cm, providing a convenient and economic system for equipment to follow the same tracks year after year (Jensen et al. 2012). CTF can increase yields (Williford 1980) and reduce production costs relative to non-CTF systems (Tullberg 2007). CTF was used on 22% of the Australian grain production area in 2016-2017 (ABS 2017), and adoption is increasing rapidly.

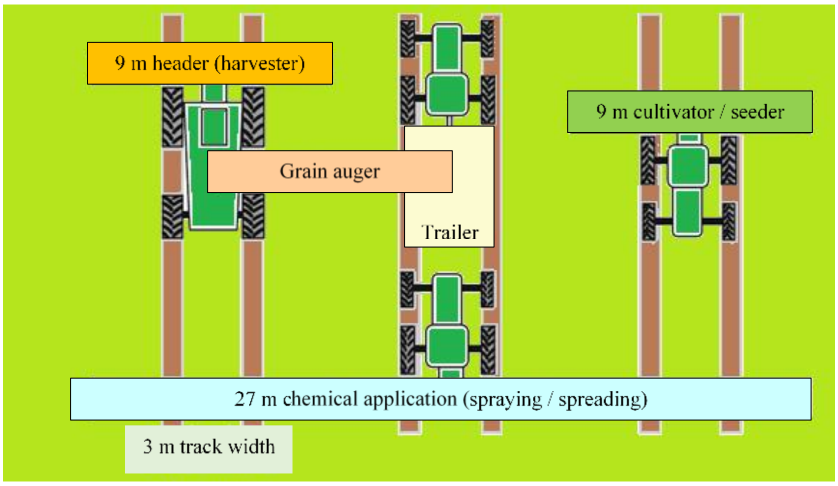


Figure 2.18: Illustration of common CTF systems

2.5.1. International CTF Adoption

Some of the original research on controlled traffic started in the USA in 1950 (Taylor 1983), using modified tractors or specifically designed wide-span machines (gantries) (Taylor 1994). That research often focused on wide-span gantries, with implements normally working within their widely spaced tandem wheels (Chamen et al. 1992b). (**Figure 2.19**). Gantries appear to be an optimal solution, halving the area of permanent lanes compared to tractor-based CTF, and gantry track gauge to date has varied from 4 to 12 m – and even 21 m in one case. With no large machinery manufacturer yet producing a gantry however, there is no commercial on-farm adoption.

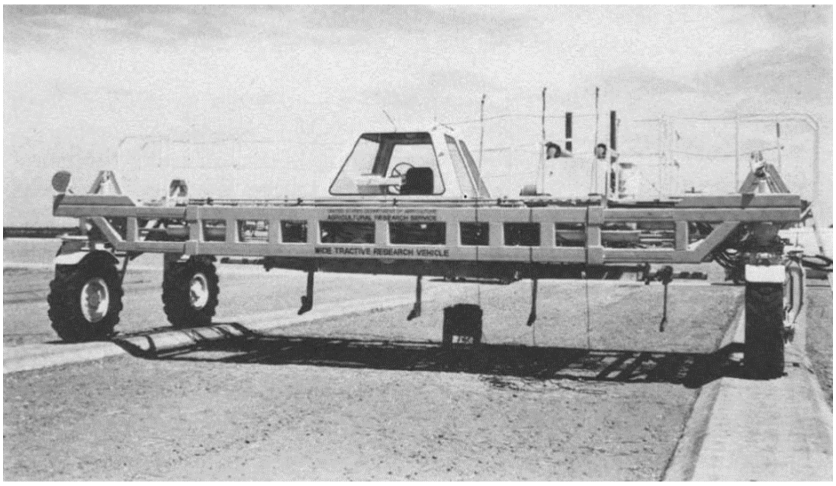


Figure 2.19: Gantry for controlled traffic research (Taylor 1983).

Research groups in the United Kingdom, Switzerland, Slovakia, the Czech Republic, the Netherlands, Denmark and Germany have all investigated the effects of controlled traffic farming (e.g. Lamers et al. 1986; Sommer et al. 1988; Chamen et al. 1990;

Chamen et al. 1992a, 1992b; Chamen & Audsley 1993; Chamen et al. 1994a, 1994b; Chamen & Longstaff 1995). Positive results from much of this work have encouraged adoption. European road regulations disallow normal use of vehicles wider than 2.55 m (Vermeulen et al. 2010). Most European CTF is based on smaller gauge widths (**Figure 2.20**), but CTF adoption is nevertheless increasing, with around 28,000 ha in CTF now, and another 44,000 ha in planning or transition (Chamen 2013).

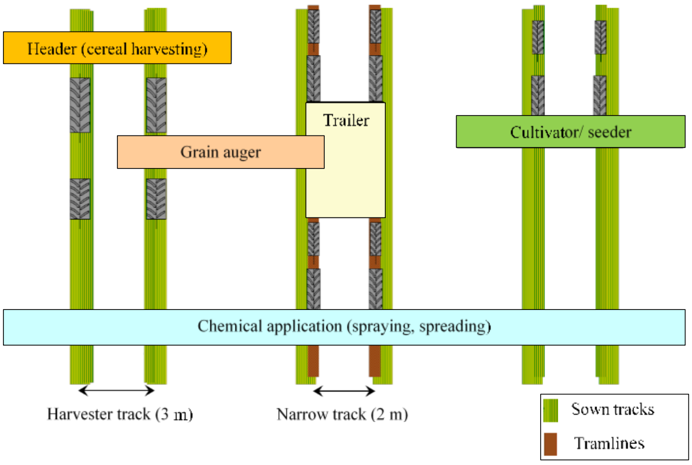


Figure 2.20: Common CTF adopted in Europe known as OutTrac. (Chamen 2006)

A group of Canadian farmers began transferring the Australian CTF experiences to Canadian farms in 2010, with two three-year projects to help western Canadian farmers assess CTF under Alberta conditions. Five farmers co-operated in the original project using field-scale equipment on demonstration plots ranging from 577 to 1945 ha, and more farmers joined a second project so the work covered a wide range of soils and climatic conditions. More time is needed to see all the benefits, but nearly all their cropland is now farmed using CTF (Gamache 2013).

In China, controlled traffic was demonstrated in dryland farming in Shanxi province in 1998 confirming that CTF would improve current farming systems (Chen et al. 2008; Bai et al. 2009), addressing the cropping problems of the Loess Plateau (e.g. He et al. 2012; Chen & Yang 2015). Despite the potential benefits, adoption is minimal in this environment of very small farms where opportunity costs, land scarcity, policies and subsidies inhibit adoption (Wang et al. 2008).

2.5.2. Adoption of Controlled traffic farming in Australia

CTF is not new, Australian farmers have been perfecting it for two decades. Tullberg and Murray (1987), at Queensland Agricultural College, reported on research to assess the effects of controlled traffic on tractor energy losses and tillage requirements as well as soil and crop effects. Their results showed that controlled traffic can reduce the fuel consumption up to 40%, allow similar output and capacity from a tractor of at least 30% less power; maintain yields without the necessity for deep tillage operations; and increase rainfall infiltration, which also reduces runoff and erosion in some circumstances.

As a result of the benefits of CTF, its adoption rapidly increased to a point where Yule et al. (2000) estimated for Australia, an increase in activity from 3,000 ha in 1995 to 300,000 ha in 2000. In 2009, about 3 million hectares were estimated in controlled traffic across Australia (Edwards et al. 2012). As mentioned previously, the 3m track width system commonly used in Australian dryland grain production, with standard setup of 9 m header and seeding 27 m sprayer, has a machinery-matching ratio of 3:1. The increased working widths of the machines and satellite guidance systems made it possible to practice CTF without widespan vehicles. Thus, nowadays many growers are using a standard setup of a 12.2 m header and seeding, and 36.6 m sprayer, and in some cases they are using whether setup of a 1:3:2 or 2:1:3 machinery matching ratio depending on the work width of farm machines.

2.5.3. Soil, yield and energy requirements under controlled traffic farming

CTF works by reducing compaction, which can produce economic loss by increasing grower input costs, preventing a plant from accessing deep soil moisture. There is a growing need to apply CTF for increasingly sustainable productivity and decreasing production costs in many regions of the world. CTF research has been carried out in many different environments, soils and cropping systems around the world (Lamers et al. 1986; Chamen et al. 1990-1994; Bakker & Barker 1998; Braunack & McGarry 2006; Tullberg et al. 2007; Chen et al. 2008; Vermeulen & Mosquera 2009; McPhee et al. 2015) (**Table 2.6**).

In Australia, CTF research and development has been conducted in sub-tropical, rain-fed and irrigated grain and cotton systems on Vertisols, dry land grain or deep sands, and in the sugarcane industry (Braunack & McGarry 2006; Blackwell 2007; Li et al. 2007; Tullberg et al. 2007; McHugh et al. 2009). The soil physical properties such as bulk density, soil strength, cone index (Chamen & Longstaff 1995; Unger 1996) infiltration (Li et al. 2007) and soil water content have been used to evaluate soil management systems (Alvarez & Steinbach 2009; Bai et al. 2009; Chamen 2011; Smith et al. 2014). Braunack and McGarry (2006) found a significantly lower bulk density and penetration resistance to 30 cm depth in sugarcane controlled traffic trials in north Queensland, Australia. In another study in Brazil, Souza et al. (2014) also found that bulk density and compaction in the seedbed and plant row under the managements of traffic control were both lower than trafficked soil.

A number of authors have investigated the effect of CTF on crop yield. Demmel et al. (2015) investigated the effect of a controlled traffic farming system on different farms between 2009 and 2014. The results illustrated the complexity of soil stress and soil compaction, with significant differences between soil parameters in wheeled and non-wheeled areas, and no clear yield or agronomic trends in first year. However, there was a general tendency to slightly higher yields in the non-wheeled areas compared with the wheeled areas. The different yield reaction by first year could be related to the natural soil recreation processes take a long time to adjust. In addition, annual plant and yield development is strongly influenced by other factors such as the course of temperature and precipitation.

Souza et al. (2014) found that sugarcane productivity and sugar yield increased by 18.72% and 20.29%, respectively, with traffic control. Chamen (2006) reported that with CTF and compaction trials, the yield on untrafficked areas reached 80-160 % compared to trafficked ones; permanent tramlines always had the lowest yields. Godwin et al. (2017) also found that CTF has a significant impact on crop yield where the replicated plot experiments in non-traffic soil produced a maximum and significant differential of +11% compared to random traffic. Numerous articles on the impact of traffic systems on crop yield in different soil texture have been reviewed by Chamen (2011). In comparison to zero traffic soil; those with conventional traffic yielded reductions of 16% for clay, 18.5% for loam and 7% for silt. It was concluded that CTF under European cropping conditions might lead to a general yield increase of 5-8 % (Anken et al. 2016).

In term of energy requirements, reductions in energy requirements are primarily due to:

(1) Relatively low soil specific resistance in the absence of traffic compaction

(2) Tillage operations conducted at shallower depths when remediation of deep compaction is not required

(3) Reduced power loss in ground drive due to lower motion resistance and reduced wheel slip (Tullberg 2000; Godwin & O'Dogherty 2007; Chen & Yang 2015).

Draught force and motion resistance are components of energy requirements in agricultural systems. Taylor (1983) was probably the first researcher to recognize the additional benefits brought to a controlled traffic system by optimising the design of the permanent traffic lanes. It was well known that the first pass across a relatively soft soil brought with it high motion resistance and poor tractive efficiency. However, by the fourth pass, efficiency had risen from less than 50% to close to 75% on a Decatur silty loam. Lamers et al. (1986) also indicated that a 13% increase in the relative tractive efficiency of permanent traffic lanes (tramlines) is brought about by a reduction in motion resistance and increased coefficient of traction. In addition, the expected improvements in soil structure and the reduction of fuel occurred (Lamers et al. 1986). A study by Jensen et al. (2012) in Denmark on the socio-impacts of controlled farming in Denmark concluded that the Danish Gross Domestic Product (GDP) increased by 34 million euros due to the implementation of precision farming (PF) and CTF on larger farms in Denmark. The results also clearly showed that adoption of PF and CTF farming systems will benefit the environment. They were able to verify a reduction of environmentally harmful agricultural inputs such as pesticides and fuel.

Chamen et al. (1990, 1992a) examined the draught force aspect while working on a clay soil in England, and comparing conventional and zero traffic. They reported that zero traffic reduced the draught requirements for shallow (100 mm) primary tillage by up to 60%, while a 20% reduction in draught for conventional ploughing at depth (200 mm). Chamen and Longstaff (1995) also indicated a 37% reduction in draught when ploughing 200 mm deep after a longer period without traffic on the clay soil. Energy demands for seedbed preparation fell by up to 87% (Chamen et al. 1992b). In fact, all the above studies and others may not have taken full measurements of energy, and most measured only total draught force requirements (**Table 2.6**).

Table 2.6: Summary of studies and parameters which have been studied in CTF in field around the world (*after* Chamen 2011).

Country	Soil	Depth, mm	Tillage system	Traffic system	Irrigation	Draught force			Motion resistance	Soil properties		Crop	Resourses
						Off traffic	On traffic	Total		BD	CI		
Argentina	Clay	-	NT, CP	CTF, Non-CTF	-					√	√	-	Botta et al. (2009)
Australia	Clay	0-220	Tines	- CTF, Non-CTF	-	√	√					Grains	Tullberg (1986)
Australia	Clay	0-170	various	CTF, Non-CTF	Irrigated					√		Maize	Braunack et al. (1995)
Australia	Clay	0-200	NT, ST, CP	CTF, Non-CTF	Irrigated						√	-	McPhee et al. (1995)
Australia	Clay	0-220	Tines	- CTF, Non-CTF	-	√	√					Grains	Tullberg (2000)
Australia	Silty clay, silty clay loam, loam	0-400	ST, CP	CTF, Non-CTF	-					√	√	Sugarcane	Braunack & McGarry, (2006)
Australia	Clay	-	NT, ST	CTF, Non-CTF	Rainfed					√	√	-	McHugh et al. (2009)
Australia	Clay loam	-	MP, CP	CTF, Non-CTF	Irrigated			√		√	√	Vegetables	McPhee et al. (2015)
Australia	Clay	-	-	CTF, Non-CTF	Irrigated					√	√	Cotton	Bennett et al. (2017)
Brazil	Clay	-	-	CTF, Non-CTF	-					√	√	Sugarcane	Souza et al. (2014)
China	Silt loam	0-200	NT, ST, CP	CTF, Non-CTF	Irrigated					√	√	Wheat & Maize	Bai et al. (2008)
China	Silt loam	0-200	NT, ST	CTF	Rainfed					√	√	Wheat	Chen et al. (2008)
China	Silt loam	0-200	NT	CTF	Rainfed					√	√	Wheat	Qingjie et al. (2009)
Czech Republic	Loam	-	-	CTF	-					√	√	Wheat & Barley	Gutu et al. (2015)
Denmark	Sandy loam	-	-	CTF, Non-CTF	Irrigated							Vegetables	Hefner et al. (2019)
Netherlands	Loam ,clay	-	-	CTF, Non-CTF	Irrigated			√	√	√	√	Vegetables	Lamers et al. (1986)
Netherlands	Loam	-	-	SCTF, Non-CTF	Irrigated						√	Vegetables	Vermeulen & Mosquera (2009)
Slovakia	Silt loam	-	-	CTF, Non-CTF	-					√	√	Cereal	Galambošová et al. (2017)
Turkey	Clay loam	0-200	MP4, CP5	CTF, Non-CTF	Rainfed					√	√	-	Yavuzcan (2000)
Turkey	Clay loam	0-230	CT, ST	Non-CTF	Rainfed					√	√	Corn, Wheat	Yavuzcan et al. (2002)
UK	Clay	0-350	MP	CTF, Non-CTF	Rainfed					√	√	Cereal	Blackwell et al. (1985)
UK	Clay	various	NT, ST	CTF, Non-CTF	Rainfed					√	√	Wheat	Chamen et al. (1990)

Country	Soil	Depth, mm	Tillage system	Traffic system	Irrigation	Draught Force			Motion resistance	Soil properties		Crop	Resourses
						Off traffic	On traffic	Total		BD	CI		
UK	Clay	0-200	CP	CTF, Non-CTF	Rainfed			√		√	√	Wheat	Chamen et al. (1992a)
UK, Germany, Netherlands	Sandy loam, loam, clay	0-250	various	CTF, Non-CTF	Rainfed					√	√	various	Chamen et al. (1992b)
UK	Clay	0-550	DP	CTF, Non-CTF	Rainfed			√		√	√	Cereal	Chamen & Cavalli (1994)
UK	Clay	0-200	various	CTF, Non-CTF	Rainfed			√		√	√	Wheat	Chamen & Longstaff, (1995)
UK	Clay loam	0-250	MP	CTF, Non-CTF	Rainfed			√				Barley, Potatoes & Oil seed rape	Dickson and Ritchie (1996)
UK	Sandy loam	0-250	DP, ST, NT	CTF, Non-CTF	Rainfed	√	√					-	Arslan et al. (2015)
UK	Sandy loam	0-250	DP, ST, NT	CTF, Non-CTF	Rainfed					√	√	Wheat, Barley, Oats	Godwin et al. (2017)
USA	Sandy loam	0-500	CP	CTF, Non-CTF	Irrigated					√	√	-	Meek et al. (1992)
USA	Sandy loam	various	various	CTF, Non-CTF	Irrigated			√			√	Cotton	Burt et al. (1994)
USA	Clay loam	0-500	NT	CTF	Irrigated					√	√	-	Unger (1996)

CT - conventional tillage; CP - chisel plough; ST - shallow tillage; MP - mouldboard plough; DP - deep ripping; BD - bulk density; CI - cone index; NT – no-tillage

Overall, CTF is widely regarded as a practical and cost-effective technology to reduce field traffic-induced soil compaction and is the basis for a more precise cropping system. CTF farmers have provided many anecdotal reports of reduced power requirements and fuel consumption, so the energy effects of CTF are clearly important, but published evidence is not unanimous. Tullberg (1986, 2000) working on a clay soil in Australia observed that the traffic effect of wheels on the draught of tillage implements increased total draught by 30% or more compared with the same implement operated in non-trafficked soil.

Burt et al. (1994) in the USA and Arslan et al. (2015) in UK however, found that traffic systems had no significant effect on energy requirements. In Burt's case, they demonstrated that operating depth for tillage implements in non-trafficked soil was greater than trafficked soil. As these implements operate only on the surface soil, the traffic could have created a resistance to penetration and therefore, forced the implements to operate at a lesser depth.

But, in Arslan et al.'s case, they found differences for tine tillage draught in traffic systems, but these were not significant. Meanwhile, in zero tillage, they indicated that there were no differences in traffic system for seeding in particular. This is because measurement was for the whole planter, therefore, it could be that the draught due to rolling resistance of depth and press wheels was considerably greater than draught due to the "tillage" component of seeding. However, these studies considered only the draught force effects, not motion resistance. It also appears that there are still no studies of CTF energy effects, which include motion resistance effects.

2.6. Draught force prediction models of soil-engaging tines

2.6.1. Factors affecting draught force

The aim of this section is to show the factors influencing draught force in a field. Draught force as defined by ASABE (2005) is, "The force to propel an implement in the direction of travel". The draught force of soil-engaging implements is affected by a number of parameters such as physical and mechanical properties of soil, soil strength (soil compaction, soil texture and soil moisture) (Arvidsson et al. 2004), tine parameters (tine type, tine shape and size, tine rake angle) and operational conditions (speed of tine and work depth of tine) (Godwin 2007). In terms of soil compaction, draught force requirements of soil-engaging implements may be drastically increased by soil compaction (Iler & Stevenson 1991). They reported that a 43% draught force increase to plough a soil that had been previously compacted by five passes of a 7 tonne tractor and a 25% increase in draught force when compacting the soil with just one pass (Voorhees 1979; Iler & Stevenson 1991). For more details please see **section 2.3.3**.

In terms of soil texture, several studies investigating the effects of soil texture on draught force requirements of a soil-engaging implement in several countries have showed that the highest draught force was found in clay soils compared to sandy soils. Draught force of soil-engaging implements in clay soils can be more than twice that in sandy soils (Summers et al. 1986; Harrigan & Rotz 1995). Kiss and Bellow (1981) and Van Bergeijk et al. (2001) found that the clay content in the soil has a strong influence on draught force. Their results of two years of experiments showed that the range of specific draught force was 30 $kN.m^{-2}$ to 50 $kN.m^{-2}$, when the range of clay content was from 6% to 22%. In another study, Novák et al. (2014) demonstrated that the draught force was increased 30% at work in clay soil in comparison to sandy soil. This was caused by increased traction in soils with a high content of clay particles, high soil cohesion strength, and possibly adhesion (McKyes 1985; Chen et al. 2013).

The draught force of a soil-engaging implement can also be affected by soil moisture content, which affects mechanical behaviour and soil strength (Ayers 1987). The relationship between soil strength and soil moisture content is dependent on the soil type and its bulk density. The moisture weakens the inter-particle bonds, causing swelling and reducing internal friction making the soil more workable and compactible (Hillel 1982). Experiments have shown that strength of fine particles soils varies directly with bulk density and inversely with moisture content (Perumpral 1987). Draught force of a soil-engaging implement may decrease by increasing the moisture content of loamy sand soil (Nkakini 2015). According to an investigation by Raper and Sharma (2004) to determine the effect of the range of soil moisture content on energy requirements including draught force in sandy loam soil, the draught force in very dry soil conditions was 8.7 kN compared to draught force in wet, moist and dry soil conditions which were 6.4 kN, 6.8 kN and 5.7 kN respectively. These studies cannot be adopted as a general rule, as draught force depends on soil type and condition.

In another study, Grisso et al. (1996) examined force operating with different implements and a range of soil moisture content from 12% -25% in silty clay loam soil. They found that the wide range of soil moisture content did not significantly affect the implement draught force of chisel ploughs and field cultivators in particular. In a different experimental study in clay loam soil, Karmakar et al. (2009) found that significantly increasing draught force response of a soil-engaging implement was observed with increasing soil moisture content. The cause may be the increased soil compressibility level at high moisture content, so during tine movement, more of the soil ahead is compressed before it could leave the line of movement. Accordingly, the increased force is required to cut and slide the compressed soil over the tine surface, and this results in increased draught force (Karmakar et al. 2009). The most significant results is that draught force of tine is not directly proportional to the soil moisture content.

In terms of tine parameters, draught force can be strongly affected by parameters including type of tine, width of tine and rake angle of tine. There have been several studies in the literature reporting the effects of tine parameters on draught force. Manuwa (2009) performed experimental investigations on the performance of three tillage tines (very narrow tine, narrow tine, and wide tine) in a sandy clay loam soil. His results showed that the draught force at 100 mm depth in a sandy clay loam soil was 0.06 kN for very narrow tine, whereas draught forces were 0.183 kN and 0.603 kN for narrow tine and wide tine respectively. This is mainly due to the amount of soil disturbed by narrow tines being much less than that displaced by wide tines. However, Godwin (2007) demonstrated that the draught force of tine increases in proportion to width of tine in very narrow tine, then at a decreasing rate (narrow tine range) and finally at a linear but lower rate than the initial phase (blade or wide tine range). These findings show that draught force of tine is not directly proportional to width of tine (**Figure 2.21**).

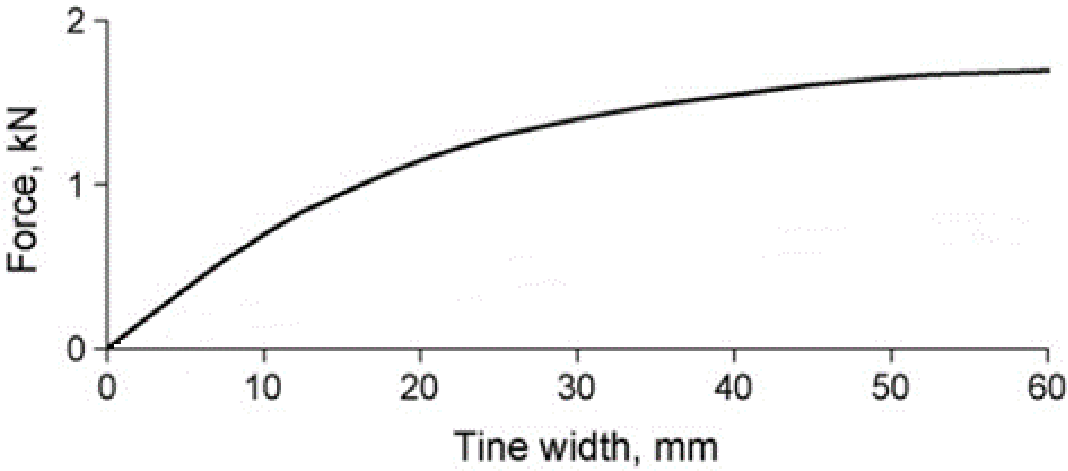


Figure 2.21: Effect of tine width on the horizontal (draught) force acting on a 90º rake angle tine (Godwin 2007)

Rake angle is the angle of the tine's plane to the horizontal plane in the direction of travel. The rake angle can affect draught force of a soil-engaging tine. Godwin (2007) showed that draught force is slowly increased by increasing the rake angle between 20° to 67°, and then rapidly increases after 67°. The cause of this increase may be the vertical force which is acting on the tool to assist or prevent penetration into the soil (Godwin 2007). **Figure 2.22** shows the effect of tine rake angle on draught force.

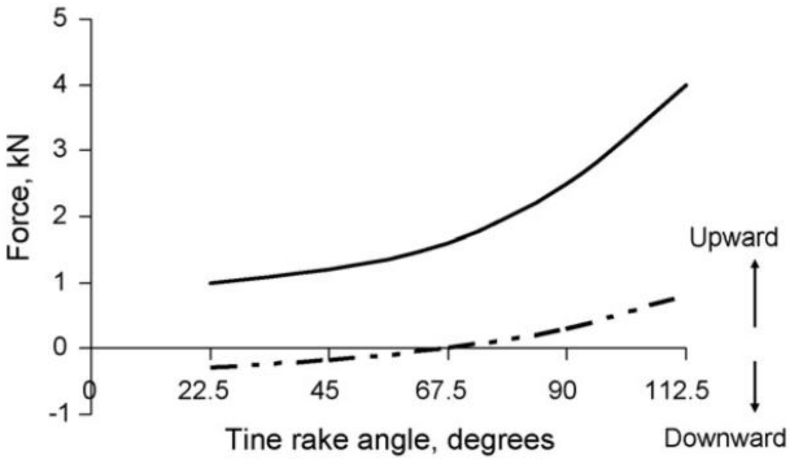


Figure 2.22: Effect of tine rake angle on draught (solid) and vertical (broken) forces (Godwin & Spoor 1977)

A number of studies have examined the influence of operational conditions (speed and working depth) on the draught force of soil-engaging implements. Summers et al. (1986) demonstrated that draught force is linearly proportional to work depth and ground speed for sweep and chisel tines particularly. Mak and Chen (2014) indicated that draught force of a sweep tine in a loamy sand soil increased rapidly with working depth from 0.4 kN to 1.6 kN as depth changed from 50 to 200 mm. This occurs not only because greater depths increase the disturbed soil volume, but also because soil density and strength varies due to overburden pressure (Manuwa 2009). They also demonstrated that increasing ground speed resulted in a significant increase in the draught force at all the depths tested. This is caused by the larger force necessary to accelerate the soil at higher tine speeds (Rowe & Barnes 1961). **Figure 2.23** illustrates the effect of work depth on draught force.

Studies have reported different relationships between draught forces of a soil-engaging implement and operating depth e.g. linear (Summers et al. 1986), quadratic (Grisso et al. 1996), polynomial (Kiss & Bellow 1981), and exponential relationships (Godwin, 2007; Manuwa 2009). The draught force response to operating depth has a linear component when operating depth is less than 70 mm, while the response curve could be explained by other models when operating depth is higher than 70 mm. This is because the draught force of tines is rapidly increased as the depth increased due to the increase of bulk density with depth (Collins & Fowler 1996).

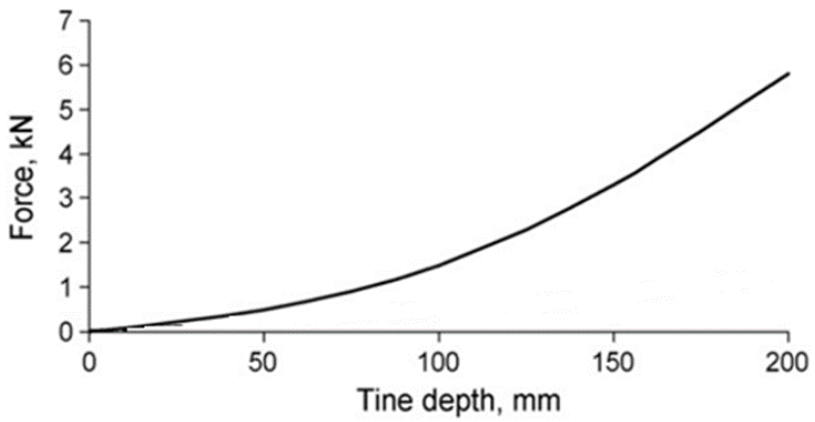


Figure 2.23: Effect of tine depth on the draught force acting on a 90° rake angle tine (Godwin 2007)

A number of studies have examined the relationship between draught forces of a soil-engaging implement and ground speed. Wheeler and Godwin (1996), for example, reported similar increases of draught with speeds up to 5.6 $m.s^{-1}$ in field and laboratory tests with narrow tillage tools in frictional and cohesive soils. Different studies have reported the relationship between them as linear, quadratic, polynomial, parabolic and exponential (Rowe & Barnes 1961; Swick & Perumpral 1988; Gupta & Surendranath 1989; Grisso et al. 1996; Manuwa 2009), respectively. These different characteristics might be related to the inertia required to accelerate soil, the effect of shear rate on soil shear strength and/or the effect of shear rate on soil-metal friction, all of which vary with soil type and condition.

In clay soil, increased draught force of tine has been explained by a corresponding increase in soil shear strength due to an increase in the shear rate (Rowe & Barnes 1961). However, it has been shown that the strength of frictional soils does not increase greatly with increasing shear rate (Stafford & Tanner 1983; McKyes 1985). This indicates that, in cohesionless soils, the increase in draught associated with an increase in speed is attributable to an increase in the inertial forces required to move the soil blocks.

However, studies carried out by Al-Janobi and Al-Suhaibani (1998) and Mak and Chen (2014) showed that depth had the greater and speed the lesser effect on draught force (**Figure 2.24**). Accordingly, the major considerations, as drawn by Godwin (2007), is never work the equipment deeper than necessary and small reductions in working depth can make a very significant difference to the magnitude of the draught force.

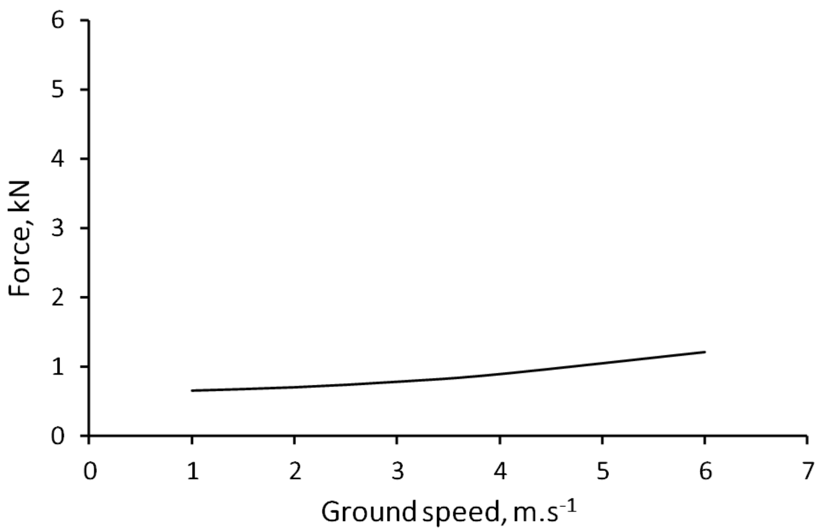


Figure 2.24: Effect of ground speed on the draught force of tine (after, Wheeler & Godwin 1996)

2.6.2. Prediction of draught force

Draught force is an important performance indicator of a soil-engaging implements as it affects the power requirement of the implement. Prediction of a soil-engaging implement's draught requirement is of great value to both implement designer and farmers (Desbiolles et al. 1997). Many and varied models can be used to predict draught force. These models can be grouped into two categories: Analytical (mathematical) and numerical modelling (Abo Al-Kheer et al. 2011). In this study, the analytical modelling method is used to quantify and predict the draught force produced by tine. This model enables draught and vertical forces to be calculated for a wide range of soil engaging implements from the knowledge of tool geometry, operating depth, soil physical properties and the form of the soil disturbance pattern produced by the tines. Several analytical models have been developed for predicting the draught force of a soil-engaging tine. Most of these have been reviewed by Grisso and Perumpral (1985) and Kushwaha et al. (1993), including both two-dimensional models and three-dimensional models. Depending on the operating depth, at greater depths soil failed and flowed around the tine much like soil failure in deep foundations (Upadhyaya et al. 2009). O'Callaghan and Farrelly (1964) observed that the depth at which the transition occurred from the crescent type of failure at the top to sideways failure in a horizontal direction at greater depth was proportional to tine width. Depending also on the depth-to-width ratio (d/w) for such tines, three categories have been distinguished, via wide tines (d/w < 0.5); narrow tines (1 < d/w < 6); and very narrow tines (d/w > 6) (Godwin & O'Dogherty 2007). Later Godwin and Spoor (1977) used the term "critical depth" for the depth at which the soil failure pattern changed from crescent failure to sideways failure (**Figure 2.25**).

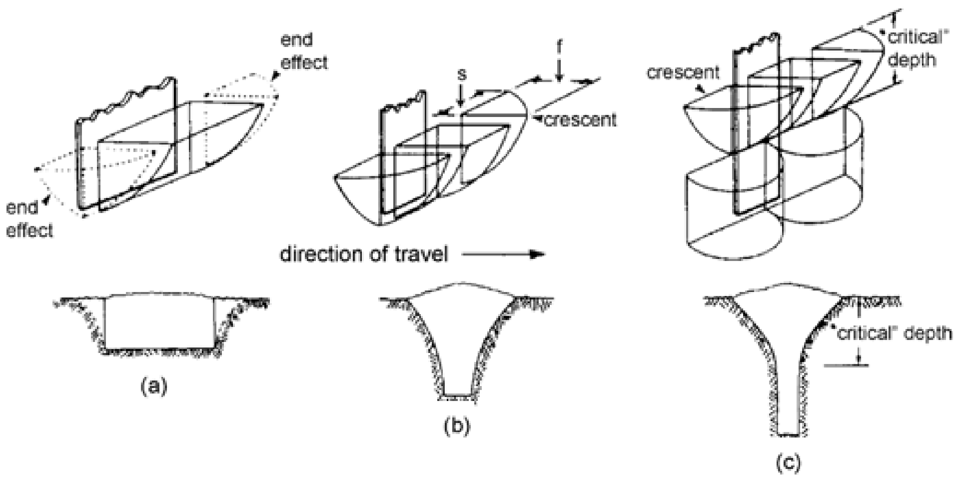


Figure 2.25: Illustration of the patterns of failure for each tine category. Figure shows (a) Blade; (b) Narrow tine; (c) Very narrow tine (Smith et al. 1989; Godwin 2007)

Terzaghi's passive earth pressure theory is the common framework for the analytical approach, and the basis for the equation proposed by Reece (1965) as the Universal

Earthmoving Equation (UEE), describing the force required to cut the soil by a tine. The UEE uses soil weight, cohesion and surcharge, and accounts for varying soil friction angles, simplified tine geometry and soil-tine interface strength properties. This equation has been employed successfully by a number of researchers (Reece 1965; Hettiaratchi & Reece 1967; Godwin & Spoor 1977; McKyes & Ali 1977; Perumpral et al. 1983).

$$\boldsymbol{P = (\gamma g d^2 N_\gamma + c d N_c + c_a d N_a + q d N_q) w} \qquad \textbf{Equation 2.1}$$

Where the symbols are:

symbols	Definition
P	Total tine force, N
γ	Total soil density, N m^{-3}
g	Acceleration due to gravity, 9.81 m s^{-2}
d	Tine working depth below the soil surface, m
c	Soil cohesion, N m^{-2}
ca	Soil adhesion, N m^{-2}
q	Surcharge pressure vertically acting on the soil surface, N m^{-2}
w	Tine width, m
Nγ, Nc and Nq	Factors which depend not only on the soil frictional strength, but also on the tool geometry and tine to soil strength properties

In the subsequent subsections, a detailed analysis of the existing analytical models is presented.

a Reece model

As stated previously, the Reece model is based on UEE. Reece (1965) proposed the Equation (2.1), to describe the force required to cut the soil by a tine. He made some simplifying assumptions about soil failure in two dimensions. As well, a failure zone was assumed to exist ahead of the cutting blade. The soil in the failure zone was assumed of be in the critical failure state (**Figure 2.26a**) at less than the critical depth. However, when a cutting tine is not very wide, a large proportion of the cut soil moves sideways (Payne 1956). Since more soil must be moved per unit width of the tine in the three-dimensional cases compared to the wide blades (two-dimensions), a larger draught is expected for three-dimensional cases than that of wide tines.

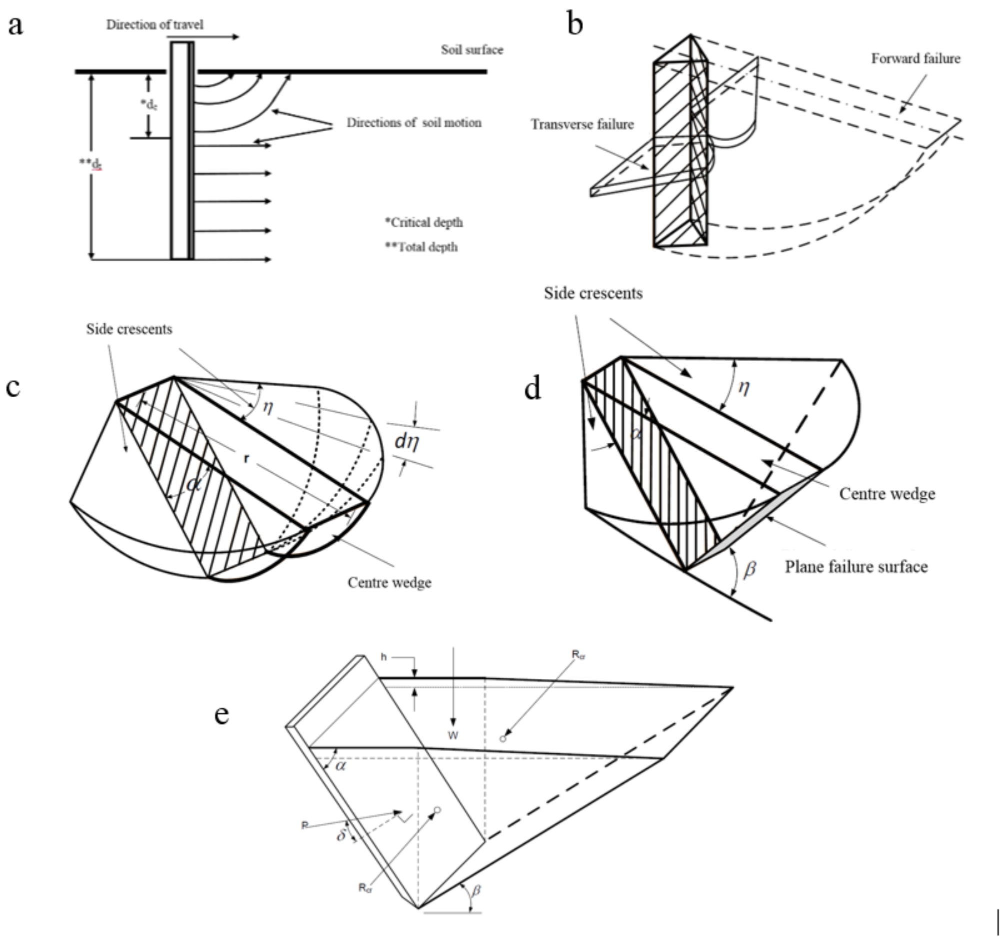


Figure 2.26: Different soil failure in front of narrow tines: (a) O'Callaghan and Farrely (1964); (b) Hettiaratchi and Reece (1967); (c) Godwin and Spoor (1977); (d) McKyes and Ali (1977); (e) Perumpral et al. (1983), (McKyes 1985)

b Hettiaratchi-Reece model

Hettiaratchi and Reece (1967) developed a three-dimensional soil failure model that was similar to the earlier model developed by O'Callaghan and Farrely (1964) in some aspects. This model also assumed a critical depth for the operating tine and two traversal failure zones only below the critical depth (**Figure 2.26b**). In the model, a two-dimensional equation are used to calculate the forward failure forces ahead of a soil-tine interface and a three-dimensional equations for the transverse failure away from the centre line of the interface. The equations were used in the same way as for the O'Callaghan-Farrely model except that the mass of soil was counted in this model. According to Grisso and Perumpral (1985), this model has been found to overestimate the draught force for tines, yet the model underestimated draught force for inclined tines.

c Godwin-Spoor model

Godwin and Spoor (1977) developed a model to predict draught force on narrow tines with a wide range of depth to width ratios. In this model, they studied the soil failure patterns, proposed a three-dimensional crescent failure at depths less than the critical depth and a two-dimensional horizontal failure pattern at depths greater than the critical depth. For the three-dimensional crescent failure, a failure model was proposed as a parallel centre wedge flanked with two side crescents (**Figure 2.26c**).

The lateral failure below the critical depth was similar to earlier horizontal failure models proposed by O'Callgahan and Farrelly (1964) (**Figure 2.26a**) and Hettriaratch and Reece (1967). The model included an addition parameter, *r*, the rupture radius. In this model, *r* was defined as the total forward distance of soil failure on the surface from the tine face.

The total force was calculated as the sum of the forces due to the three sections. The centre wedge force was calculated using **Equation (2.1)**. This two-dimensional expression was also used to calculate the force for small elements cut from the side crescents using the N-factors of Hettiaratchi and Reece (1974). The total applied force due to the side crescents was obtained by integration.

According to Payne and Tanner (1959), the difficulty with such a model is that *r* changed when the aspect ratio of the tine (*d* / *w*) varied and soil strength changed. As a result, Godwin and Spoor (1977) developed a graph using the data from Payne (1956), Payne and Tanner (1959) and Hettiaratchi and Reece (1967) to determine the aspect ratio (rupture distance over depth, i.e., *d/w)* and the tine rake angle. However, the application of this model required prior knowledge of *r* which is difficult to measure in practice (Shen & Kushwaha 1998).

d McKyes and Ali model

McKyes and Ali (1977) developed another model for narrow tines. It is similar to that of Godwin and Spoor (1977) but did not require prior knowledge of the rupture distance (r) for computing the forces on the tine. A failure wedge was proposed ahead of the cutting tine (**Figure 2.26d**). The model also consisted of a centre wedge and two side crescents. The failure shape of the centre wedge's bottom was assumed to be a plane, while the two side crescents were assumed to be a straight line, and make an angle with the horizontal.

In this model, the draught force contribution from the centre wedge and the two side crescent wedges were calculated by using Equation 2.1 to estimate the total draught force expression. However, in this equation the N-factors are re-evaluated for failure wedge.

Moreover, the model uses a technique that increases the magnitude of N-factors as the tine becomes narrower (Grisso & Perumpral 1985). In addition, by setting $w = \infty$, the researchers compared the N-factors with the N-factors used for two-dimensional models. It was found that for smooth tines, the results were very close, yet for the all rough define tines with $\alpha > 90° - \varphi$, rupture angle and the N-factors were much higher than those for the two-dimensional soil cutting cases. McKyes (1985) published a set of charts to determine the N-factors for some rake and rupture angles.

e Grisso et al. model

Grisso et al. (1980) and Perumpral et al. (1983) developed a model with a similar shaped failure zone to that of the Godwin and Spoor and the Mckyes and Ali models. However, the side crescents were replaced by two forces (R_{cr}) acting on the centre wedge. Soil weight of the two side crescents was neglected, and side planes of the centre wedge were treated as slip planes, therefore, the failure zone of this model included only a centre wedge (**Figure 2.26e**). As in the Mckyes and Ali model, the bottom slip surface was assumed to be straight. As well, the soil in front of the tine was assumed to move upward. This model produced equal values of $c\,N$ and $ca\,N$ from the previous two models, but $\gamma\,N$ value of the Grisso et al. model was less than one half of the same quantity resulting from the Mckyes and Ali model.

f Godwin and O'Dogherty model

In the models discussed previously, a constant friction angle δ was used. As well, the effect of the travel speed of the tine is not considered. However, increasing speed means that the shear failure in front of the tine occurs more frequently (Arvidsson & Keller 2010). An increase in draught force with speed was found to be due to increasing shear strength with increasing strain rate (Stafford 1979). This can have a significant effect on soil-engaging tine forces (Wheeler & Godwin 1996).

The first model was introduced by McKyes (1985) who proposed another model that was basically the same as the Reece (1965) model, with an additional term that accounted for the effect of tool speed on the draught force requirements.

The second model was developed by Swick and Perumpral (1988) and the third model by Zeng and Yao (1992). The Swick and Perumpral model had some assumptions which overestimated the size of the side crescents. Therefore, a new angle of η based on the experimental data was proposed, which was a function of the rupture distance r and the rake angle α. In the Zeng and Yao dynamic model, the acceleration and strain-rate effects were included.

The main difference between this model and the McKyes and Ali model is that this model needs a prior knowledge of shear strain at failure to determine the position of shear failure boundary. Another difference is that total draught of the tine P_x , is divided into five components as shown in the equation below:

$$P_x = P_G \sin\alpha + (P_{SH} + P_A) \cos\beta + P_F \cos\alpha + P_C \qquad \textbf{Equation 2.2}$$

Where: P_x = total draught of the tine, N; P_G = compressive force of soil along the blade, N; P_{SH} = side-edge shear force, N; P_A = inertia force of soil in acceleration, N; P_F = frictional force along the cutting blade surface, N; P_C = bottom-edge cutting force, N.

The final model by Godwin and O'Dogherty (2007) modified the Godwin and Spoor (1977) model and proposed a dynamic soil-cutting model that incorporated the tine dynamic effects. The general soil mechanics equation for the prediction of the forces acting on tines was developed through a series of stages.

The model formulation included soil properties effects, soil inertial forces and soil-tine interaction parameters. The soil failure zone for this model was same as that of the Godwin and Spoor (1977) model and consisted of a three-dimensional crescent failure above critical depth and a two-dimensional horizontal failure pattern below critical depth. For the three-dimensional crescent failure, a failure model was proposed as a parallel centre wedge flanked with two side crescents (**Figure 2.26c**).

In this model, the forces' contribution from the centre wedge and the two side crescent wedges were calculated using **Equation (2.1)**. The equation was modified by Godwin et al. (1984) and Wheeler and Godwin (1996), with an additional term that accounted for the effect of tine speed on the draught force requirements for improving the estimation. The equations for the horizontal and vertical forces due to the passive force then become:

$$\boldsymbol{H} = \left[\left(\gamma d^2 N_\gamma + C d N_C + q d N_q\right)\left(w + d\left(m - \frac{1}{3}(m-1)\right)\right) + \frac{\gamma v^2}{g} d N_a (w + 0.6d)\right] \sin(\alpha + \delta) \quad \textbf{Equation 2.3}$$

$$\boldsymbol{V} = \left[\left(\gamma d^2 N_\gamma + C d N_C + q d N_q\right)\left(w + d\left(m - \frac{1}{3}(m-1)\right)\right) + \frac{\gamma v^2}{g} d N_a (w + 0.6d)\right] cos(\alpha + \delta) \quad \textbf{Equation 2.4}$$

The different in this model enables draught and vertical forces to be calculated for a wide range of soil engaging implements from a knowledge of tool geometry, working depth, soil physical properties and the form of the soil disturbance pattern produced by the tines. The effects of soil-tine adhesion were also taken into account to improve the prediction of draught force. The final equation for the draught force in Godwin and O’Dogherty model become:

$$\boldsymbol{P} = \left(\gamma d^2 N_\gamma + C d N_C + C_a d N_{ca} + q d N_q + \frac{\gamma v^2}{g} d N_a\right) w \quad \textbf{Equation 2.5}$$

Where:

P = draught force; γ = bulk unit weight of soil; d = operating depth, C = cohesion, Ca = soil-metal adhesion; q = surcharge pressure; g = gravitational acceleration, *v* = working velocity; *w* = width of tine; and. Nγ, Nc, Nca, Nq, and Na = dimensionless factors.

This model is also the most widely accepted analytical model. In addition to its advantages, Godwin and O’Dogherty prepared a number of spreadsheets, covering single tines, interacting tines, cultivating discs, land anchors, and mouldboard ploughs to facilitate the measurement, calculation, and prediction of draught force.

As well as all of these features, the model has the ability to predict the draught force within error bounds of ±20%. Additionally, the main advantage of the Godwin and O’Dogherty model is its simplicity. However, this model has not been validated for

Australian soils that typically have a very high clay content within the soil-engaging implement (Bennett et al. 2016).

2.7. Motion resistance modelling

Modelling of soil-wheel interaction to predict motion resistance should take into account all vehicle design and operational parameters, as well as the soil parameters. The approaches used to predict motion resistance are many and varied, but can generally be grouped into three categories: theoretical, semi-empirical, and empirical methods (Crossley et al. 2001). In the agricultural field, considerable research has been conducted using the empirical approach. This method utilises soil penetration resistance as measured by a cone penetrometer as well as the measure of tyre dimensions and characteristics to predict motion resistance in the field. Freitag (1965) conducted experiments using dimensional analysis of tyres in two soft soils, and sand and clay soils to develop dimensional numbers, explained by factors such as a CI, tyre dimensions, and the defection of the tyre. Similar relationships were developed by Turnage (1972) and extended Freitag's work of the form:

$$\boldsymbol{N} = \frac{\boldsymbol{CI\,.b\,.d}}{\boldsymbol{W}}\ .(\boldsymbol{k}) \quad \textbf{Equation 2.6}$$

Where,

N = mobility number; CI = cone index in kPa; b = tyre section width in m; d = tyre diameter in m; W = tyre load in kN; k = a unique coefficient in this equation is $\sqrt{\frac{\boldsymbol{\delta}}{\boldsymbol{h}}}$; $\boldsymbol{\delta}$ = tyre deflection in m; and h = tyre section height in m.

Wismer and Luth (1973) developed relationships of a similar form to predict the coefficient of motion resistance, which was later modified by Gee-Clough (1978b, 1980), and McAllister (1983).

Brixius (1987) further developed a similar mobility number to account for more tyre factors. **Table 2.7** shows some of the most commonly recognized coefficients that researchers have used for calculating the wheel mobility number. Modelling and simulation of tyre performance was reviewed by Taheri et al. (2015). The mobility models in agricultural equipment that are most widely used are those by Gee-Clough (1980), and Brixius (1987). They are accepted by the ASAE Standards (Tiwari et al. 2010), because of their acceptable accuracy. Several studies have modified the values of constants in Brixius equations for more accurate results relating to their operating conditions (Evans et al. 1991; Al-Hamed et al. 1994).

Table 2.7: Wheel mobility number coefficients and coefficients of motion resistance (after Taheri et al. 2015)

Author	Wheel mobility number Coefficient	Coefficient of motion resistance	References
Wismer and Luth	$k_w = 1$	$0.04 + \frac{1.2}{N}$	**1973**
Freitag	$k_F = \sqrt{\frac{\delta}{h}}$	-	**1965,1970**
Turnage	$k_T = \sqrt{\frac{\delta}{h}} \frac{1}{1+b/2d}$	-	**1972**
Gee-Clough	$k_G = \sqrt{\frac{\delta}{h}} \frac{1}{1+b/2d}$	$0.049 + \frac{0.287}{N}$	**1978-1981**
Brixius (ASABE)	$k_B = \left(\frac{1+5\delta/h}{1+3b/d}\right)$	$\frac{1}{N} + 0.04 + \frac{0.5S}{\sqrt{N}}$	**1987**
Maclaurin	$k_M = \frac{\delta^{0.4}}{b^{0.2}\, d^{0.2}}$	-	**1981, 1997**
Rowland and Pee	$k_T = \sqrt{\frac{\delta}{h}} \frac{d^{0.15}}{b^{0.15}}$	$3 \times N^{-2.7}$	**1972, 1975**
Hegazy and Sandu	$k_{HS} = \sqrt{\frac{h-\delta}{d}}$	-	**2013**

Furthermore, many researchers (e.g. Tiwari et al. 2010; Hegazy & Sandu 2013) have used several empirical techniques in their studies, and have claimed that predicted performance was lower with some models and higher with others. However, many of empirical wheel-soil prediction models based on the mobility number approach have been developed in the USA and European countries to suit the conditions in those countries. The use of models relevant to mobility in Australian agricultural activities is rare in the literature.

2.8. Relationship between CTF and timeliness

In controlled traffic farming, the separation of permanent traffic lanes and permanent cropping areas can give compacted traffic lanes, which are known as tramlines. Firm traffic lanes generally improve wheeled machinery performance because components of soil strength are responsible for motion resistance and for wheel slip (travel loss). Motion resistance decreases as an inverse function with soil strength (cone idex)(CI) (see **Section 2.3.3**). This can indicate an improvement of mobility/trafficability because these are outcomes of soil-wheel interactions and determine wheeled vehicle performance in given field conditions (also see **Section 2.3.3**). Those parameters including motion resistance and mobility/trafficability are an indicator of timeliness improvement. Compacted soils do provide better support to farm equipment than loose soils (McKyes 1989) by providing traction, motion resistance and mobility for the machinery, and greater flexibility for timeliness season after season (Taylor 1994; Beard et al. 1995). Soil moisture content constitutes another important issue in non-CTF systems. Traction and mobility of farm machinery are decreased in wet soil conditions, detrimentally affecting the timeliness of field operations (Carter 1985; Burt et al. 1986). However, lower soil bearing capacity is the worst access condition in a wet and soft soil. **Figure 2.27** shows examples of small vehicle with less than 2 Mg (left picture) in a paddock during a grower inspection in a Western Australian paddock. What is likely to happen to a heavy tractor is easily imagined (right picture).

Figure 2.27: Field access in wet and soft soil condition (Henning 2018), right (Becker 2003)

In CTF systems, with compacted soil in permanent wheel tracks, there is a dual benefit with respect to mobility and motion resistance of farm machinery compared to soft soil: increased load support capacity and, reduced water infiltration and absorption (Laguë et al. 2003). Thus, CTF systems can particularly improve field access conditions for all farm machinery during wet periods (Guerif 1994).

This can lead to improved timeliness which is a measure of the ability to perform various machinery operations such as planting, spraying and harvest at the optimum time; an important aspect for most agricultural enterprises. Improvement of timeliness could allow more timely spraying, particular in no tillage cropping as an essential component of effective no tillage cropping (Tullberg 2007; Tullberg et al. 2007).

CHAPTER 2: LITERATURE REVIEW

Proper timing of field operations significantly improves both the quantity and the quality of produce (Taylor 1994). Delay in harvesting and planting can cost a grower between approximately 0.5% and 2% yield loss for every day of delay (Tullberg 2007). In USA, Oskoui and Voorhees (1991) found that the cost of a 3 to 4 week delay in planting of corn in a 300 to 400 ha farm can be as high as $50,000 per year. Tullberg (2007) argued that CTF growers have access to the paddock after rain two days or more before growers in non-CTF. Burt et al. (1986) also found that CTF growers could advance field operations following rain by up to two days in extremely wet conditions. But, the benefits of this timeliness are often dependent on soil type and conditions. Dickson and Ritchie (1996) noted that their 'zero traffic' system sometimes allowed field access for secondary cultivations five days earlier than ordinary cropping. In the UK, spring barley, winter barley and spring oil-seed rape have been grown under zero traffic system, which compares favourably with other traffic systems (Godwin et al. 2017).

In a different study in UK, Spoor (1997) found that availability of days for drilling is increasing up to 14 days depending on soil and season after using controlled traffic in a sugar beet farm. Increased timeliness makes early planting possible, which often results in yield increases. In Australia, improved timeliness provides greater cropping opportunities, including double cropping where it was not possible before particular in Australia (Vermeulen et al. 2010).

Generally, timeliness can be improved by:

- Working faster (increased speed and/or increased implement width)
- Working longer hours (in the day, in the season, or after rain)
- Providing comfort to the drivers by using CTF to provide a smoother passage along firm wheel tracks , enabling them to work for a longer time
- Reducing the number of operations required (Isbister et al. 2013).

CTF systems can provide timeliness improvements through all of these avenues (McPhee et al. 1995; McPhee et al. 2015). A number of farmers in Australia also claim that improved timeliness is one of the most important characteristics of CTF, but this has not yet been properly investigated and validated (McPhee 2011).

2.9. Synthesis of CTF

Without doubt, CTF has many benefits compared with non-CTF systems such as:

- Reductions in power and fuel requirements of cropping operations (Tullberg 1986, 2000)
- Improvements to field efficiency and timelines of sowing, spraying and harvesting (Bochtis et al. 2010), because the draught requirement of tilling or seeding should be less in non-compacted soil, and motion resistance to traffic should be less on permanent lanes, and compacted paths also provide a firm base for tractor and combine tyres
- Flotation and traction are both improved
- Eliminated overlaps and skips during pesticide and fertilizer application and while seeding crops (Reeder 2006)
- Improved soil porosity and structural conditions hence, hydraulic conductivity, surface infiltration and water use efficiency (Li et al. 2001; Tullberg et al. 2001; Li et al. 2007; McHugh et al. 2009; He et al. 2012)
- Improving fertiliser use efficiency (Antille et al. 2015; Hussein et al. 2017);
- Decreasing greenhouse gas emissions (Tullberg et al. 2011; Gasso et al. 2013; Antille et al. 2015; Tullberg et al. 2018)
- Increasing biological activity (Isbister et al. 2013)
- Increasing grain yield and grain quality improvements (Tullberg et al. 2007; Isbister et al. 2013; Smith et al. 2014; Hussein et al. 2017, 2018)
- Improved resource use efficiency translates into greater economic returns (Chamen 2011; Kingwell & Fuchsbichler 2011; Chamen et al. 2015)
- Compatibility with no-tillage and precision agriculture technologies with most major crops (wheat, sorghum, cotton, and other small grains) (Tullberg et al. 2007; Smith et al. 2014; Antille et al. 2015; Godwin et al. 2015).

In summary, CTF can have major positive impacts on energy use on-farm, production costs, cropping sustainability, timeliness, crop water and fertiliser use efficiency, crop yields, environmental conditions, and can work with most conservation tillage systems, and with most major crops.

Controlled traffic farming has some recognised limitations such as costs of conversion. CTF adoption relies on all machines having the same wheel spacing (Chamen 2006).

In some cases, this requires an extra cost to extend the axels of machines and auto-steering systems, and the guidance technology as recommended with CTF are also sources of costs (Chamen 2011). In case of a damaged machine, the exchange with another machine may cause a problem, as the replaced machine has to fit into the chosen working track width (Isbster et al. 2013). The potential interference of in-field infrastructure for soil erosion control (e.g. contour banks) or surface drainage, particularly for steep slopes can also increase costs (McPhee et al. 2013; Antille et al. 2015). Careful design of permanent traffic lanes' layout is also required (McPhee et al. 2013). CTF also requires a higher level of skill and knowledge from the farmer (Jensen et al. 2012).

2.10.Summary and the Research Gap

This chapter has given an extensive review of literature related to the aims and objectives and the concept employed in the present study. The review of the literature provided a broad overview of issues relating to compaction of agricultural soils due to random conventional vehicular traffic and its impacts on soil properties, yield, and energy requirements. The techniques, which are used for overcoming soil compaction, with more focus on controlled traffic farming systems was reviewed. The role of controlled traffic farming in the world and Australia in eliminating worries about soil compaction and enhancing overall farm efficiency, in particular draught force and motion resistance, was presented. A brief overview of draught force and motion resistance modelling was also presented. This helps to understand the role of CTF in reducing the energy use on-farm, including draught force and motion resistance, and improving timeliness. Finally the relationship between controlled traffic farming systems and timeliness was presented.

From the literature review, it can be seen that soil compaction has long been recognised as a great problem for agriculture, and extensive research work has been carried out on the subject; usually under non-CTF cropping systems (Dwyer 1983; Voorhees 1986; Arvidsson, 2001; Pagliai et al. 2003). The effects of soil compaction on energy requirements, field conditions, and yield have also been explored (e.g. Negi et al. 1981; Chamen et al. 1990; Jorajuria & Draghi 1997; Håkansson and Lipiec 2000; Lipiec & Hatano 2003; Keller 2004; Botta et al. 2006, 2012; Chamen et al. 2015).

CHAPTER 2: LITERATURE REVIEW

In recent decades, CTF has been the subject of considerable research, but most has focused on the agronomic and environmental aspects of CTF. Little work has been done on the matter of energy requirements in CTF. Therefore, the assessment of the CTF is of great importance because of its consequences on soil compaction, and its effect on energy requirements. There appears to be a paucity of information concerning the effects of compaction of wheel track on the energy requirements caused by using modern, heavy tractors and harvesters, some of which are more than 40 Mg. In addition, CTF farmers have provided many unofficial reports of reduced power requirements and fuel consumption, so the energy effects of CTF are clearly important, but published evidence is not unanimous. In Australia, Tullberg (1986, 2000) working on a clay soil observed that the traffic effect of wheels on the draught of tillage implements increased total draught by 30% or more compared with the same implement operating in non-trafficked soil. But, the heaviest traffic used in that study was produced by a 6 Mg tractor, and in only one cropping system.

Burt et al. (1994) in the USA and Arslan et al. (2015) in UK however, found that traffic systems had no significant effect on energy requirements. Burt demonstrated that operating depth for tillage implements in non-trafficked soil was greater than trafficked soil. These implements operate only on the surface soil, the traffic could have created a resistance to penetration and therefore forced the implements to operate at a lesser depth.

But, in Arslan et al.'s case, they found differences for tine tillage draught in traffic systems, but these were not significant. Meanwhile in zero tillage, they indicated that there were no differences in traffic system for seeding in particular. This is because measurement was for the whole planter, therefore it could be that the draught due to rolling resistance of depth and press wheels was considerably greater than draught due to "tillage" component of seeding. However, these studies considered only the draught force effects, but not motion resistance. It also appears that there are still no studies of CTF energy effects, which include motion resistance effects. There are only two studies (Tullberg 1986, 2000), which investigated traffic impacts on tillage energy requirements, but the heaviest traffic used in that study was produced by a 6 Mg tractor, and in only one cropping system. Furthermore, no consideration was given to the detrimental effects of wheel traffic on the motion resistance of equipment.

CHAPTER 2: LITERATURE REVIEW

Agricultural soils vary from almost pure sands to soils very high in clay and/or organic matter. Sand has almost no cohesive strength, while soils having a large percentage of clay are quite cohesive, but all physical properties are strongly influenced by moisture content (Barger et al. 1967).

Australia has a great diversity of soils. This variety has had a significant effect on mechanical soil properties (soil strength), which affects the efficiency of traffic and traction of machinery in the field. The soils are typical of the 14 Soil Orders in the Australian soil classification such as Vertisols, Calcarosols, Tenosols, Kandosols, Rudosols and Dermosols (Isbell 2002). It was, therefore, considered important to investigate the validation of draught force and motion resistance modelling under Australian CTF conditions

Thus, this study will first investigate the effect of wheel traffic on the energy requirements of soil-engaging implements in a number of cropping environments. The study will also assess the effect of permanent traffic lanes on the motion resistance of farm equipment for crop production. The impact of CTF on the timeliness of crop operations will also be considered. The study will use modelling and validation to extend the usefulness of the results on both draught force and motion resistance. To achieve this, the Godwin and O'Dogherty model (2007) will be used to predict draught force, while the Gee-Clough and Brixius (ASABE) models will be used to predict motion resistance. The latter models will also be used to determine impacts of CTF on timeliness by comparing the results of mobility and coefficient of motion resistance under uncontrolled and controlled traffic conditions.

CHAPTER 3

METHODOLOGY

3. METHODOLOGY

3.1. Introduction

The literature review (**Chapter 2**) has shown that most of the attention paid to soil compaction has been to its effects on soil properties and yield rather than to energy aspects, and there is little information on CTF system energy effects (see **Table 2.6**). In Australia, only Tullberg (1986, 2000) has looked at traffic impacts on tillage energy. But the study's heaviest traffic was produced by a 6 Mg tractor, and applied to only one soil type and cropping system. Broader studies of CTF energy effects, which should include both draught force and motion resistance effects, are completely absent.

Agricultural soils vary widely in texture from almost pure sand to soils with a very high clay and/or organic matter content, with very different draught -related physical properties. Sand has almost no cohesive strength, while high-clay soils are relatively cohesive, and all physical properties are strongly influenced by moisture content (Barger et al. 1967). Australia has a great diversity of soils so it is important to investigate the effects of CTF on cropping energy requirements in contrasting conditions typical of the Australian grain industry.

CTF can be expected to affect energy requirements by its impacts on soil engaging implement draught, and on tractor/machine motion resistance. Because the Australian grain industry is largely no till, CTF draught effects might mostly be seen in seeding operations, but other implements are sometimes used for strategic tillage. Motion resistance effects will apply to most cropping operations, and these are probably the most relevant to the reduction in timeless constraints of CTF systems (v. non-CTF cropping).

Draught and motion resistance models, if calibrated and validated for Australian soil conditions, should be helpful in enabling a greater generalisation of CTF energy impacts across a greater range of soil conditions, and perhaps also for exploring timeliness effects.

The objectives of this study are summarised below:

1. For a representative range of grain farming equipment performing within its normal range of operating parameters, and used over a range of typical grain cropping soils:

    a. Quantify the impact of prior wheel traffic on soil-engaging (tillage and seeding) equipment draught

    b. Quantify the motion resistance encountered by farm tractors, sprayers and harvesters

    c. Assess the textural and physical parameters of each soil site in both wheeled and non-wheeled conditions.

2. Use this data to:

    a. Demonstrate the impact of CTF on the energy requirements of cropping operations at each site

    b. Calibrate and if possible validate the draught and motion resistance models for each soil site

    c. Use the outcome of a and b as the basis for a broader exploration of CTF effects.

Industry-relevant results require commercial-scale equipment in normal farming situations which are only available on commercial farms. This implies an on-farm research protocol that would be acceptable to farmers in terms of the imposition on their time and equipment, and any damage associated with experimental tillage and unnecessary wheeling. Where possible, this study was carried out on farms that have been in CTF for some years (up to 15 years).

3.2. Sites Selection

The experimental works were conducted in two broad sets of soil conditions – clay in Northern region sites, sand/loam soils in Southern region sites, using several sites within each region, as illustrated in **Figure 3.1**. In the Northern region where CTF is most widely used on larger crop area sites, the study sites selected for this research were located on CTF farms situated at Felton, 27^{o}, 49′, 3815 S, 151^{o}, 45′.541 E, Pittsworth 27^{o}, 45′, 4603 S, +151^{o}, 27′.7265 E, and on non-CTF sites at Gatton, 27^{o}, 32′, 2204 S, 152^{o}, 20′.1376 E, and Kingaroy 26°44'49.84" S, 151°41'59.27" E. The CTF farms were located in the Darling Downs region of Queensland, growing grain crop such as wheat, barley, sorghum and a variety of pulses. They were selected because the farmers have been applying controlled traffic for long periods (up to 15 years). Gatton and Kingaroy were non-CTF sites used for some preliminary tests, but nevertheless provided some useful information.

The Southern region sites were situated in two states, Victoria and South Australia. The Victorian measurements were carried out at, Woomelang (Hopetoun), 35^{o}, 35′, 6782 S, 142^{o}, 42′, 204 E, and Kooloonong (Swan Hill), 34^{o}, 55′, 8049 S, 143^{o}, 2^{o}, 6826 E. In South Australia, the study sites were located on farms situated at Loxton, 34^{o}, 28′, 2801 S, 140^{o}, 34′, 5579 E, and Waikerie, 34^{o}, 19′, 9882 S, 139^{o}, 59′, 8517 E. All Southern region farms were in the Murray Mallee region, with the Loxton and Swan Hill farms operating under long-term CTF, while Hopetoun operated with an incomplete CTF system, and Waikerie was non-CTF. All were producing grain crops such as wheat, barley and canola, and were under no till systems.

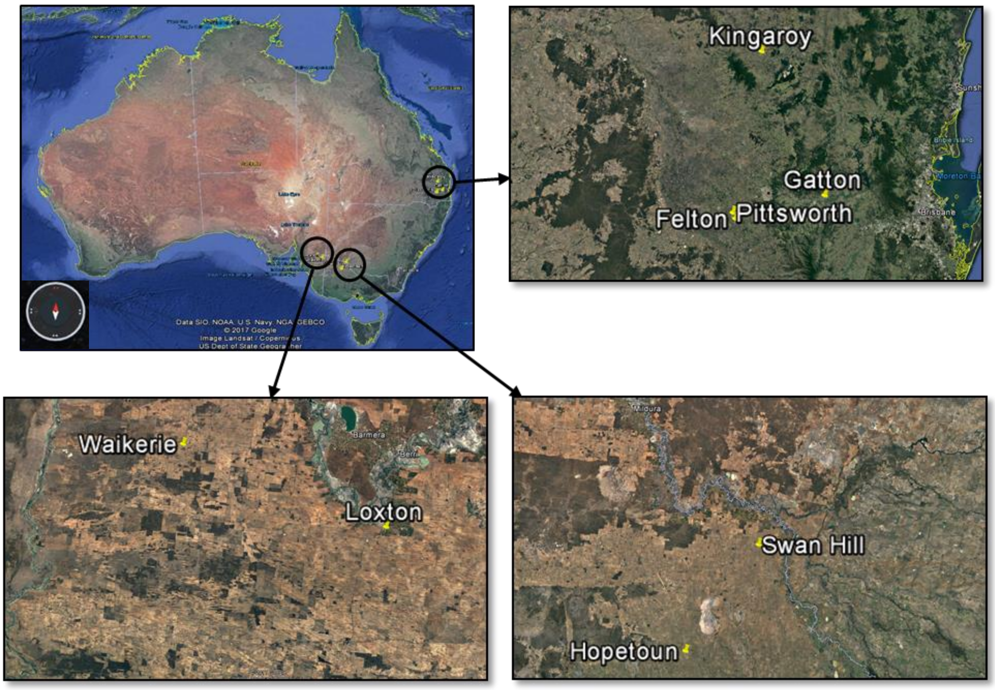


Figure 3.1: Map of farms and location of trails sites

3.3. Soil Characteristics

Agricultural soils vary from almost pure sands to soils very high in clay and/or organic matter. Sand has almost no cohesive strength, while soils having a large percentage of clay are quite cohesive. All physical properties are strongly influenced by moisture content (Barger et al. 1967). Australia has a great diversity of soils. This variety has had a significant effect on mechanical soil properties (soil strength) as it changes the efficiency of traffic and traction of machinery in field. The soils are typical of the 14 Soil Orders in the Australian soil classification such as Vertisols, Calcarosols, Tenosols, Kandosols, Rudosols and Dermosols (Isbell 2002).

Thus, four soil types were considered as part of this study. The soils addressed were divided into two groups of heavy clay soils from the Northern region sites, and medium-textured and light soils, from the Southern region sites. The soils in Northern region sites were mainly clay (Tables 3.1). In contrast, the soils in Southern region sites were between loam and sandy soils (Tables 3.2). Soil texture was determined by the hydrometer method that is explained in the following section. The identification of other characteristics during the research program used a series of laboratory-based and in-situ tests:

- Bulk density
- Penetration resistance of soil
- Shear force
- Moisture content measurement
- Soil surface assessment.

These parameters were selected for testing as they were considered to be the factors most likely to influence energy consumption during field operations of agricultural equipment. As an example soil strength varied with soil suction, texture and structure. Soil strength is affected by soil texture and initial soil bulk density (Hillel 1982). The coarser the soil texture, the lower the soil strength (Smith et al. 1997; Peng et al. 2004).

The variations of soil conditions and types have an impact on energy requirements through the difference in soil strength and bulk density. Energy requirements such as motion resistance, mobility and traction can be improved by compacted soil, which increases soil strength (for more details, see **section 2.3.3**, **section 2.6** and **section 2.7**). Particle-size distribution is the most obvious test because texture is the most common means of soil identification. Soil's texture describes the amount of sand, silt and clay particles in the soil.

3.3.1. Soil texture

Texture of soils was measured by the hydrometer method suggested by the (Standards Association of Australia (1976) and Laker and Du Preez (1982). A soil auger was used to sample the soil at depths up to 400 mm. This was repeated ten times randomly to obtain a more representative sample of the plot's soil (**Appendix A3.1**). The soil samples for each depth were mixed and the soil passed through a 2 mm sieve to remove the gravel fraction. 40 g of oven dried soil from each depth was weighed into 300 cm^3 plastic bottles. 50 cm^3 of 10% Calgon and 5 cm^3 of 0.6 M Sodium hydroxide (NaOH) were added, and made up to 300 cm^3 with distilled water.

The bottles were tightly sealed and placed on a shaker for 24 hours. The suspension was transferred to 1000 cm^3 cylinders by washing with distilled water and the cylinders were then made up to 1000 cm^3. A blank solution was prepared by adding 50 cm^3 of 10% Calgon and 5 cm^3 of 0.6 M Sodium hydroxide (NaOH) into 1000 cm^3 cylinder and the cylinder was then made up to 1000 cm^3 with distilled water. The cylinders were left on the laboratory bench to equilibrate at 25 C°. The suspensions were then mixed vigorously and thoroughly and left to settle for 5 minutes.

The hydrometer measurement was taken after 5 minutes of suspension and of the blank solution. The suspensions were then left to settle for 5 hours. Then the hydrometer measurement was taken for both samples. The differences in hydrometer reading for the suspension and blank solution after 5 minutes was used to calculate silt and clay percentages. The clay percentage was calculated by measuring the hydrometer reading for suspension and blank solution after 5 hours as below:

$$\%\ \mathbf{Clay} + \mathbf{Silt} = \frac{\mathbf{Hydrometer\ reading\ (Soil)_{5\ minute} - Hydrometer\ reading\ (blank)_{5\ minute}}}{\mathbf{Mass_{soil}}} \times \mathbf{100} \quad \textbf{.Equation 3.1}$$

$$\%\ \mathbf{Clay} = \frac{\mathbf{Hydrometer\ reading\ (Soil)_{5\ hours} - Hydrometer\ reading\ (blank)_{5\ hours}}}{\mathbf{Mass_{soil}}} \times \mathbf{100} \ldots\ldots\ldots\ldots \textbf{Equation 3.2}$$

% Silt = Outcome of Equation 3.1 – Outcome of Equation 3.2

% Sand = 100 – Outcome of Equation 3.1

Table 3.1: Texture of soil of Queensland experimental sites

Sites	Depth (mm)	Particle size distribution (%)			Texture
		Clay	Silt	Sand	
Felton (Black Vertisol)	0-100	51.25	23.25	25.5	Clay
	100-200	53.5	21.5	25	Clay
	200-300	54.25	21.25	24.5	Clay
	300-400	55.5	20.5	24	Clay
	Average	53.625	21.625	24.75	Clay
Pittsworrth (Grey Vertisol)	0-100	46.25	23.75	30	Clay
	100-200	47.5	25	27.5	Silt clay
	200-300	47.5	23.75	28.75	Clay
	300-400	52.5	22.5	25	Clay
	Average	48.4375	23.75	27.8125	Clay
Gatton (Brown Chromosol)	0-100	48.25	23.25	28.5	Clay
	100-200	50.5	21.5	28	Clay
	200-300	53.25	20.25	26.5	Clay
	300-400	54.5	20	25.5	Clay
	Average	51.625	21.25	27.125	Clay
Kingaroy (Grey Vertisol)	0-100	47	23	30	Clay
	100-200	49	22	29	Clay
	200-300	51	21.5	27.5	Clay
	300-400	52.5	22	25.5	Clay
	Average	49.875	22.125	28	Clay

Table 3.2 Texture of soil of Victorian and South Australian experimental sites

Sites	Depth (mm)	Particle size distribution (%) Clay	Silt	Sand	Texture
Hopetoun (Red Calcarosol)	0-100	15	2.5	82.5	Sandy Loam
	100-200	22.5	5	72.5	Sandy Clay Loam
	200-300	40	2.5	57.5	Sandy Clay
	300-400	45	7.5	47.5	Sandy Clay, Clay
	Average	30.625	4.375	65	Sandy Clay
Swan Hill (Red Sodosol)	0-100	15	12.5	72.5	Loam
	100-200	25	10	65	Clay Loam
	200-300	27.5	11.25	61.25	Clay Loam
	300-400	30	6.25	63.75	Clay Loam
	Average	24.375	10	65.625	Clay Loam
Loxton (Calcic Calcarosol)	0-100	7.5	2.5	90	Sandy
	100-200	11.25	2.5	86.25	Sandy Loam
	200-300	12.5	2.5	85	Sandy Loam
	300-400	23.75	5	71.25	Sandy Clay Loam
	Average	13.75	3.125	83.125	Sandy Loam
Waikerie (Calcarosol)	0-100	5	2.5	92.5	Sandy
	100-200	6.25	1.25	92.5	Sandy
	200-300	6.25	1.25	92.5	Sandy
	300-400	6.25	2.5	91.25	Sandy
	Average	5.9375	1.875	92.1875	Sandy

3.3.2. Bulk density (BD) ($Mg.m^{-3}$)

Bulk density is the ratio of dry soil mass to total soil volume (Cresswell & Hamilton 2002). The core method was used to measure the bulk density (Blake 1965). For this method, cylindrical metal samplers (48 mm dia. x 52 mm length) were used (**Figure 3.2**). These were pressed into the soil to the desired depth and were removed to preserve a known volume of samples. The samples were immediately placed into bags to minimize evaporation. The samples were then weighed before dried on a digital scale in the laboratory for later determining soil moisture. The samples were transferred to containers and placed in an oven at 105° (24 to 48 hours). The samples were then reweighed and the weight of each marked. The bulk density was calculated using **Equation (3.3)**.

$$\rho_b = \frac{m_z}{V_s} \quad \text{Equation 3.3}$$

Where ρ_b is bulk density, $Mg.m^{-3}$; m_z is a mass of dry soil, Mg; V_s is a volume pf the soil sample, M^3.

Measurements of bulk density and other strength-related soil measurements were made in Permanent Traffic Lanes (PTL) (tramlines) and Permanent Crop Beds (PCB) at each CTF site, and random locations in non-CTF sites (**Table 3.3**). The measurements were collected at soil depths: 0-50; 50-100; 100-150 mm. The measurements were randomised into plots to decrease the effect of soil heterogeneity, and were repeated four times for each main plot to obtain a more representative bulk density measurement of the plots (**Appendix A3.1)**.

Figure 3.2: Procedure of bulk density sampling

Table 3.3: Physical properties of the soils for all studied sites

Sampling site	Depth (mm)	Bulk density ($Mg.m^{-3}$)		Shear force (MPa)		Moisture content (%)	
		Mean	SD	Mean	SD	Mean	SD
Felton site							
PTL	**50**	1.130	± 0.020	0.164	± 0.015	33.39	± 2.33
	100	1.208	± 0.012	0.187	± 0.003	39.42	± 1.67
	150	1.248	± 0.014	0.209	± 0.012	40.49	± 0.82
PCB	**50**	0.881	± 0.039	0.027	± 0.005	24.75	± 1.76
	100	1.126	± 0.051	0.071	± 0.010	38.85	± 1.08
	150	1.227	± 0.012	0.092	± 0.007	43.19	± 0.92
Pittsworth Site							
PTL	**50**	1.543	± 0.032	0.251	± 0.017	17.11	± 1.64
	100	1.654	± 0.027	0.328	± 0.016	24.36	± 1.20
	150	1.607	± 0.049	0.340	± 0.023	24.73	± 1.59
PCB	**50**	1.005	± 0.105	0.051	± 0.014	14.74	± 1.33
	100	1.227	± 0.060	0.074	± 0.057	25.28	± 0.81
	150	1.294	± 0.047	0.118	± 0.015	26.13	± 1.83
Gatton site							
Paddock	**50**	1.074	± 0.099	0.063	± 0.034	11.57	±1.05
	100	1.213	± 0.043	0.083	± 0.064	13.91	± 0.14
	150	1.299	± 0.037	0.149	± 0.014	14.86	± 0.32
Kingaroy site							
Paddock	**100**	1.091	± 0.057	-	-	9.79	± 2.39
	200	1.214	± 0.042	-	-	21.54	± 0.58
Hopetoun site							
PTL	**50**	1.660	± 0.049	0.212	± 0.020	8.63	± 0.72
	100	1.750	± 0.055	-	-	10.75	± 1.19
	150	1.575	± 0.031	-	-	13.94	± 1.41

Soils properties

PCB	**50**	1.329	± 0.029	0.092	± 0.014	7.16	± 2.05
	100	1.437	± 0.092	-	-	9.13	± 1.54
	150	1.555	± 0.104	-	-	13.73	± 1.17
Swan Hill site							
PTL	**50**	1.820	± 0.058	0.276	± 0.019	9.49	± 0.72
	100	1.796	± 0.089	-	-	9.43	± 1.4
	150	1.630	± 0.033	-	-	12.74	± 0.63
PCB	**50**	1.216	± 0.055	0.082	± 0.017	8.12	± 0.78
	100	1.312	± 0.010	0.128	± 0.025	7.12	± 0.80
	150	1.444	± 0.048	0.191	± 0.017	8.23	± 1.54
Loxton site							
PTL	**50**	1.587	± 0.024	0	0	5.04	± 0.41
	100	1.671	± 0.035	0	0	5.67	± 0.41
	150	1.768	± 0.056	0	0	6.02	± 0.39
PCB	**50**	1.422	± 0.080	0	0	4.63	± 0.23
	100	1.530	± 0.112	0	0	5.96	± 0.64
	150	1.679	± 0.062	0	0	5.02	± 0.33
Waikerie site							
On-track	**50**	1.512	± 0.076	0	0	4.34	± 0.40
	100	1.617	± 0.057	0	0	4.57	± 0.83
	150	1.656	± 0.033	0	0	5.62	± 0.67
Off-track	**50**	1.398	± 0.075	0	0	4.08	0.38
	100	1.556	± 0.033	0	0	4.21	0.65
	150	1.590	± 0.061	0	0	4.38	0.41

3.3.3. Penetration resistance of soil (PR) (MPa)

The force per unit cone base area required to press the cone through the soil layers is called the Penetration Resistance (PR) (ASABE 2013b). The soil cone penetrometer is traditionally used to assess the soil strength within a soil profile, and measures the force required to insert a cone tip into the soil. PR is calculated by dividing this insertion force by the base area of the cone (ASABE 2013a).

A 'Rimik" power-insertion penetrometer (Rimik, CP4011) (http://www.rimik.com), was used for PR determination (**Appendix A3.2**). This provided a constant insertion velocity, which should produce significantly more accurate and consistent results than hand-held technology (Moraes et al. 2014). CI measurements were conducted over the 0 – 500 mm depth range with 20 replicates over the depth range (ASABE, 2013a).

3.3.4 Shear force (MPa)

The CI mentioned above relate to motion resistance. Measurements of the shear strength of soil have been claimed to provide better relationships with implement performance (Shoop 2009). The shear vane device was used for assessing the shear strength of soil in-situ (**Appendix A3.3**). A shear vane device is a simple tool designed to measure the shear strength of soils. Shear force measurements were carried out with the same process used for bulk density **(Table 3.3)**.

3.3.5 Moisture content measurement (MC) (%)

Soil strength is affected by soil moisture and bulk density (Ayers 1987), so this was the reason to determine the moisture content of the sites' soils. The gravimetric with oven drying method was used to determine moisture content. This method is described by Gardner (1965). Two different sampling methods were used to determine the soil moisture: the samples were taken for bulk density measurement were also used to determine the moisture content to cover the entire work depth. The soil sample was weighed before being placed in an oven at 105ºC for 24 hours. The samples were then re-weighed and the soil moisture content calculated (**Table 3.3**).

A soil auger was used to sample the soil at different depths. The samples were immediately placed in sampling bags to minimize evaporation from the samples. Sampling was done at 100mm up to 500 mm depth. This was done to cover the entire depth range encountered in PR. The soil samples were collected from the same locations as the bulk density samples. They were then weighed on a digital scale in the laboratory before being placed in an oven at 105ºC for 24 hours. The samples were then weighed again and the weight of each marked. The moisture content was also calculated (**Chapter 6)** and (**Appendix A6.2**).

3.3.6 Soil surface assessment

A profile meter was used to measure soil profile and to provide values for tyre rut profile and soil roughness. Rut profile was measured to record the changes in soil surface deformation, which is considered to be closely related to soil compaction and reduction of motion resistance (Soane et al. 1980a; Botta et al. 2009; Botta et al. 2012). These were measured using a profile meter, which consists of a frame with 32 adjustable pins spaced 20 mm apart (**Appendix A3.4**).

The frame was placed across the tyre rut profile at a right angle, and the pins dropped to the soil surface. The pins were then locked, and the meter carefully placed on a graph of plastic sheet aligned to the grid, and photographed. Four rut profile measurements were taken for permanent traffic lanes and permanent crop bed at CTF sites, and wheeled and non-wheeled soils at non-CTF sites before and after measuring the motion resistance. The after measurements were taken from each tyre rut profile four times at random locations in the rut.

Soil roughness is the irregularities of the soil surface, and is caused by factors such as soil texture, aggregate size, rock fragments, vegetation cover and land management (Thomsen et al. 2015). Moreover, agricultural terrain roughness plays an important role in soil–tyre interaction and tractor vibration, and its measurement provides an additional parameter defining the quality of the work.

This quality is not only influenced by soil conditions and implement parameters such as tools, work speed, depth (Bögel et al. 2016), it can also be affected by trafficking of agricultural equipment. The same measurements and procedures carried out for rut profile were repeated for the determination of soil surface profile. Hoverer, these measurements were taken four times from wheeled soil and non-wheeled soil for all tine at each depth.

3.4. Draught force and soil roughness measurements in field (Methodology of Chapter 4):

A number of methods have been used to measure draught force in a field, depending on the type of implement hitch (pull (wheel-mounted), semi-mounted (semi-integral) and rear-mounted (three-point integral) (ASABE 2009)). Most of the standard methods of measuring implement draught also include an undesirable component of motion resistance, and are incapable of looking at comparative draught of tines in wheel tracks and neighbouring soil. This study needed to measure draught forces of the soil-engaging implement in CTF wheel-tracks and non-wheeled soil (permanent crop beds) simultaneously, necessitating the use of a specialised tillage energy unit for this study.

3.4.1. Tillage energy unit

This unit has four identical instrumented tine assemblies mounted on a 4m wide toolbar with transverse adjustment allowed positioning of two tine assemblies in the tractor wheeltracks, and two in non-wheeled soil, with all at in the same vertical position relative to the toolbar. The tillage energy unit was originally manufactured at the University of Queensland for work reported by Tullberg (2000), and is shown in **Figure 3.3**.

Figure 3.3: Overview of the experimental tillage unit used in the study; (A): Close-up of data-logger, (B): Close-up of force transducer; and (C): Plan view of tractor and tillage unit

Draught-sensing was achieved with edge-on chisel plough shanks attached to parallel link assemblies, the movement of which was restricted by shear beam force transducers (SKT model 1500). These were monitored by a data logger (Rimik DataNode) (**Figure 3.4**) providing an oversampling and decimation system for filtering signal noise and recording the mean draught force measurement at two-second intervals for each transducer (**Appendix A3.5**). The four-tines on their parallel link assemblies were mounted on a 4m wide three-point linkage toolbar fitted with adjustable depth control wheels at its extremities (**Figure 3.3**). It could be fitted with proprietary soil engaging tools (shares): chisels, sweeps and seeder openers.

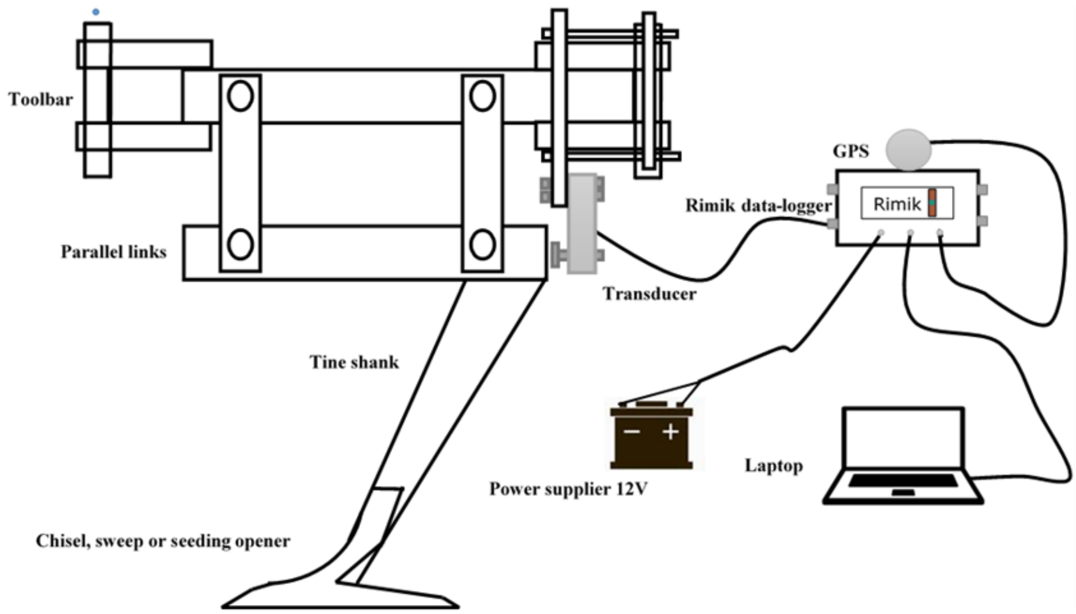


Figure 3.4: Assembly of Draught-sensing tine

A limitation of the tillage unit is that the operating depth in wheeled soil is lower than in non-wheeled soil. Because all tines were fitted to one frame (toolbar) all operated at the same depth relative to the toolbar, so wheel track tines, normally positioned directly behind each tractor wheel, operated at reduced depth relative to the depressed soil surface of the wheel track. A further limitation was the transducer capacity (8 kN), which restricted operating depth to 150mm.

3.4.2. Calibration Tests

All the shear beam force transducers (SKT model 1500) were calibrated in the Material Laboratory at the University of Southern Queensland (**Figure 3.5**), with compression loads of 0 to 8 kN, the expected working range so sensitivity and repeatability could be recorded (Cox 1988). All tests were repeated after the initial field trials and after completion of this work, but transducer characteristics were unaffected (**Appendix A3.6**). The strain gauge pull-meter, used to measure the motion resistance, was also calibrated in tension at this time (**Figures 3.5**) and (**Appendix A3.6**).

Figure 3.5: Calibration procedure for transducers (top) and pullmeter (bottom)

3.4.3. Experiment design

A major consideration in designing these experiments was what would be acceptable on commercial grain farms. These are the only places where long-term controlled traffic soil is available; the only sites which can provide realistic (scientifically valid) data on long-term effects of wheel traffic, or the absence of such traffic.

The draught force experiments were carried out using 550-m × 15-m, plots arranged in a block design, with three replications. Three factors and different levels of comparison, namely soil conditions (non-wheeled to represent CTF, wheeled to address non-CTF), working depth (75, 100, and 125 mm, respectively) and type of tine (chisel, sweep, and seeder opener, respectively) were used. The working depths were chosen to represent those commonly used for fertilizer application, shallow tillage, and deep placement of fertilizer, respectively.

"Strategic" tillage is occasionally conducted in long-term no-tillage soil for control of glyphosate-resistant weeds (Melland et al. 2016). Sweep tines, and chisel tines are commonly used to deal with surface compaction. Both leave significant amounts of crop residue on the soil surface to protect the soil from wind and water erosion (Harrigan & Rotz 1995). Opener tines are also commonly used for planting and fertilizing operations on Australian farms. All tines were used at the normal working speed of 8 km.h^{-1} for all draught measurements, because this speed is commonly used in farm practice to avoid the negative performance effects of faster speeds in no-tillage systems (Barr et al. 2016).

Draught force measurement for all selected tines (**Appendix A3.7**) at a range of operating depths (50-125 mm) were compared in (relatively) soft soil of the non-wheeled Permanent Crop Beds (beds, or PCB) and in the (relatively) wheeled soil. In all cases, tests were carried out with generous assistance from the farmers (**Section 3.2**), using their equipment. In some cases, all tests could not be completed, two sites (Gatton and Waikerie) were not managed in CTF, and at one site (Hopetoun) CTF was incomplete (one machine not part of the system).

Soil roughness measurements were also carried out for all selected tines at a range of operating depths (50-125 mm) and were compared in (relatively) soft soil of the non-wheeled soil and in the (relatively) firmer wheeled soil. In all cases, the measurements were conducted using a profile meter which was previously described in **Section 3.3.6**. Soil roughness measurements were made at all sites except the Kingaroy (QLD) site, where the measurement of draught force was completed with only the chisel tine at one depth (150-200 mm).

3.4.4. Soil surface roughness

The method used to measure soil surface was described previously. The results of the method were computed through the standard deviation (SD). This was used to calculate the soil surface roughness as follow:

$$SSR = 100 * \log SD \quad \ldots\ldots\ldots\ldots \textbf{Equation 3.4}$$

Where: SSR = soil surface roughness (%); SD = standard deviation

3.4.5. Specifications of Experimental Tractors

The purpose of this section is to describe the tractors, which were used in this study. In all cases, the tractors were those normally used on the host farms, and it all cases were considerably larger than the tractors for which the tillage unit was originally designed (Category 2 hitch systems, ASABE 2015). Commercial farms with larger tractors use linkage systems or “quick hitches” conforming to Category 3 or 4 (**Appendix A3.8**), so a new headstock adapter, illustrated in Figure 3.6, was manufactured at the University of Southern Queensland (USQ) workshop, allowing use with both larger and smaller tractors. Details of all tractors used in this study are reported in **Appendix A3.9**.

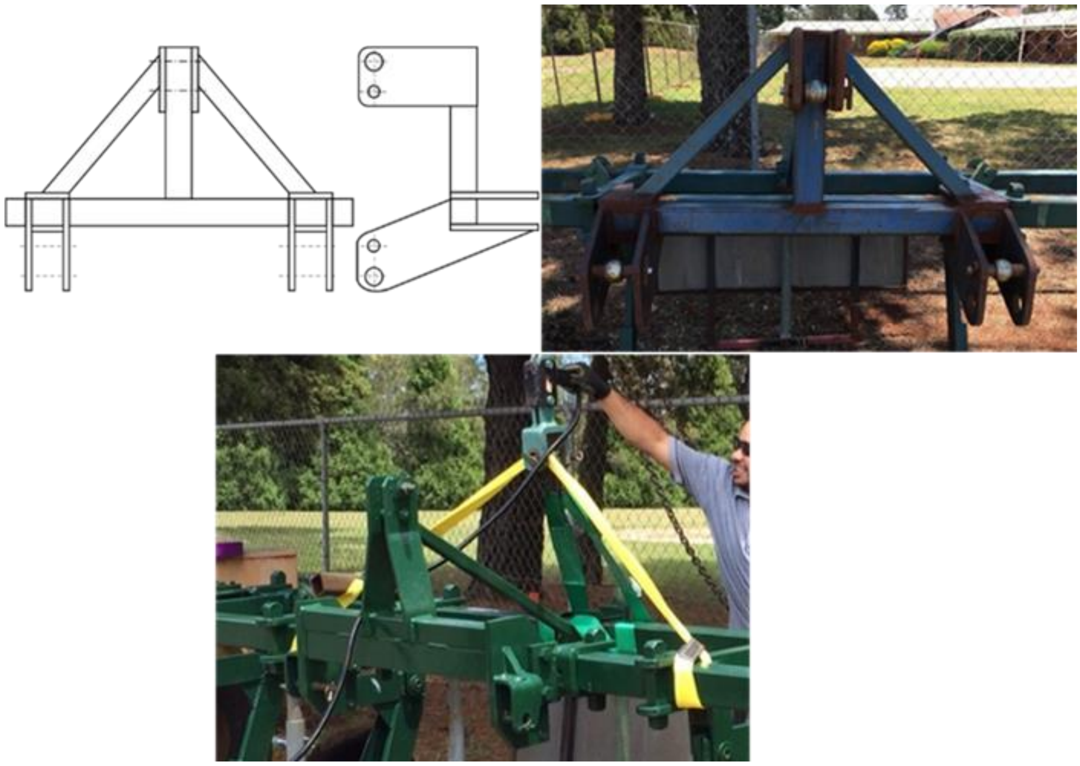


Figure 3.6: Hitches of tillage unit

3.4.6. Statistical analysis

The Statistical Package for the Social Sciences (SPSS-version 23) software was used to analyse the experimental data (Swan & Sandilands 1995), and determine the effects of the factors in **Section 3.4.3** on the draught force and soil surface roughness. This included analysis of variance (ANOVA) and Duncan’s multiple range test which were used to compare the means at a probability level of 5%. The results of analyses are presented in **Appendix A.4**.

3.5. Modelling of draught force (Methodology of Chapter 5)

The draught force requirements of selected tines at range of operation at different sites (which described in the previous section), were compared with the predicted results. Godwin and O’Dogherty (2007) model was applied to predict the draught force of tines in all studied sites. To accurately predict draught force, the model required parameters for soil condition and geometry of implements, in addition to operating depth and ground speed of each site. The implement parameters, including rake angle and width of the foot (tip), were calculated for all tines, and working depth and ground speed were also calculated. These parameters along with the soil parameters were used as inputs in the Godwin and O'Dogherty model. The values which are presented in **Table 3.4**, are considered in most draught force models.

Table 3.4: Tines parameters of soil-engaging implements

Tine parameters	Parameters symbol	Tines		
		Sweep	Chisel	Seeder opener
Width of the foot (tip) (m)	**w**	**0.45**	**0.05m**	**0.025m**
Rake angle (°)	**α**	**20-23°**	**22-24°**	**43-45°**
Ground speed ($m.s^{-1}$)	**v**	**2.2**	**2.2**	**2.2**

Among the soil parameters, are bulk unit weight and the mechanical soil properties. Bulk unit weight was calculated from wet bulk density multiplied by acceleration of gravity. Wet bulk density was measured using the procedure previously described in **Section 3.4.1**. The mechanical soil properties included soil-soil parameters (cohesion and internal friction angle) and soil-metal parameters (adhesion and external friction angle). These parameters were measured using direct shear box.

Direct shear box was used to determine the mechanical soil properties, such as cohesion, internal friction angle, adhesion and external friction angle. These parameters are mainly used to feed a number of models to predict the energy requirements of soil-engaging implements. New rings were manufactured to dimensions the same as those used for the direct shear test. These rings were used to take undisturbed soil samples at different depths. Sampling was done at 50 mm up to 150 mm depth except for the Kingaroy site which was 100 mm up to 200 mm. These were used to cover the entire depth range encountered in operating depths.

For each sample, excess soil was trimmed away from the sample ring. The samples were immediately wrapped and covered to reduce evaporation from the samples. These samples were kept in a box, and the box was refrigerated to keep the samples in the same condition as they were in the field where the experiments were conducted. Soil core samples were taken to direct shear equipment, model ShearTrac II at the

Civil Engineering Laboratory at the University of Southern Queensland (**Appendix A3.10**). The soil sample was placed in the shear box to fill two halves of the shear box. Each sample was subjected to four load increments of 25; 50; 100 and 200 kPa.

Shear stress at failure against normal stress during the direct shear box test was graphed. With this graph, internal friction angle and cohesion of soil were estimated for each sample's soil and depth. The same procedures and tests conducted for cohesion and angle of internal friction were repeated for the determination of adhesion and angle of soil–metal friction. However, a new sold core of the same material used in the manufacturing of tillage unit and tines was manufactured. This sold core was placed at the bottom half of shear box and the soil sample was placed at the top half of shear box. An excess soil outside the top half of shear box was trimmed off.

Soil parameters in **Table 3.5** are an example for range of those parameters, which are considered by McKyes & Desir (1984) and McKyes (1985). The values presented in **Table 3.6** are the soil parameters, considered in most draught force models, including the Godwin and O'Dogherty (2007)'s model.

Table3.5: Values of soil parameters for sand and clay soils (McKyes, 1985)

Soil type	*C (kPa)*	φ (°)	BD (Mg m^{-3})
Sand	0	18-50	1.75-2.11
Clay	0-28.2	0-37	0.84-1.89

In **Table 3.6**, soil parameters include soil-soil and soil-metal parameters determined for all sites except the Loxton and Waikerie sites which were based on historical data.

Table 3.6: Values of soil parameters for studied soils

Sites	Soil parameters	Parameters symbol	Working depth (m)		
			0.075	0.1	0.125
Felton (Black Vertisol)	Bulk unit weight (kN m^{-3})	γ	10.61	15.34	17.21
	Cohesion (kN m^{-2})	C	62.1	63.6	66.3
	Adhesion (kN m^{-2})	C_a	2	2.4	2.7
	Internal friction angle (°)	ϕ	20.8	21.3	21.8
	Soil-metal friction angle (°)	δ	21.4	22.1	22.3

Pittsworth (Gray Vertisol)	Bulk unit weight (kN m^{-3})	γ	12.03	16.3	18.03
	Cohesion (kN m^{-2})	C	61.3	65.2	65.3
	Adhesion (kN m^{-2})	C_a	1.7	2	2.3
	Internal friction angle (°)	ϕ	21.4	21.9	22.2
	Soil-metal friction angle (°)	δ	21.4	21.4	21.4
Gatton (Brown Chromosol)	Bulk unit weight (kN m^{-3})	γ	11.6	14	15
	Cohesion (kN m^{-2})	C	42.7	45.8	45.8
	Adhesion (kN m^{-2})	C_a	1.3	2	2
	Internal friction angle (°)	ϕ	21	22	22
	Soil-metal friction angle (°)	δ	20	21	21
Kingaroy (Gray Vertisol)	Bulk unit weight (kN m^{-3})	γ	-	13.92	14.85@ 0.2
	Cohesion (kN m^{-2})	C	-	-	65.8
	Adhesion (kN m^{-2})	C_a	-	-	2
	Internal friction angle (°)	ϕ	-	-	21.8
	Soil-metal friction angle (°)	δ	-	-	21.4
Hopetoun (Red Calcarosol)	Bulk unit weight (kN m^{-3})	γ	13	14	17
	Cohesion (kN m^{-2})	C	9.1	9.1	9.7
	Adhesion (kN m^{-2})	C_a	6.3	6.4	6.9
	Internal friction angle (°)	ϕ	37.8	38.1	38.9
	Soil-metal friction angle (°)	δ	32.2	32.7	33.7
Swan Hill (Red Sodosol)	Bulk unit weight (kN m^{-3})	γ	14.1	16.1	16.8
	Cohesion (kN m^{-2})	C	9.2	9.5	9.5
	Adhesion (kN m^{-2})	C_a	6.1	6.8	6.8
	Internal friction angle (°)	ϕ	38.9	38.9	38.9
	Soil-metal friction angle (°)	δ	33.7	33.7	33.7
Loxton (Calcic Calcarosol)	Bulk unit weight (kN m^{-3})	γ	17.1	17.2	18.1
	Cohesion (kN m^{-2})	C	14	14	14
	Adhesion (kN m^{-2})	C_a	1	2	3
	Internal friction angle (°)	ϕ	35	35	36
	Soil-metal friction angle (°)	δ	26	26	28

Waikerie (Calcarosol)	**Bulk unit weight (kN m^{-3})**	**γ**	**14.14**	**16**	**16.5**
	Cohesion (kN m^{-2})	**C**	**7.1**	**7.4**	**7.4**
	Adhesion (kN m^{-2})	**C_a**	**1**	**2**	**3**
	Internal friction angle (^{o})	**ϕ**	**40**	**41**	**41**
	Soil-metal friction angle (^{o})	**δ**	**28**	**29**	**29**

3.5.1. Godwin and O'Dogherty model component

The soils' physical and mechanical properties for all soil sites in the previous section were entered into draught force model (Godwin & O'Dogherty, 2007) to predict the draught forces for soil-engaging implements. In addition, operating condition parameters and geometry of the tines, including operating depth and ground speed, were also reported in previous section. The values of all of these parameters, which were entered into the draught force modelling, are presented in **Table 3.4** and **Table 3.6**.

3.5.2. Sensitivity of Godwin and O'Dogherty model

This section discusses the relationships between the output and input parameters of the draught force model. A number of sensitivity tests were conducted to find which factors may have a major influence on draught force requirements for different soil-engaging implements to quantify the degree of sensitivity of the model. Baseline scenarios were dictated by the model input parameters, which include three categories: soils' physical and mechanical properties, tine parameters and operational conditions. The scenarios were constructed by changing the values of a single input factor while keeping all other input parameters constant.

The first category included bulk unit weight, both soil-soil parameters (cohesion and internal friction angle) and soil-metal parameters (adhesion and external friction angle). The second category included the width tine and rake angle of tine. The third category included operating depth and operating speed. These categories were included for sensitivity testing. A quantitative, relative sensitivity, referred to as the sensitivity index, was calculated to quantify the impacts of input factors on certain output results(Walker et al. 2000).

$$SI = [(OP2 - OP1)/OPaverg]/[\,(IP2 - IP1\,)/IPaverg] \qquad \textbf{Equation 3.5}$$

Where: SI = the relative sensitivity index; IP1and IP2 = the minimum and maximum input values tested for a given parameter; IP averg. = the average of IP1and IP2; OP1and OP2 = the model output values corresponding to IP1and IP2, and OP averg. = the average of OP1and OP2. A higher absolute value of the sensitivity index indicates a greater impact of input data on the output, and a negative value shows that there is an inverse relationship between the input and the output (Walker et al. 2000).

The data entered into **Equation 3.5** to test the sensitivity of model were based on measured data, which were determined during lab and field measurements in this study, as well as the historical data found from Godwin and O'Dogherty (2007); McKyes and Desir (1984); McKyes (1985). The outcomes of the **Equation 3.5** are listed in **Table 3.7**.

Table 3.7 Input parameters tested

Parameters description	Input parameters			
	IP2	**IP1**	**IP avg.**	**SD**
Bulk unit weight (kN m^{-3}) (γ)*	18	10	13	2.1
Cohesion (kN m^{-2}) (C)*	100	7	49	31
Adhesion (kN m^{-2}) (C_a)*	7	1	4	2.2
Internal friction angle (°) (ϕ)*	40	22	31	8.3
Soil-metal friction angle (°) (δ)*	34	20	26	5.4
Width of the tine (m) (*w*)*	0.45	0.02	0.12	0.15
Rake angle of the tine (°) (α)*	90	20	53	24.4
Ground speed (m s^{-1}) (*v*)	3	0.5	1.75	0.85
Operating depth (m) (d)*	0.175	0.05	0.113	0.04
Surcharge (kN m^{-2}) (q)	0.055	0.040	0.047	0.005

* Including the data of lab and field measurements in this study

3.5.3. Validation of Godwin and O'Dogherty model

Validation is usually defined as "substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model" (Schlesinger 1979). The aim of the Godwin and

O'Dogherty model validation is to investigate the reliability and accuracy of the model under Australian soil conditions.

The validation technique used to investigate the validity of the model was based on measured data (the results of draught force obtained for all tines in all study sites reported in **Chapter 4** compared with predicted data which were acquired with the Godwin and O'Dogherty model). Once again, the parameters used to feed the model, corresponded with the parameters used in the draught force measurement for all tines in all the studied sites.

3.5.4. Statistical analysis

Statistical analyses (**Appendices A.5.1** and **A5.2**) were undertaken using SPSS. Linear regression analyses were used to investigate the relationship between measured and predicted draught force based on the Godwin and O'Dogherty (2007) tillage force prediction model for all study sites. This analysis was undertaken using a 95% confidence interval for the linear model fitted to the data. The results are presented in **Appendix A.5.2**.

3.6. Motion resistance measurements and modelling (Methodology of Chapter 6)

3.6.1 Motion resistance in field (MR) (kN)

As previously discussed, motion resistance is related to soil strength, so the soil's physical properties were measured using the procedure previously described in **Section 3.3.3** and **Section 3.3.5**, respectively are equally relevant here the effect of wheel tracks on the motion resistance of farm machinery was determined using the farm tractor because this was used in almost all agricultural operations during farm activities. Motion resistance was measured on on PTL, PCB, and road at a range of ground speeds that were also in accordance with Australian growers' practices.

3.6.2. Experimental design

Motion resistance experiments were arranged in a block design, with three replications. Two factors were used: permanent traffic lanes (PTL) to represent motion resistance in CTF and the non-wheeled soil of permanent crop beds (PCB) to represent motion resistance in non-CTF systems. Motion resistance on the best available hard surface (e.g., dirt track or road) was also measured to assess the internal (powertrain friction and energy loss in tyre deflection) component of tractor motion resistance.

Measurements covered the range of common ground speeds (8, 12 and16 km.h^{-1}), chosen to represent those commonly used for conservation tillage and seeding, harvesting and spraying. However, in one non-CTF site field area limitations and tractor capacity restricted ground speeds to 2 and 3.5 km.h^{-1}. Motion resistance was assessed in all cases by towing via a pullmeter and long strap to minimise the effect of the vertical and sideways horizontal components to the measurement. The arrangement of towing and toad tractors for the motion resistance experiments is illustrated in **Figure 3.7**. All measurements were replicated three times in opposite directions to cancel out any topographical effects.

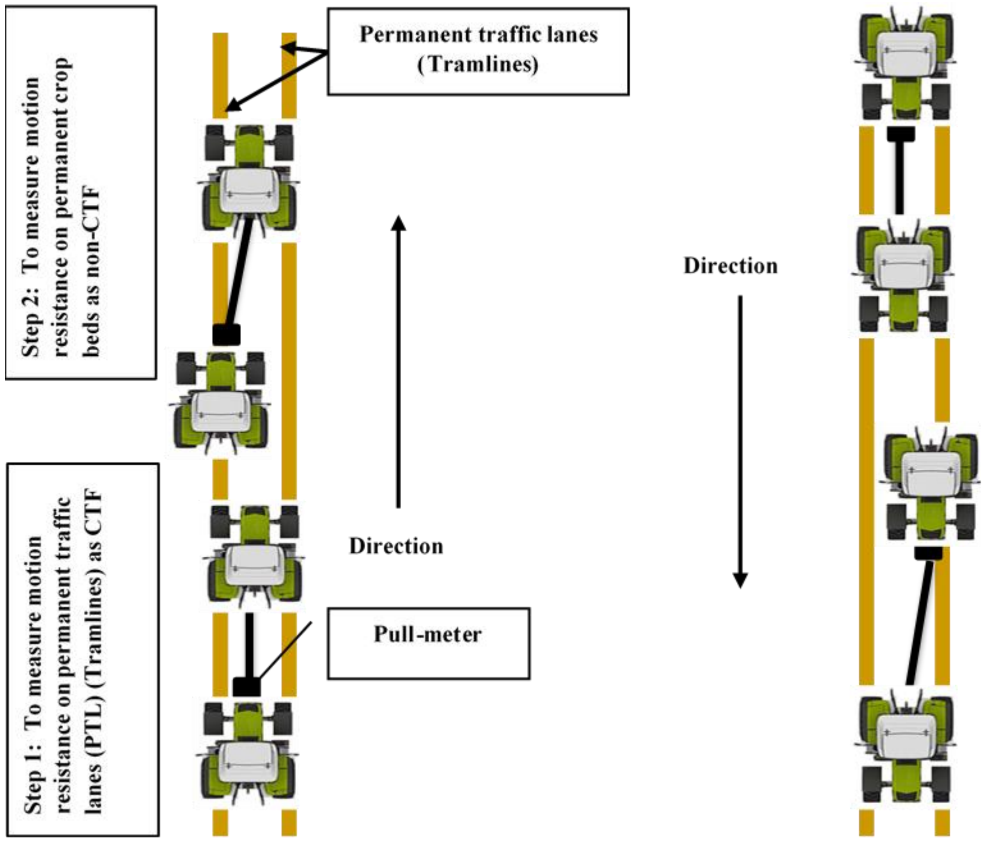


Figure 3.7: : Layout of the motion resistance experiment

3.6.3. Motion resistance coefficient (CMR)

The motion resistance is often expressed in terms of coefficient of motion resistance, which is called as the motion resistance per unit wheel load, and was calculated as follows:

$$\mathbf{CMR} = \frac{\boldsymbol{MR}}{\boldsymbol{W}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{Equation\ 3.6}$$

Where: CMR is coefficient of motion resistance; MR is motion resistance (kN); W is wheel load (kN).

3.6.4. Reduction in motion resistance (%)

Reduction of motion resistance was calculated. This calculation was based on motion resistance which comes from deformation of the soil under the tyre and belt track, and is attributable to friction within the drivetrain and deformation of the tyre itself. Therefore, calculation of the reduction in motion resistance was done as follows:

a) Internal (frictional) motion resistance (kN) = MR on road
b) External (soil) motion resistance on Permanent Traffic Lanes (kN) = MR on PTL- a MR on road
c) External (soil) motion resistance on Permanent Crop Beds (kN) = MR on PCB – MR on road
d) Change in motion resistance as a result of CTF (kN)= c-b
e) Reduction in gross motion resistance as result of CTF (%) = d/MR on PCB *100
f) Reduction in external motion resistance as a result of CTF (%) = d/c * 100

This procedure was also used to calculate the reduction in gross and external motion resistance as a result of wheel traffic in non-CTF sites.

3.6.5. Modelling of motion resistance

As discussed in the literature review, a number of models have been used to predict motion resistance. Accordingly, two models were adapted to predict motion resistance in this study. These models were Gee-Clough’s model (1980) and Brixius’s (ASABE) model (1987). These models were previously reported in **Chapter 2, Section 2.7**. The models require the following input parameters, cone index and tyre parameters, (**Figure 3.8**) and are based on the following equations:

$$\mathbf{MR} = \mathbf{W}\left(\mathbf{0.049} + \frac{\mathbf{0.287}}{\mathbf{N}}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{Equation\ 3.7\ (Gee - Glough\ 1980)}$$

$$\mathbf{N} = \left(\frac{\mathbf{CI\,.\,b\,.\,d}}{\mathbf{W}}\right) \times \sqrt{\frac{\boldsymbol{\delta}}{\mathbf{h}}}\ \frac{\mathbf{1}}{\mathbf{1 + b/2d}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{Equation\ 3.8\ (Gee - Glough\ 1980)}$$

$$\mathbf{MR} = \mathbf{W}\left(\frac{\mathbf{1}}{\mathbf{N}} + \mathbf{0.04} + \frac{\mathbf{0.5S}}{\sqrt{\mathbf{N}}}\right) \ldots \ldots \textbf{Equation 3.9 (Brixius 1987)}$$

$$\mathbf{N} = \left(\frac{\mathbf{CI}\,.\,\mathbf{b}\,.\,\mathbf{d}}{\mathbf{W}}\right) \times \left(\frac{\mathbf{1} + \mathbf{5}\boldsymbol{\delta}/\mathbf{h}}{\mathbf{1} + \mathbf{3b}/\mathbf{d}}\right) \ldots \ldots \textbf{Equation 3.10 (Brixius 1987)}$$

$$\mathbf{C_n} = \left(\frac{\mathbf{CI}\,.\,\mathbf{b}\,.\,\mathbf{d}}{\mathbf{W}}\right) \ldots \ldots \textbf{Equation 3.11 (Wismer \& Luth 1974)}$$

Where the symbols are, MR = Motion resistance, kN; W = Wheel load, kN; N = Mobility number; Cn = Wheel numeric; CI = Cone Index for the soil, kPa; b = Tyre section width, m; d = Overall unloaded tyre diameter, m; δ = Tyre deflection, m; h = Tyre section height, m; s = Slip, decimal.

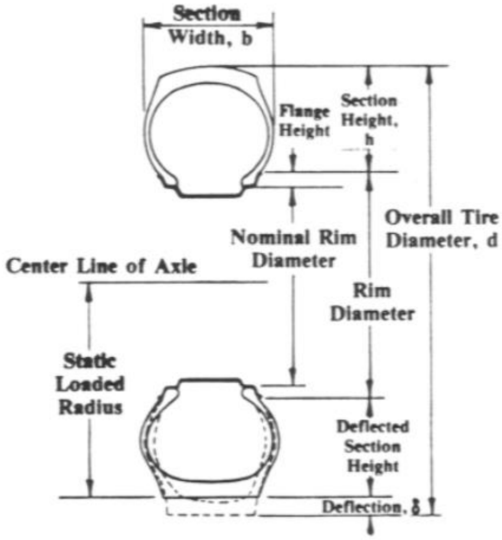


Figure 3.8: Tyre parameters (Brixius 1987)

Tractor weights are provided in **Appendix A3.8**, and were based on the database of OESD (2018) and farmer's measurement, however other parameters (soil-wheel parameters) were measured during the field experiments at each site. CI was measured using the procedure previously described in **Section 3.3.3**. Slip was neglected because the tractor was towed (unpowered wheel). Tyre parameters such as tyre section width and overall tyre diameter were measured. Additionally, the tyre section height and tyre deflection were measured based on the following equations:

$$\mathbf{h} = \frac{\mathbf{d} - \mathbf{Rd}}{\mathbf{2}} \ldots \ldots \textbf{Equation 3.12 (Brixius 1987)}$$

$$\boldsymbol{\delta} = \frac{\mathbf{d}}{\mathbf{2}} - \mathbf{SLR} \ldots \ldots \textbf{Equation 3.13 (Brixius 1987)}$$

Where:

Rd = Rim diameter

SLR = Static Loaded Radius (standard information in tyre data books)

Tyre parameters were measured for both front tyres and rear tyres. The results of wheel parameters are presented in **Table 3.8**. The prediction of motion resistance was calculated for both front tyres and rear tyres because the models predicted the motion resistance for a single tyre only. Then, the prediction of motion resistance for a whole tractor was calculated at each site. The results were predicted and compared with the measured results.

Table 3.8: Wheel parameters for all studied sites

Wheel parameters	Felton		Pittsworth		Gatton		Hopetoun		Swan Hill		Waikerie	
	Front	Rear	Front	Rear	Front	Rear	Front	Rear	Front	Rear	Front	Rear
W	52	54	50	57	23	29	38	47	84	68	26	39
b	0.45	0.49	0.45	0.48	0.27	29	0.47	0.64	0.55	0.55	0.54	0.65
d	1.59	2.03	1.59	2.03	1.43	1.74	1.43	1.81	1.94	1.94	0.82	1.92
δ	0.0286	0.0292	0.03	0.04	0.021	0.022	0.03	0.04	0.04	0.03	0.02	0.08
h	0.35	0.37	0.35	0.36	0.26	0.28	0.31	0.42	0.47	0.47	0.35	0.42
s	-	-	-	-	-	-	-	-	-	-	-	-

3.6.3 Statistical analysis

Statistical analyses were conducted using SPSS version 24 to determine the impact of CTF (trafficked and untrafficked area) on soil physical properties (PR and MC) and motion resistance. This included analysis of variance (ANOVA) and Duncan's multiple range test which was used to compare the means at a probability level of 5%. Linear regression analyses were used to describe the relationship between motion resistance and PR at each site. This relationship was undertaken for only PTL and PCB in CTF sites, and wheeled and non-wheeled soil in non-CTF sites. The results of all analyses are presented in **Appendix A.6**.

Linear regression analyses were used to describe the relationship between PR and motion resistance at each site **(Appendix A.6)**, before the outlier values were identified and removed. In all cases, the PR value was taken as the average of 20 cone index data points within the 0-150 mm depth range (Botta et al. 2012), while motion resistance values were the mean of 30 data points with missing values generated during regression analyses. Linear regression analyses were also used to describe the relationships between predicted and measured motion resistance at each site **(Appendix A.6)**.

3.7. Timeliness (Methodology of Chapter 7)

The results from the experimental work on motion resistance and its predictions (mobility number) were brought together at this stage to investigate the effect of CTF on timeliness. The mobility number was calculated using the procedure previously described in **Section 3.6.2**.

3.7.1. Statistical analysis

The SPSS-version 24 software was used to analyse the mobility number. This included analysis of variance (ANOVA). Means of mobility number was compared for significance using Duncan at 5% level of probability. The relationship between motion resistance coefficient and mobility number was investigated by regression analyses. The results of these analyses are presented in **Appendix A.7**.

CHAPTER 4

DRAUGHT FORCE AND SOIL ROUGHNESS MEASUREMENT IN THE FIELD

4. DRAUGHT FORCE AND SOIL ROUGHNESS MEASUREMENT IN THE FIELD

4.1. Introduction

The literature review of **Chapter 2** explored the effects of soil compaction caused by traffic on tillage energy requirements, particularly draught force, and the role of controlled traffic farming systems in managing soil compaction and reducing tillage energy requirements. In this chapter, a brief literature review of the effects of CTF on draught force and soil roughness is considered. The effects of wheel traffic on draught force of range of tines at different operating depths for different soils are presented together with their impact on soil roughness.

4.2. Energy requirements in a field

Tillage systems can be grouped into three main categories: (i) conventional tillage systems as defined by ASABE (2005) which are the sequence of operations traditionally or most commonly used in a given geographic area to produce a given crop, (ii) conservation tillage systems which are any tillage or seeding system that maintains 15–30% residue cover on the soil surface after planting (ASABE 2005) and (iii) no-tillage systems which are also defined by ASABE (2005) as systems where crops are grown in narrow slots or tilled strips in previously undisturbed soil. These systems can be used under either non-CTF (conventional) or CTF systems. Energy consumption is an important consideration in selecting grain-cropping systems, and one of the main energy requirements is soil-engaging equipment accounting for up to 45% of energy use according to Sánchez-Girón et al. (2007).

Numerous studies of non-CTF tillage systems in several countries have shown that conventional tillage systems are the most energy consuming methods depending on the number of activities involved in this system. Košutić et al. (2005) found that energy saving in no tillage systems was almost 85%, while in reduced tillage systems the energy saving was almost 38% in comparison with conventional tillage systems. Mileusnic´ et al. (2010) also reported that energy consumption was up to 2-4 times higher in conventional systems than in no-tillage systems. Moreover, farmers in many countries are being urged by governments to adopt conservation or no-tillage systems to minimise soil erosion and waterway pollution, and conserve organic matter and improve soil health (Komatsuzaki & Ohta 2007). Consequently, conservation and no-tillage farming have been widely adopted (Sarauskis et al. 2014). In Australia, the majority of grain growers have adopted this techniques (Llewellyn & D'Emden 2010).

The weed control function of tillage is replaced by herbicides or agronomic methods in no-till, but tillage also provides a means of dealing with surface compaction caused by field traffic, so the impact of traffic associated with non-CTF systems must be considered when determining its potential benefits. In non-CTF systems, different equipment operating and track widths translate into disorganised or conventional traffic patterns, which can cover about 50% of the crop area in no till systems, and >80% of area in conventionally tilled systems each time a crop is produced (Kroulík et al. 2009). This might be part of the reason that research in many countries has shown that reduced or no-tillage systems do not always result in significant changes in soil physical, mechanical and biological properties, or demonstrate crop yields that are better than those of conventional systems (Baan et al. 2009; Fan et al. 2012; Godwin et al. 2017). Compaction can reduce yield for most crops (**Section 2.3**), and increase on-farm energy use and costs. There are also significant, though less quantified, costs associated with the heavy tillage compaction repair treatments occasionally used in no-till. Draught requirements for tillage operations may also be drastically increased by soil compaction (Iler & Stevenson 1991) (**Section 2.3.3**) which often has the indirect effect of increasing surface cloddiness after tillage, requiring more intensive tillage to produce a seedbed (Chancellor 1976) and increasing the time required for tillage operations.

CTF systems manage compaction by confining all load-bearing wheels to the least possible area of permanent traffic lanes (Taylor 1983). In well-designed grain-cropping systems, permanent traffic lanes typically occupy ≤15% of the total cultivated area (Tullberg 2010). This can improve soil physical properties in crop beds, and yields have increased in all tillage systems under CTF according to Smith et al. (2014). It also plays a major role in reducing draught force requirements of soil-engaging implements.

In a CTF system, the crop zone and traffic lanes are distinctly and permanently separated. In practice this means that the working widths of all implements must fit a modular system, the heavy load-bearing wheels of all equipment must conform to a common wheel track gauge width, and all operations carried out with precise guidance so all wheeling is confined to specific traffic lanes (Isbister et al. 2013). Adoption of such systems should: (1) minimize traffic-induced soil compaction and therefore tillage draught, (2) optimise crop growth conditions within non-compacted permanent beds), and (3) improve traction on compacted permanent traffic lanes (Burt et al. 1986; Chen & Yang 2015; McPhee et al. 2015). Energy requirements for tillage of soil subject to random (uncontrolled) machinery traffic is also significantly greater compared to CTF (Carter 1985; Tullberg 2000). These benefits suggest a growing need for the adoption of controlled traffic systems, but on-farm adoption has been slowed by factors such as incompatible equipment operating widths and wheel track gauge widths. Associated costs of equipment conversion, concern about warranties and the resale value impacts modifications have also inhibited widespread adoption of CTF in some cropping systems (e.g. Bennett et al. 2015; Antille et al. 2016).

In Australia, as highlighted in **Chapter 2,** previous research has focused primarily on the agronomic and environmental, rather than the energy effects of CTF systems. And, while the literature includes some reports on the draught force impacts of CTF, they cover an inadequate range of soils or systems. CTF farmers have provided many anecdotal reports of reduced power requirements and fuel consumption, so the energy effects of CTF are clearly important. But there are still few studies of CTF energy effects, and published evidence is not unanimous. Tullberg (2000), working on a clay soil in Australia, observed that the traffic effect of wheels on the draught of tillage implements increased total draught by 30% or more compared with the same implement operated in non-trafficked soil.

On the other hand, Burt et al. (1994) in the USA and Arslan et al. (2015) in UK, found that traffic systems had no significant effect on energy requirements. In Burt et al.'s case, use of "draught control" implements probably ensured little difference in draught between treatments because the tillage depth in non-trafficked soil was greater than that in trafficked soil. In Arslan et al.'s case, tine tillage draught differences were not significant and they found no traffic system differences in no-till seeder draught. This might be because whole planter draught measured included motion resistance of depth and press wheels, which would be expected to increase in softer soils. More evidence is clearly required.

This chapter describes the field experiments used to assess the effect of CTF on draught force requirements in different soils and systems, which were intended to:

- Determine the effects of wheel track versus non-wheel track operation on draught force requirements for different tines at normal operating depths in different soils/sites
- Determine the effects of wheel track versus non-wheel track operation on soil surface roughness for different tines at normal operating depths in different soils/sites.

4.3. Materials and methods

The experimental work was conducted at different sites in three Australian states Felton, Pittsworth, Gatton and Kingaroy (Northern region sites in Queensland) in which the soil is heavy clay. Sites at Hopetoun and Swan Hill (Victoria), and Loxton and Waikerie (South Australia), are in the Southern region where the soil is medium and light-textured, respectively. CTF is widely used on larger crop areas in the Northern region, but less common in the Southern region (more details in **Chapter 3**).

4.4. Results

The results of the field experiments are reported in the following sections. The effect of wheel tracks on draught force is presented for Northern region (Queensland) sites, and Southern region (Victoria and south Australian) sites in **Section 4.4.1**. The effect of wheel tracks on soil surface roughness for all sites is presented in **Section 4.4.2**. An overall discussion for all sites is presented in **Section 4.5** prior to the conclusions on the field experimental work in **Section 4.6**.

4.4.1. Draught force

The method used for measuring draught force in this study was discussed in **Chapter 3**. Draught force was measured in both wheel track and non-wheel track for examples of commonly used tines (sweep, chisel and narrow point seeder opener tines), all which are widely used in Australian farming. Measurements were conducted for each tine at depths of 75, 100, and 125 mm, selected to represent depths commonly used for planting and fertilizer application in conservation tillage, and deep placement of fertilizer, respectively, as reported in **Chapter 3**. Soil moisture and other soil physical properties were also noted on these sites, and all (other than Gatton and Wailkerie) had been under controlled traffic and no-tillage for at least five years.

The draught force results are presented in two groups: Northern region (Queensland) sites, and Southern region (Victoria and South Australian) sites, because they have very different soil characteristics. Northern region sites are heavy clay soil with annual rainfall of 600 – 700 mm, but Southern region sites are medium and light-textured soils with rainfall of 300 – 400 mm.

4.4.1.1 Northern region sites

The draught force of tines operating in wheeled and non-wheeled soil in Northern region sites are illustrated in **Figure 4.1**, with the corresponding regression equations and statistical detail for each in **Table 4.2.** Statistical analysis of the results appears in **Appendix A4.1**. The results illustrated in **Figure 4.1** are summarised in the relative tables of **Appendix A4.2**. It is important to note that, overall, there is a significant effect for each of the traffic type, tine and depth on draught force (p-values <0.001) (**Appendix A4.1**).

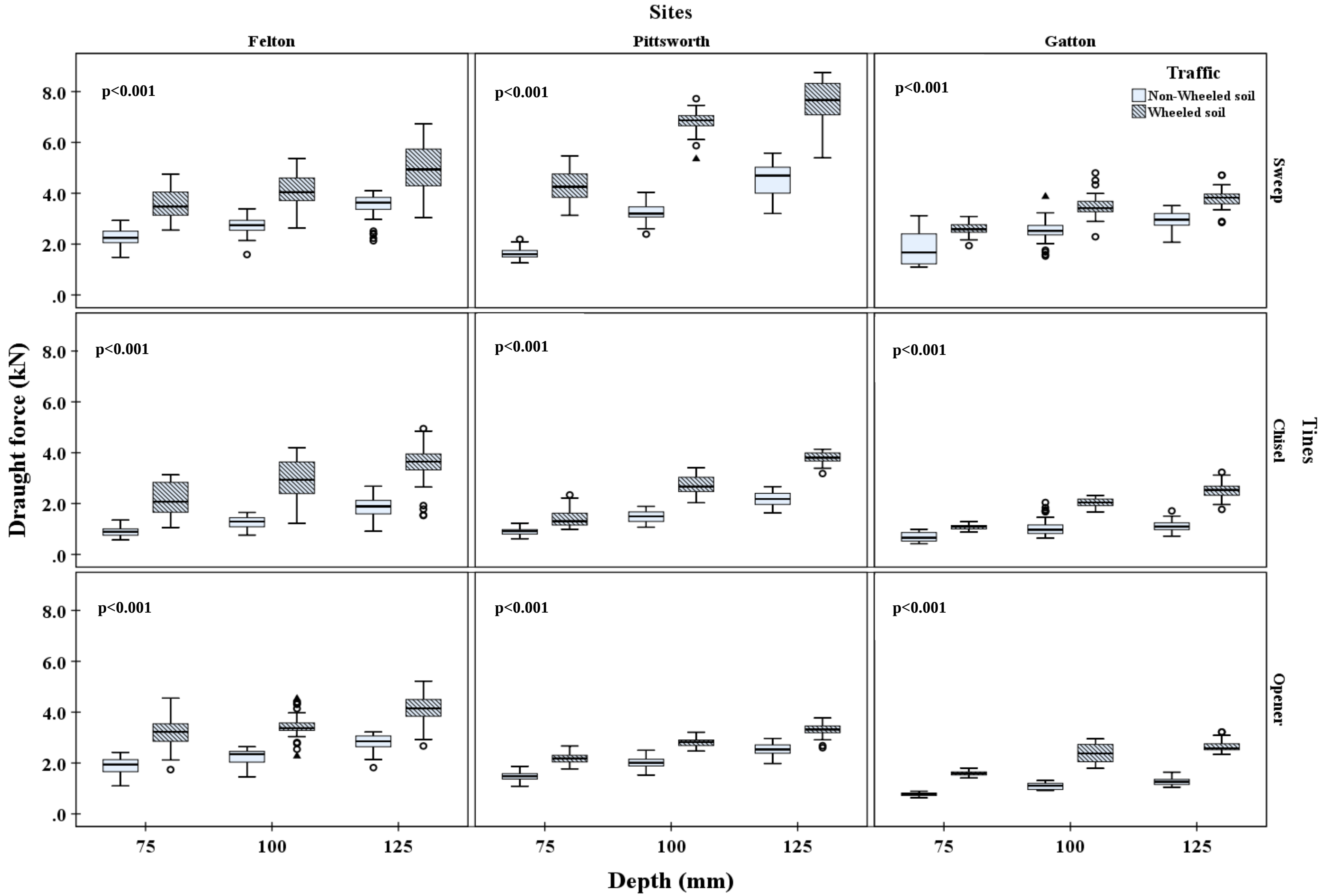


Figure 4.1: The effect of tractor wheel traffic and operating depth on draught force of different tines. Box plots show: Min, Q1, Med, Q3 and Max (n=40). P < 0.001. The symbols (○) and (▲) denote mild and extreme outliers, respectively. Figures show: Sweep (top), Chisel (centre) and Opener (bottom) for Northern region sites, Felton (left), Pittsworth (centre) and Gatton (right), respectively

Generally, with regards to traffic types, the results of draught force in Northern region sites showed a similar pattern for all tines, with wheeled soil requiring the highest draught force (typically 1.88-6.25 kN), and non-wheeled soil the lowest (typically 0.96-3.14 kN). This was due to wheel traffic which increased the strength of both soil mass and aggregates within that mass, ensuring that more draught and energy was required to disturb it (Chamen et al. 2015). The difference between draught force in wheeled and non-wheeled soil found in this study was similar, but rather greater than those reported in earlier work (e.g. Tullberg 2000).

In this study, the variation of draught force between different tines reflect the effect of tine geometry such as shape, size, and rake angle of tines, which also reflects the diversity of their purpose. The sweep and chisel tines had almost the same rake angle but different tine widths, so the wide sweep tine (normally used for weed control and seedbed preparation) produced the greatest draught forces 6.25 kN, while the lowest draught force of 1.52 kN was found for the chisel tine commonly used in tillage operations. This is consistent with the existing soil cutting theory that a tool with a wider cutting width requires a higher draught force (McKyes 1985).

Manuwa (2009) found that draught force is related to tine width, and that winged tines have a significant effect on energy requirement. He concluded that increasing the wing width from 50 mm to 200 mm increased the draught force by approximately 143%. This observation is also in close agreement with those made by Reeder et al. (1993) who reported that 250 mm wings increased draught by about 70% and 350 mm wings more than doubled the draught of a 50 mm point in a silt loam soil. This is mainly because the volume of soil disturbed by narrow tines is drastically less than that displaced by wide tines.

Interestingly, opener tines normally used for planting and fertilising operations in no-tillage systems, had a smaller tine width but required rather greater draught forces than the chisel tines. Opener tines had the highest rake angle at 45° so rake angle appeared to have a greater effect on draught force than tine width in this case (**Chapter 3**). Both horizontal and vertical forces increased with increased rake angle, as consistently shown in the literature (Godwin & O'Dogherty 2007; Manuwa 2009). The cause might be the vertical force, which can act on the tool in a manner that assists or prevents penetration into the soil (Godwin 2007). Soil bin measurements by Godwin and O'Dogherty (2007) report that draught force is slowly increased by increasing the rake angle between 20° to 67° which is in close agreement with the results for opener and chisel tine results at Felton.

It is also important to note that the draught force was significantly affected by the operating depth for all tines in both wheeled-track and non-wheeled-track soil at all sites. Operation at 75 mm depth in non-wheeled soil had the lowest mean value of draught force for all tines, while 125 mm operating depth in wheeled soil had the highest mean value of draught force for all tines. This is unsurprising as greater depth means a greater volume of soil disturbed, increased frictional resistance, and soil generally becomes stiffer and denser with depth due to overburden pressure (Manuwa 2009; Godwin, 2007).

The differences in draught between tines in wheeled and non-wheeled soil for Northern region sites are set out in **Table 4.1**, illustrating the draught effects of a single wheeling on tine draught. The general case for CTF sites was also observed for tines at the Felton and Pittsworth sites. These results demonstrate that conservation tillage produced the greatest saving value of 99% while the lowest draught saving was found to be 55% for no-tillage when the tines follow a tractor wheel. The draught saving at the Pittsworth site, for sweep tines in particular, was extremely high in comparison with the Felton site. The reason being interactions between tines. At the Pittsworth site, a CTF tractor (3 m) was used to conduct the trial, thus the distance between the edges of sweep tines follow the tractor wheel, and outside the tractor wheel was approximately 450 mm, while in Felton site, the distance was approximately 150 mm as result of using a standard tractor (1.8 m) to conduct the trial. As can be seen in the **Table 4.1**, by avoiding till, the wheel track can save about 99%, 74% and 55% of energy in seedbed preparation, conservation tillage and fertilising and planting operations, respectively. Overall, the mean effect was 64% draught increase in wheeled soil. The effect was clearly greatest for sweeps, smaller for chisels and smaller still for openers. The effect was greatest at the shallowest depth, and reduced with depth in most cases.

Table 4.1: Effect wheel traffic and operating depth on tine draught for Northern region sites

		Draught increase				
Site	**Tines**	**Depth (mm)**	**75**	**100**	**125**	**Mean**
Felton	Sweep	**Differences (ratio)**	1.61	1.51	1.44	**1.51**
		SD	± 0.07	± 0.07	± 0.11	**± 0.11**
		Percentage (%)	60.94	51.08	44.36	**50.71**
		SD	± 6.84	± 7.35	± 11.18	**± 11.07**
	Chisel	**Differences (ratio)**	1.78	1.71	1.57	**1.66**
		SD	± 0.25	± 0.21	± 0.11	**± 0.22**
		Percentage (%)	78	71	57	**66**
		SD	± 24.75	± 20.59	± 10.80	**± 21.67**
	Opener	**Differences (ratio)**	1.49	1.39	1.29	**1.38**
		SD	± 0.04	± 0.06	± 0.03	**± 0.9**
		Percentage (%)	49	39	30	**37.81**
		SD	± 3.55	± 5.64	± 3.02	**± 9.15**
		n	40	40	40	**120**
Pittsworth	Sweep	**Differences (ratio)**	2.63	2.11	1.68	**1.99**
		SD	± 0.06	± 0.09	± 0.21	**± 0.40**
		Percentage (%)	163	111	68	**99**
		SD	± 6.16	± 8.71	± 20.82	**± 40**
	Chisel	**Differences (ratio)**	1.58	1.81	1.76	**1.74**
		SD	± 0.15	± 0.04	± 0.10	**± 0.16**
		Percentage (%)	58	81	76	**74**
		SD	± 15.27	± 4.46	± 10.04	**± 15.47**
	Opener	**Differences (ratio)**	1.71	1.53	1.49	**1.55**
		SD	± 0.11	± 0.33	± 0.06	**± 0.23**
		Percentage (%)	71	53	49	**55**
		SD	± 11.06	± 33.71	± 6.39	**± 23.10**
		n	40	40	40	**120**
Gatton	Sweep	**Differences (ratio)**	1.43	1.40	1.28	**1.35**
		SD	± 0.41	± 0.12	± 0.05	**± 0.27**
		Percentage (%)	43	40	28	**35**
		SD	± 41	± 12	± 5	**± 27**
	Chisel	**Differences (ratio)**	1.56	1.90	2.24	**1.95**
		SD	± 0.33	± 0.41	± 0.35	**± 0.45**
		Percentage (%)	56	90	124	**95**
		SD	± 33.38	± 40.97	± 35.16	**± 44.92**
	Opener	**Differences (ratio)**	2.06	2.16	2.07	**2.09**
		SD	± 0.05	± 0.13	± 0.08	**± 0.099**
		Percentage (%)	106	116	107	**109**
		SD	± 5.41	± 12.55	± 8.14	**± 9.95**
		n	40	40	40	**120**
Kingaroy*	Chisel	**Differences (ratio)**				**1.10**
		SD				**± 0.05**
		Percentage (%)				**10**
		SD				**± 5.29**
		n				**40**

***Operating depth at Kingaroy site was 150-200 mm; SD = Standard Deviation; n = Number of observations**

For all tines, the draught force increased with an increase in operating depth. Different models have been applied to describe the relationship between draught and operating depth, such as polynomials (e.g. Grisso et al. 1996; Desbiolles et al. 1997) and exponential (e.g. Kiss & Bellow 1981; Godwin 2007; Manuwa 2009). In most cases, however, this relationship has a linear component when the operating depth is less than 70 mm (Collins & Fowler 1996).Work undertaken by Godwin (2007), Manuwa (2009) and Mak and Chen (2014) showed that an exponential response relationship better accounted for observed variability and had an acceptable fit to the measured data for 50-200 mm depth interval. This is because the draught force of tines increases as with depth due to the increased soil resistance.

In **Table 4.2**, for each of the tines, the regression analyses showed that the relationship between draught and depth was significant both for non-wheeled and wheeled soil ($P < 0.001$), respectively when a non-linear model was fitted to the data. For the wheeled soil, the estimates of parameters for all tines show significance ($P < 0.001$) and the R^2 were lower than 0.49. For non-wheeled soil the estimates of parameters for all tines show significance ($P < 0.001$) and the R^2 were higher than 0.53. In addition, the standard error of estimate (SE) was the lowest compared with polynomials and linear models (**Appendix A4.2**). The exponential functions are, therefore, justified as all responses produced acceptable fits and all response were significant with all tines. This appears to be a fair justification based on the work of Godwin (2007) and Manuwa (2009).

Table 4.2: Non-linear regression analyses – relationships between operating depth and draught force for each of the tines in non-wheeled soil and wheeled soil for Northern region sites (Figure 4.1)

Site	Traffic	Non-wheeled					Wheeled				
	Tine	**Response**	**R^2**	**P-value**	**M(kN)**	**SE**	**Response**	**R^2**	**P-value**	**M (kN)**	**SE**
Felton	**Sweep**	$y = 1.14e^{0.009x}$	0.58	p<0.001	**2.82**	0.15	$y = 2.16e^{0.007x}$	0.37	p<0.001	**4.25**	0.177
	Chisel	$y = 0.28e^{0.015x}$	0.67	p<0.001	**1.34**	0.218	$y = 0.64e^{0.012x}$	0.49	p<0.001	**2.23**	0.248
	Opener	$y = 0.654e^{0.011x}$	0.53	p<0.001	**2.01**	0.155	$y = 1.21e^{0.008x}$	0.42	p<0.001	**2.77**	0.143
	Tine	**Response**	**R^2**	**P-value**	**M(kN)**	**SE**	**Response**	**R^2**	**P-value**	**M(kN)**	**SE**
Pittsworth	**Sweep**	$y = 0.375e^{0.02x}$	0.88	p<0.001	**3.14**	0.153	$y = 1.923e^{0.02x}$	0.74	p<0.001	**6.25**	0.139
	Chisel	$y = 0.239e^{0.018x}$	0.86	p<0.001	**1.52**	0.146	$y = 0.317e^{0.02x}$	0.84	p<0.001	**2.65**	0.181
	Opener	$y = 1.021e^{0.008x}$	0.83	p<0.001	**2.32**	0.102	$y = 1.962e^{0.006x}$	0.80	p<0.001	**3.60**	0.083
	Tine	**Response**	**R^2**	**P-value**	**M(kN)**	**SE**	**Response**	**R^2**	**P-value**	**M(kN)**	**SE**
Gatton	**Sweep**	$y = 0.788e^{0.011x}$	0.46	p<0.001	**2.43**	0.242	$y = 2.215e^{0.189x}$	0.64	p<0.001	**3.29**	0.117
	Chisel	$y = 0.329e^{0.010x}$	0.37	p<0.001	**0.96**	0.274	$y = 0.759e^{0.421x}$	0.85	p<0.001	**1.88**	0.144
	Opener	$y = 0.375e^{0.010x}$	0.78	p<0.001	**1.05**	0.110	$y = 1.29e^{0.254x}$	0.74	p<0.001	**2.20**	0.124

In non-CTF sites such as the Gatton site, draught force was also measured in wheeled and non-wheel soil for different tines. Measurement was also taken for all tines at different depths. The data analysis for draught force showed that there were significant differences in draught force with respect to traffic system, tines, operating depth and the interactions (p-values <0.001). In general, the results of draught force show a similar pattern to that presented for the Felton and Pittsworth sites. However, the results of draught force for all tines in non-wheeled soil were lower than draught forces at the Felton and Pittsworth sites. This was because the Gatton site was used as a research station for University of Queensland under non-controlled traffic and conventional tillage. The site had been deep cultivated and irrigated before the experiment was conducted, and this was reflected in draught saving which was greater than for the CTF sites as wheel traffic had a greater effect on cultivated soil compared with no-tillage systems soil in CTF sites.

The reverse effect was evident at the other non-CTF site, Kingaroy, where draught force was measured for wheel track and non-wheel track for chisel tines only, and at only one greater depth (150-200mm). The effect of wheel traffic at this site was non-significant and lower compared with the other Queensland sites (p=0.91) (**Appendix A4.2**). The value of draught saving at the Kingaroy site was also the lowest (**Table 4.2**) compared with the other Queensland sites, in spite of the operating depth at Kingaroy site being the greatest. The reasons are that the Kingaroy site was under a non-CTF system where the traffic of farm equipment was random. This could have affected the capability to compact the soil by one pass. This is in close agreement with Jorajuria and Draghi (1997) who demonstrated that the first pass of a tractor causes a greater increase in soil bulk density compared with five subsequent passings.

Finally, in Queensland sites with high clay-content soils, according to draught force measurements in CTF and non-CTF sites, it is important to highlight that growers and farmers who apply full CTF in their farm will, in the short term, make more energy savings than non-CTF farmers when they move from conventional systems. Such in conservation tillage (chisel and sweep tines) resulted in more than 124% of energy saving, while no-tillage systems (opener tine) resulted in more than 107% of energy saving, However, in long-term CTF, the energy saving in CTF system could be approximately 49% under no-tillage systems, but under a conservation tillage system, the energy saving could be approximately 76%. At same time, non-CTF farms typically lose 39-98% of cultivation energy through a no-tillage system, but conservation tillage systems typically lose 66-112% of tillage energy. According to saving in energy requirements of soil engaging implements therefore, the controlled traffic practitioners have the possibility of downsizing tractors (Boydell & Boydell 2003).

4.4.1.2 Southern region sites

In Southern region sites, draught force was also measured in wheel track and non-wheel track for different tines (**Figure 4.2**). In general, the results show a similar pattern to those found for Northern region sites, but the draught force requirements for all tines in Southern region sites were lower than Northern region sites. This is due to the lower clay content in Southern region sites compared to Northern region sites. This is caused by increased traction in soils with a high content of clay particles; high soil cohesion strength, and possibly adhesion (McKyes 1985; Chen et al. 2013). Kiss and Bellow (1981) and Van Bergeijk et al. (2001) demonstrated that clay content has a strong influence on draught force. Their results of two years of experiments showed that the range of specific draught force was 30 $kN.m^{-2}$ to 50 $kN.m^{-2}$, when the range of clay content was 6% to 22%.

The soils in the Southern region sites are medium-textured and light soils. The results of draught force are presented in two groups. Analysis of the complete dataset for the Swan Hill (VIC) site, indicates a significant effect of traffic type ($p<0.001$) and, as expected, a significant effect of operating depth on draught force, which was also observed for the tine type. The same was true when factoring in the effect of traffic type with respect to both the operating depth and the tine type (p-values <0.001). This shows a similar pattern to that presented for each of the tines at the Pittsworth (QLD) site. As expected, sweep tines required the greatest draught force in both wheeled soil and non-wheeled soil, while chisel tines had the least draught force, with opener tine draught force between these. Increasing the operating depth also led to an increase in the draught force of chisel tines in both of non-wheeled soil and wheeled soil for reasons similar to those at the Pittsworth (QLD) site (discussed above).

At the Hopetoun (VIC) site**,** the results show a similar pattern to that presented for the Queensland sites. However, the statistical analyses of draught force results of sweep and chisel tines indicated that traffic type did not produce a significant effect ($p=0.304$ and $p=0.282$), respectively. The wheel traffic did not significantly affect draught force compared with Swan Hill (VIC) site and the other Northern region sites. The Hopetoun (VIC) site used an incomplete CTF system. The main issue was that different track width equipment were used at this site so there were some wheel tracks on the crop beds. The combination of wheeling on the beds and historical compaction of the site resulted in very high draught levels, particularly with the sweep tine. This is because the compacted soil dragged the sweep tine underneath the compacted layer. To avoid tine and transducer overload, other tines were used only at shallower operating depths (75 mm and 100 mm) at Hopetoun. The results for this site are reported in **Appendix A4.2**.

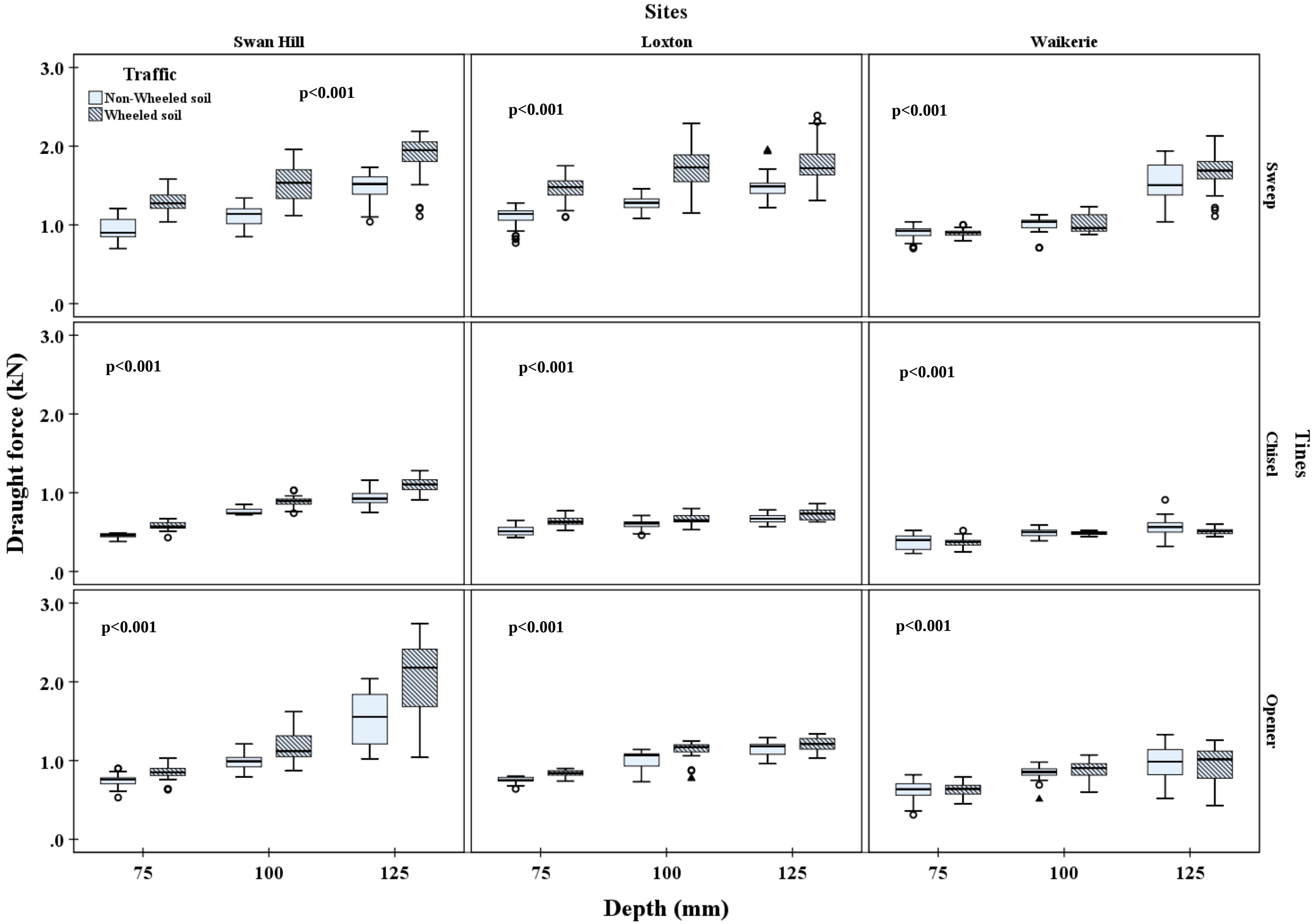


Figure 4.2: The effect of tractor wheel traffic and operating depth on draught force of different tines. Box plots show: Min, Q1, Med, Q3 and Max (n=40). P < 0.001. The symbols (○) and (▲) denote mild and extreme outliers, respectively. Figures show: Sweep (top), Chisel (centre) and Opener (bottom) for Southern region sites, Swan Hill (left), Loxton (centre) and Waikerie (right), respectively

Overall, these results show a small mean wheeling effect on draught force requirements for all tines at the Hopetoun (VIC) site. The site was completely under a CTF system, and was also suffering from historical compaction was caused by previous random traffic of farm machinery. Results showed an increase in the physical and mechanical properties of the Hopetoun site's soil such as bulk density and shear force (**Table 3.3**). One pass by a tractor weighing 85 kN could not make that much different in compacted soil particularly. This is consistent with the results of the Kingaroy site. It is also in close agreement with Jorajuria and Draghi (1997) who demonstrated that the first pass of a tractor causes a greater increase in the soil bulk density compared with five subsequent passes.

In South Australia, an analysis of the complete dataset for the Loxton site, indicated a significant effect of tine type; there was, as expected, a significant effect of operating depth on draught force, which was also observed for the traffic type (p values <0.001), respectively, and the same was true when factoring in the effect of the traffic type with respect to both the operating depth and also the tine type (p-values of <0.001and 0.004 respectively) (**Appendix A4.1**).

In general, this shows a similar pattern to that presented for each of the tines in previous sites (**Figure 4.2**). As expected, the sweep tines required the greatest draught, while the lowest draught force was required by chisel tines. However, in opener tines, the draught force was between the sweep and chisel tines. With respect to the operating depth, increasing the operating depth also led to an increase in the draught force of tines for both non-wheeled and wheeled soils. However, at 75 mm operating depth the draught force requirements for all tines were unexpected, being slightly higher than the Swan Hill (VIC) site results. This is because vegetation covered the Loxton site. Subsequently the roots of the vegetation spread in the upper layers of soil, affecting soil strength. These results closely agree with those previously reported by Raper et al. (2000) who found that cover crops did result in a small increase in draught and energy requirements.

Table 4.3: Effect of wheel traffic and operating depth on draught tines in Southern region sites

			Draught increase			
Site	**Tines**	**Depth (mm)**	**75**	**100**	**125**	**Mean**
Hopetoun	Sweep	Differences (ratio)	1.03	1.10	1.04	**1.06**
		SD	± 0.17	± 0.11	± 0.10	**± 0.13**
		Percentage (%)	3	10	4	**6**
		SD	± 16.87	± 10.61	± 9.76	**± 13.37**
	Chisel	Differences (ratio)	1.06	1.06	-	**1.05**
		SD	± 0.22	± 0.16	-	**± 0.19**
		Percentage (%)	6	6	-	**6**
		SD	± 22.05	± 16.33	-	**± 19.43**
	Opener	Differences (ratio)	1.08	1.03	-	**1.08**
		SD	± 0.04	± 0.03	-	**± 0.03**
		Percentage (%)	8	8	-	**8**
		SD	± 4.05	± 3.32	-	**± 3.70**
Swan Hill	Sweep	Differences (ratio)	1.38	1.35	1.27	**1.33**
		SD	± 0.09	± 0.05	± 0.07	**± 0.09**
		Percentage (%)	38.23	35.17	26.84	**32.71**
		SD	± 8.66	± 4.75	± 7.10	**± 8.76**
	Chisel	Differences (ratio)	1.27	1.17	1.17	**1.19**
		SD	± 0.06	± 0.04	± 0.04	**± 0.07**
		Percentage (%)	27.21	16.73	17.40	**19.44**
		SD	± 6	± 4.02	± 4.04	**± 6.64**
	Opener	Differences (ratio)	1.14	1.19	1.34	**1.24**
		SD	± 0.04	± 0.08	± 0.10	**± 0.12**
		Percentage (%)	14.15	19.10	34.25	**24.77**
		SD	± 3.74	± 8.27	± 10.32	**± 11.57**
Loxton	Sweep	Differences (ratio)	1.33	1.38	1.21	**1.29**
		SD	± 0.21	± 0.17	± 0.22	**± 0.21**
		Percentage (%)	33.17	37.51	20.63	**29.45**
		SD	± 20.65	± 17.05	± 22.13	**± 21.11**
	Chisel	Differences (ratio)	1.23	1.11	1.08	**1.15**
		SD	± 0.17	± 0.15	± 0.12	**± 0.16**
		Percentage (%)	23.41	10.81	7.67	**15.25**
		SD	± 16.89	± 14.86	± 12.25	**± 16.30**
	Opener	Differences (ratio)	1.11	1.12	1.06	**1.09**
		SD	± 0.081	± 0.14	± 0.06	**± 0.105**
		Percentage (%)	11.32	12.10	5.78	**9.28**
		SD	± 8.13	± 14.01	± 6.31	**± 10.48**
Waikerie	Sweep	Differences (ratio)	1	1.02	1.09	**1.04**
		SD	± 0.12	± 0.20	± 0.19	**± 0.18**
		Percentage (%)	0	1.79	8.61	**4.34**
		SD	± 12.35	± 20.22	± 18.53	**± 17.87**
	Chisel	Differences (ratio)	0.97	0.98	0.91	**0.96**
		SD	± 0.34	± 0.11	± 0.16	**± 0.231**
		Percentage (%)	-3.44	-2.22	-9.13	**-4.17**
		SD	± 33.98	± 11.31	± 16.40	**± 23.11**
	Opener	Differences (ratio)	1	1.05	0.97	**1.01**
		SD	± 0.25	± 0.15	± 0.13	**± 0.19**
		Percentage (%)	0.1	4.56	-2.75	**1.25**
		SD	± 25.39	± 14.72	± 13.47	**± 19.10**
		n	**40**	**40**	**40**	**120**

However, in non-CTF sites such the Waikerie site, the results of draught force show a similar pattern to that presented for non-CTF sites in the Northern region sites. The wheel traffic did not significantly effect draught force (p=0.365) (**Appendix A4.1**). This is because, as mentioned earlier, in the non-CTF site, random traffic in the field are common, and could significantly affect the draught force. This was clearly reflected in draught savings (typically 1- 4%) (**Appendix 4.2**), which were the lowest compared with other Southern region sites (**Table 4.3**).

At the Waikerie site, however, the chisel tine did not achieve draught saving in all cases. This is because the site was under non-CTF and there was footprint of tractor traffic from previous grower's practice in some plots. Because of this, in some cases the tines were cultivating trafficked soil, thus achieving a negative draught saving.

Generally, the values of draught saving for all tines in the CTF Southern region sites were lower compared with the Northern region sites. This draws attention to the effect of wheel traffic on the compaction of loam and sandy soils. In addition, the soil moisture values in that soil site were lower than for the Northern region sites. This is consistent with frictionless soils (clay) that are the most susceptible soil type to compaction, and silt soils and cohesion-less soils that are the least susceptible to compaction (Gill & Vanden Berg 1968; Horn et al. 1995) when they are at the optimum water content. As can be seen in the table above, avoiding tilling the wheel track can typically save 29-35%, 15-19% and 9-25% of energy in seedbed preparation, conservation tillage and fertilising and planting operations, respectively.

Table 4.4 shows that the regression analyses for draught force of all tines in Southern region sites were similar to those found in Northern region sites. These regression analyses for all tines in Southern region sites showed that the relationship between draught and depth was significant both for non-wheeled and wheeled soil ($P < 0.001$), respectively, when a non-linear model was fitted to the data. For non-wheeled soil, the estimates of parameters for all tines showed significance ($P < 0.001$) and the R^2 values were lower than 0.88. In wheeled soil the estimates of parameters for all tines also showed significance ($P < 0.001$) and the R^2 values were higher than 0.21. In addition, the standard error of estimate (SE) was the lowest compared with polynomials and linear models. The exponential functions are therefore justified as all responses produced acceptable fits and all response were significant with all tines. This appears to be a fair justification based on the work of Godwin (2007) and Manuwa (2009).

Table 4.4: Non-linear regression analyses – relationships between operating depth and draught force for each of the tines in non-wheeled soil and wheeled soil for Southern region sites (Figure 4.2).

Site	Traffic	Non-wheeled					Wheeled				
Hopetoun	**Tine**	**Response**	**R^2**	**P-value**	**M (kN)**	**SE**	**Response**	**R^2**	**P-value**	**M (kN)**	**SE**
	Sweep	$y = 0.397e^{0.021x}$	0.49	p<0.001	**4.03**	0.451	$y = 0.446e^{0.021x}$	0.52	p<0.001	**4.28**	0.411
	Chisel	$y = 0.078e^{0.032x}$	0.53	p<0.001	**1.54**	0.284	$y = 0.089e^{0.032x}$	0.71	p<0.001	**1.63**	0.257
	Opener	$y = 0.297e^{0.02x}$	0.82	p<0.001	**1.81**	0.120	$y = 0.317e^{0.02x}$	0.81	p<0.001	**1.96**	0.125
Swan Hill	**Tine**	**Response**	**R^2**	**P-value**	**M (kN)**	**SE**	**Response**	**R^2**	**P-value**	**M (kN)**	**SE**
	Sweep	$y = 0.455e^{0.009x}$	0.65	p<0.001	**1.18**	0.139	$y = 0.736e^{0.007x}$	0.55	p<0.001	**1.57**	0.138
	Chisel	$y = 0.163e^{0.014x}$	0.88	p<0.001	**0.72**	0.109	$y = 0.229e^{0.013x}$	0.88	p<0.001	**0.86**	0.100
	Opener	$y = 0.256e^{0.014x}$	0.77	p<0.001	**1.09**	0.158	$y = 0.228e^{0.017x}$	0.76	p<0.001	**1.36**	0.195
Loxton	**Tine**	**Response**	**R^2**	**P-value**	**M (kN)**	**SE**	**Response**	**R^2**	**P-value**	**M (kN)**	**SE**
	Sweep	$y = 0.689e^{0.006x}$	0.57	p<0.001	**1.29**	0.110	$y = 1.096e^{0.004x}$	0.25	p<0.001	**1.67**	0.146
	Chisel	$y = 0.348e^{0.005x}$	0.53	p<0.001	**0.59**	0.101	$y = 0.517e^{0.003x}$	0.25	p<0.001	**0.68**	0.093
	Opener	$y = 0.413e^{0.008x}$	0.76	p<0.001	**0.97**	0.096	$y = 0.502e^{0.007x}$	0.68	p<0.001	**1.06**	0.102
Waikerie	**Tine**	**Response**	**R^2**	**P-value**	**M (kN)**	**SE**	**Response**	**R^2**	**P-value**	**M (kN)**	**SE**
	Sweep	$y = 0.379e^{0.011x}$	0.71	p<0.001	**1.15**	0.143	$y = 0.328e^{0.013x}$	0.77	p<0.001	**1.20**	0.140
	Chisel	$y = 0.215e^{0.008x}$	0.38	p<0.001	**0.48**	0.202	$y = 0.232e^{0.007x}$	0.55	p<0.001	**0.46**	0.122
	Opener	$y = 0.357e^{0.008x}$	0.34	p<0.001	**080**	0.224	$y = 0.403e^{0.007x}$	0.21	p<0.001	**0.81**	0.263

Finally, in Southern region sites according to draught force measurements for CTF, incomplete CTF and non-CTF sites, it is important to highlight that growers and farmers with full CTF systems appeared to achieve a greater energy saving. Such no-tillage systems (opener tine) resulted in more than 19-33% savings, while in conservation tillage (sweep and chisel tines) resulted in more than 19-25% savings in medium and light-textured soils. However, for incomplete CTF, the energy saving could be approximately 8% under no-tillage systems, but under conservation systems the energy saving could be approximately 10% of tillage energy.

4.4.2. Soil surface roughness

The method used for measuring soil surface roughness in this study was discussed in **Chapter 3**. Generally, soil surface roughness is an important characteristic in the assessment of tillage performance, seedbed preparation and the control of runoff and soil erosion (Romkens & Wang 1986). Besides these, the measurement of soil surface roughness in this study is necessary to recognize how soil surface roughness is affected by trafficking after soil treatment. It also has an indirect effect on energy requirements by either increasing the formation of large soil clods with negative effects on seedling emergence, or creating unfavourable soil surface roughness as result of tractor wheel traffic. Soil surface roughness was also measured to identify the quality of the tillage work. Soil surface roughness was measured in wheeled and non-wheeled soil for different tines (sweep, chisel and opener tines). Measurements were conducted for each of the tines at different depths (75, 100, and 125 mm) in most sites. The results of soil surface roughness are also presented in two groups: Northern region (Queensland) sites, and Southern region (Victoria and South Australian) sites. The statistical analysis of these results is reported in **Appendix A4.3**.

4.4.2.1 Northern region sites

The results of soil roughness for tines at operating depth in wheeled-track and non-wheeled-track only for Pittsworth (QLD) site are presented in **Figure 4.5.A**, and the results of soil surface roughness for other sites such as Felton and Gatton (QLD) are reported in **Appendix A4.4**. The statistical analysis indicated a significant effect of traffic and tine type, and as expected, a significant effect of operating depth on soil surface roughness. It was also observed for interactions between the effect of the traffic type with respect to both the operating depth and the tine type (p-values <0.001).

The results show that tillage of wheeled soil resulted in greater surface roughness – 48% compared with 27% in non-wheeled traffic, which is unsurprising when traffic-induced compaction increases the bulk density and strength of the aggregates within the soil mass (Chamen et al. 2015) to produce a more cloddy surface. This is consistent with the work of Lyles and Woodruff (1961), Voorhees et al. (1978) and Lehrsch et al. (1987).

Soil surface roughness increased significantly with operating depth, being consistently least (30%) at 75 mm depth, and greatest (44%) at 125 mm depth, because soil bulk density increases with depth, together with the volume of soil disturbed. This is consistent with soil bulk density results reported in **Table 3.3** (in **Chapter 3**) and results reported in the literature (da Rocha Junior et al. 2016).

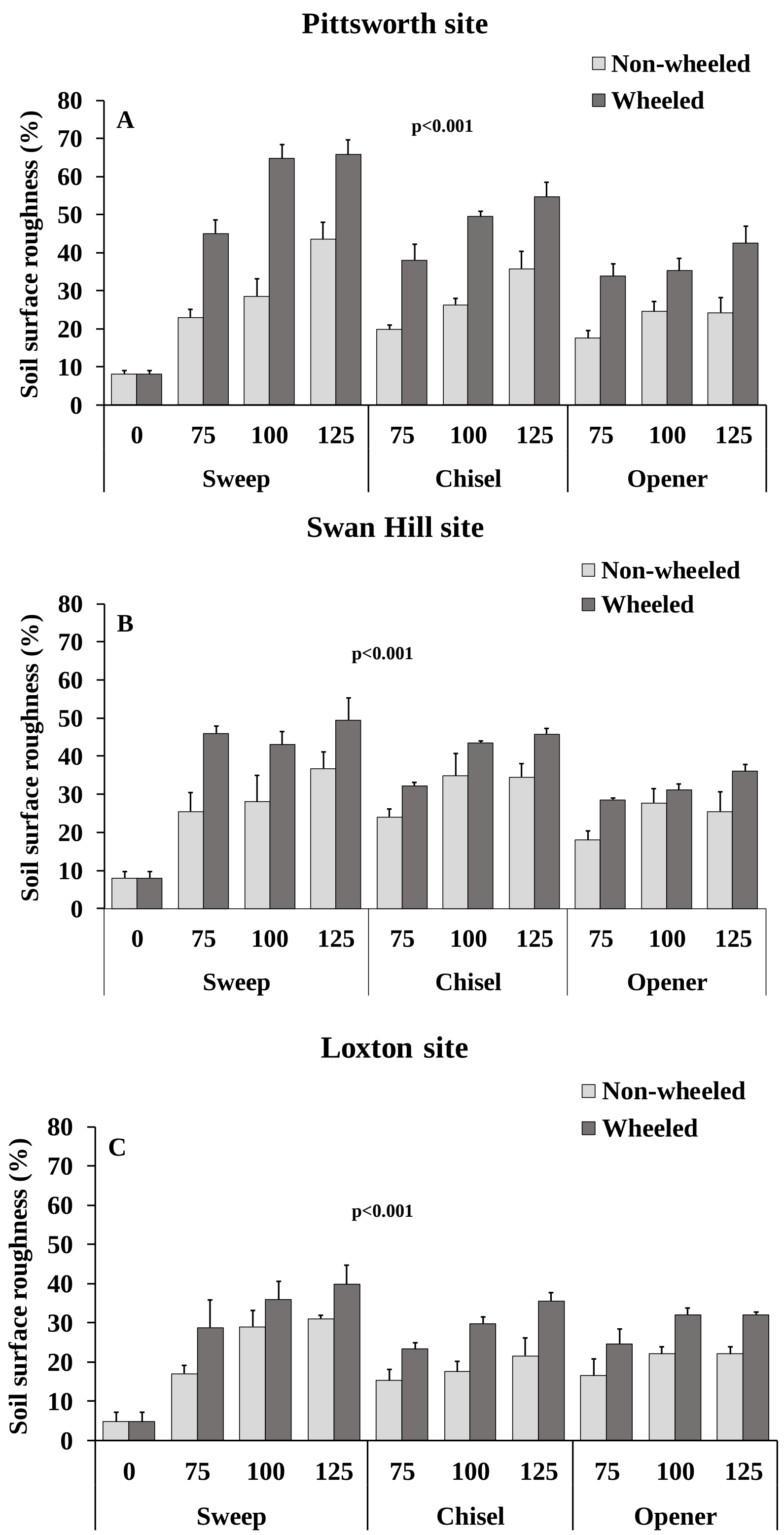


Figure 4.3: Tractor wheel traffic and operating depth effects on the soil surface roughness for different tines at Northern and Southern region sites: (A) Pittsworth (QLD) site, (B) Swan Hill (VIC) site and (C) Loxton (SA) site, respectively. Bars denote SD; the operating depth in mm; 0 = control (n=4)

Soil roughness was significantly smaller with opener tine (30%) compared with sweep tines (43%), while the average soil roughness observed from chisel tines was (36%). The wider tine generating the greatest surface roughness could be expected as the sweep disturbs a much greater volume of soil than that displaced by narrow tines. The present finding is also consistent with those of Spoor and Godwin (1978) and Hasimu and Chen (2014) who concluded that adding wings to a tine would increase soil surface roughness, disturbance, and draught force.

4.4.2.2 Southern region sites

Similarly, for Victorian and South Australian sites, the soil surface roughness is presented in **Figure 4.3.B** and **Figure 4.3.C** for the Swan Hill (VIC) site and Loxton (SA) site, respectively. Soil surface roughness results for the other sites of Hopetoun (VIC) and Waikerie (SA) are reported in **Appendix A4.4**.

At Swan Hill (VIC), the statistical analysis confirmed that soil surface roughness was significantly lower in non-wheeled soil compared with wheeled soil ($p<0.001$). There were also significant differences among operating depths ($p<0.001$) and the effect was also observed in interaction between both factors ($p<0.001$). However, the interaction among the three factors (traffic, tine and operating depth) was insignificant for surface roughness ($p=0.06$). The results of soil surface roughness at the Sawn Hill (VIC) site showed a similar pattern to that of the previous trials in Northern region sites.

However, at the Hopetoun (VIC) site, wheel traffic did not produce a significant effect on soil surface roughness. This is because the Hopetoun site was an incomplete CTF farm and suffering from historical compaction which was not eliminated when the CTF was applied. This is consistent with draught force results at this site.

At the CTF site of Loxton (SA), the results show a similar pattern to that reported for the previous sites (Pittsworth and Swan Hill sites) (**Figure 4.3.C**). Wheeled soil resulted in a significantly greater value of soil surface roughness compared with the non-wheeled soil ($p<0.001$). Significant differences in soil surface roughness were found with tine type, which was also observed in operating depth (p values <0.001). The same was also true when factoring in the effect of the traffic type (wheeled soil) with respect to both the operating depth and the tine type, (p-values <0.001). However, no significant effect was found on the interaction between traffic and tine, or the interactions among the three factors (traffic, tine and operating depth) on soil surface roughness (p-values of 0.205 and 0.830 respectively).

At the non-CTF site of Waikerie (SA), the soil surface roughness results show a different pattern to that found for other sites in respect to tine type. Chisel and opener tines generated significantly greater soil surface roughness than sweep tine (p=0.018). This was because of the interactions between sweep tines. The distance between the edges of sweep tine follow a tractor wheel and the outside tractor wheel was approximately 150 mm, while for chisel tine the measurement was approximately 500 mm. This did not happen in the Queensland sites of Felton and Gatton where standard tractors also were used to conduct the trials. This is because the soil in Queensland sites had the highest clay content and moisture content, which played an essential role in increasing the clod population after the wheel traffic.

Finally, in respect of all studied sites, it has been shown that wheel traffic significantly affects soil surface roughness in CTF sites. In this aspect, controlled traffic farming indirectly reduces energy requirements by avoiding increasing the clods population which happened at both the Queensland and Victorian sites, or by creating unfavourable soil surface roughness which happened at the South Australian sites as result of tilling the wheel track soil.

4.5. Discussions

The results presented in this chapter highlight a number of factors such as wheel traffic, operating depth and tine type effects on energy requirements. Wheel traffic on soft soil had the direct effect of increasing the draught force requirement of subsequent soil-disturbing operations. This phenomenon is a consequence of increased motion resistance of wheels when driving over soft soil. Wheel impact on soil surface profile can also be important. Motion resistance aspects will be addressed later (**Chapter 6**).

Draught force, the results reported for draught force showed that wheel traffic had a significant effect on draught force in most CTF sites which agrees with the results of Tullberg (2000), who also observed that the traffic effect of wheels on the draught of tillage implements significantly increased total draught by 30% or more compared with the same implement operated in non-wheeled soil. These results however, do not closely agree with those reported by Burt et al. (1994) in the USA and Arslan et al. (2015) in UK who found that traffic systems had no significant effect on energy requirements. In Burt's case, use of "draught control" implements probably ensured little difference in draught between treatments because tillage depth in non-wheeled soil was greater than that in wheeled soil. In Arslan's case, tine tillage draught differences were not significant and they found no traffic system differences in no-till seeder draught. This might be because measurements of whole planter draught include a large component due to motion resistance of depth and press wheels which would be expected to increase in softer soils. This is consistent with results of some cases at the Hopetoun (VIC) site (CTF) and results of non-CTF sites such as Kingaroy (QLD) site and Waikerie (SA). This is because a historical compaction in the Hopetoun (VIC) was not eliminated when the CTF was applied, while in non-CTF sites, field traffic was random. This can cover about 50% of crop area in no till systems, and >80% of area each time a crop is produced (Kroulík et al. 2009).

Furthermore, Koger et al. (1985) stated that the first traffic of equipment contributes most to total soil compaction, and that the largest increase in bulk density is induced during the first passage of agricultural machinery (Soane et al. 1980 a,b). Jorajuria and Draghi (1997) also mentioned that that 90% of the maximum change in the soil bulk density of the surface layer occurred with the first traffic of tractors compared with a further five passes which have affected the capability to compact the soil in one traffic event. This is in close agreement with Silva et al. (2008) who demonstrated that compaction of soil occurred after the first five passes of the equipment, without any increase due to subsequent traffic. Similarly, wheel traffic had a non-significant effect on draught force at the Hopetoun (VIC) site (CTF) and in non-CTF sites such as Kingaroy (QLD) site and Waikerie (SA).

The complete dataset analyses, except for the non-CTF Kingaroy (QLD) and Hopetoun (VIC) sites, indicated that there were significant differences in draught forces associated with the different sites (**Appendix A4.1.16**). The Queensland CTF sits had significantly greater draught force compared to those of CTF at Victorian and South Australian sites. This was due to the soil texture in Queensland sites which were heavy clay soils compared with the medium-textured and light soils at the Victorian and South Australian sites, receptively. The results obtained for these sites showed that the average draught force for all tines in non-wheeled soil was 2.23 kN in heavy clay soil at the Pittsworth (QLD) site, 1.26 kN in medium-textured soil at the Swan Hill (VIC) site and 0.95 kN in light soil at the Loxton (SA) site. The 76% and 134 %

increase in draught force for clay soil at the Pittsworth (QLD) site compared to medium-textured at the Swan Hill (VIC) site and light soil at the Loxton (SA) site, respectively (**Table 4.3**). The results appear to be in close agreement with the results reported by Kiss and Bellow (1981) and Collins and Fowler (1996) who highlighted that the clay content of the soil strongly influenced draught force. This is caused by increased traction in soils with a high content of clay particles; high soil cohesion strength, and possibly adhesion (McKyes 1985; Chen et al. 2013). This may be related to Coulomb's equation (Coulomb 1776. cited by McKyes, 1985) for the total soil shear strength:

$$S = c + \sigma_n \times \tan \phi \quad \text{...Equation 4-1}$$

Where s = shear strength, c = cohesion, σn = the normal pressure acting on the internal shear surface in question and ϕ = the angle of internal friction.

Table 4.5: Average draught force for all tines in non-wheeled and wheeled soil and draught saving associated with the different sites

Site	Traffic	Draught force (kN)	SD	n	Draught saving (%)	SD	n
Felton	Non-wheeled	2.16	± 0.83	**360**	66	± 19	**360**
	Wheeled	3.58	± 1.03	**360**			
Pittsworth	Non-wheeled	2.23	± 1.08	**360**	74	± 37	**360**
	Wheeled	3.89	± 2.01	**360**			
Gatton	Non-wheeled	1.48	± 0.81	**360**	66	± 43	**360**
	Wheeled	2.46	± 0.85	**360**			
Kingaroy*	Non-wheeled	4.76	± 1.22	**40**	10	± 5	**40**
	Wheeled	5.24	± 1.31	**40**			
Hopetoun**	Non-wheeled	2.01	± 1.03	**240**	7	± 15	**240**
	Wheeled	2.16	± 1.07	**240**			
Swan Hill	Non-wheeled	1	± 0.36	**360**	26	± 11	**360**
	Wheeled	1.26	± 0.51	**360**			
Loxton	Non-wheeled	0.95	± 0.33	**360**	20	± 18	**360**
	Wheeled	1.14	± 0.46	**360**			
Waikerie	Non-wheeled	0.81	± 0.36	**360**	1	± 20	**360**
	Wheeled	0.82	± 0.40	**360**			

* At this site, only chisel tine was used with one depth 200 mm.

** At this site, just two depths were used with all tines.

This is also consistent with the mechanical soil properties for studied soils in **Table 3.6** (**Chapter 3**). These results showed that Queensland sites had higher cohesion (typically 45-66 kPa) compared with the Victorian and South Australian sites (typically 10-14 kPa). Additionally, at the Queensland sites of Felton and Pittsworth draught results were greater than those of Gatton. This emphasizes the need to consider soil characteristics when determining draught force of soil engaging implement particularly in heavy clay soil, such as Vertisols, compared with medium-textured and light soils.

Draught savings that at the Queensland CTF sites were significantly greater than the draught savings at the CTF sites in Victoria and South Australia. However, at the Hopetoun (VIC) site and in non-CTF sites such as Kingaroy (QLD) and Waikerie (SA), the draught saving was negligible. This is because susceptibility of the soils to compaction varies with the soil texture. Cohesive, high-clay soils are most susceptible to compaction, and cohesion-less silt and sand soils the least susceptible to compaction (Gill & Vanden Berg 1968; Horn et al. 1995).

The soils at the Queensland sites had the greatest clay content. The clay particles in a soil play an important role by holding more moisture than sand and silt. This is because adsorbed water increases as the particle size decreases resulting from a relatively large particle surface area (specific surface) of the fine-grained soils (Martin 1962). In addition, the porosity of clay soils is higher than other soils (Hillel 1982). This results in high pore space which occupied by air and water, and is consistent with soil moisture content values in Queensland sites (**Chapter 6**). The presence of water creates films around the soil particles, thus lubricating the particles which are able to pack more closely together. Consequently, the wheel traffic can easily damage and compact the soil in Queensland sites compared with the Victorian and South Australian sites. In short, the wheeled clay soil at Queensland sites was likely to have compacted more under wheel traffic, and thus required more force to disturb.

Additionally, compactability of soil is related to bulk density under wheel traffic. Soane et al. (1980 a, b) reported that loose soils undergo greater deformation than soils with a high bulk density. In other word, the higher the bulk density, the lower the soil deformation and the soil susceptibility to compaction. This is also consistent with soil physical properties of these sites (**Table 3.3**). Therefore, CTF sites in Victoria and South Australia achieved the lowest draught saving.

Significant differences were also found in draught saving associated with the different Queensland sites. The Pittsworth site demonstrated draught saving in most circumstances in comparison with the Felton and Gatton sites, probably because the tractor weight at Pittsworth was 107 kN compared with 36 kN and 52 kN at Felton and Gatton, respectively (**Appendix A3.9**). This is in close agreement with Botta et al. (2002) who determined that soil strength (penetration resistance) increased 45% as result of the increase in axle load range from 3.7 Mg to 6.4 Mg. In addition, Jorajuria and Draghi (1997) demonstrated that the axle load of 4.2 Mg produced a high change in bulk density, 20%, compared with only 10% for 2.3 Mg, which in turn influenced the increased energy requirements to plough this soil. It is also consistent with Mouazen and Ramon (2002) and Keller (2004) who found that the draught force of a tillage implement increases with bulk density because soil strength usually increases with its bulk density.

The change in soil bulk density decreased with depth, as illustrated by Jorajuria et al. (1997), who showed that the axle load 2.3 Mg produced a maximum change in bulk density 19% at depth 0-50 mm compared with 12% and 15% at depths of 100-500 mm and 300-350 mm, respectively. Therefore, the results reported for all sites in most cases showed that draught saving decreased at increasing operating depth. This is in close agreement with Chen and Yang (2015) who also found that tine opener resistance declined by 30.3% and 21.6% at soil working depths of 50 mm and 100 mm.

Draught saving was also affected by tine type at all studied sites. The variation of draught force between the different tines in this study reflect the effect of tine geometry such as shape, size, and rake angle of tines, which also reflects diversity of purpose. The sweep and chisel tines had almost the same rake angle but different tine width. Thus, the sweep tine, normally used for weed control and seedbed preparation, produced the greatest draught forces for all studied sites, while the lowest draught force was found for the chisel tine commonly used in tillage operations at all studied sites. This is consistent with existing soil cutting theory that a tool with a wider cutting width requires a higher draught force (McKyes 1985).

Manuwa (2009) also found that draught force is related to tine width, and that winged tines have a significant effect on energy requirement. He concluded that increasing the wing width from 50 mm to 200 mm increased the draught force by approximately 143%. This observation is also in close agreement with those made by Reeder et al.

(1993) who reported that 250 mm wings increased draught about 70% and 350 mm wings more than doubled the draught of a 50 mm point in a silt loam soil. This is mainly due to the amount of soil disturbed by narrow tines which is much less than that displaced by wide tines.

However, in opener tines, (normally used for planting and fertilising operation) with the narrowest tine width, greater draught forces were produced at all sites than were with chisel tines. In this case, the rake angle had a significantly greater effect on draught force than tine width, where opener tines had the highest rake angle of 45° (**Chapter 3**). Both horizontal and vertical forces increased with increased rake angle, as is consistently shown in the literature (Manuwa 2009; Godwin & O'Dogherty 2007). The cause may be a vertical force, which is acting on the tool in a manner that assists or prevents penetration of the soil (Godwin 2007). Soil bin measurements by Godwin and O'Dogherty (2007) report that draught force is slowly increased by increasing the rake angle between 20° to 67° which is in close agreement with the results of draught force of opener tines compare to chisel tines results in all studied sites.

Draught force also varied both within and between operating depths for all tines. This is also because of the variation in soil properties across the paddocks at trial plots at the same depth (**Table 3.3**), However, draught force increased for all tines at all sites with the increase of operating depth from a minimum of 75 mm to a maximum of 125 mm in both non-wheeled soils and wheeled soils. These results were found to be consistent with the results reported by Manuwa (2009) who conducted trials tillage tines at a range of depth from 35 mm to 150 mm, demonstrating that with increased depth the draught force increased from 0.219 kN to 0.95 kN. This also agrees well with the work reported by Mak and Chen (2014). The reason being that, at higher depths more soil volume is affected. Soil becomes stiffer and denser due to overburden pressure and so strength properties vary (Manuwa 2009). Furthermore, the increased frictional resistance results in increased soil disturbance.

It has been indicated that the relationship between draught force and operating depth is exponential (Godwin 2007; Manuwa 2009) but this is very dependent on the how deep operating depth is (Kiss & Bellow 1981). If the operating depth is less than 70 mm, the relationship to draught force is linear (Collins & Fowler 1996). The relationship between draught force and operating depth reported for all tines all study sites was in agreement with the previous works on the subject. In most circumstances, the draught force data presented did not permit the use of linear and polynomial functions to describe its relationship with increasing operating depth. For the operating depth investigated, that relationship was better explained by exponential function and it was also shown that the R^2 values indicated acceptable fits of the exponential model. Additionally, the standard error of estimate (SE) was the lowest compared with polynomials and linear models.

This study's soil surface roughness results also showed that wheel traffic had a significant effect on soil surface roughness at most of the studied sites (**Appendix A4.5**). This appears to be in agreement with the results obtained by Voorhees et al. (1978) who followed wheel traffic compared with the same soil in non-trafficked areas. They highlighted that the soil surface roughness significantly increased the clod density in the wheel traffic areas. This is because the wheel traffic compacts the soil underneath the wheel by bringing the soil particles closer together. This is considered to induce the greatest changes in the soil structure, increasing the soil density and strengthening the aggregates in the mass of soil (Chamen et al. 2015). These play an effective role in producing a cloddy surface after soil-engaging implement operation. This corresponded with draught force in wheeled soil compared with non-wheeled soil in all studied sites.

These results however, were not consistent with the results of some cases in Hopetoun (VIC) (CTF) and Waikerie (SA) (non-CTF). This is because the incomplete CTF and historical compaction in the Hopetoun (VIC) was not eliminated when the CTF was applied, and at non-CTF sites the traffic from farm equipment was random. The results are, however, agreement with the results of draught force obtained for the same sites where they consistently showed a similar pattern.

The complete dataset analyses except for the Kingaroy (QLD) and Hopetoun (VIC) sites, illustrate the significant differences in soil surface roughness effects at different sites (**Appendix A4.3.6**). The heavy clay soils of the Queensland CTF sites produced the greatest soil surface roughness compared with that of the medium-textured and light soils CTF at the Victorian and South Australian sites. This is consistent with the compaction susceptibility demonstrated by (Gill & Vanden Berg 1968; Horn et al. 1995), and also with draught force at these sites.

The data analyses indicated that there were significant differences in soil surface roughness associated with the different Queensland sites. The Pittsworth site was observed to achieve the highest soil surface roughness in comparison with the Felton and Gatton sites. The reason could be the weight of tractors with which trials were conducted at these sites (**Appendix A3.9**). The weight of the tractor operating at the Pittsworth site was 107 kN compared with 36 kN and 60 kN at Felton and Gatton, respectively. This showed a similar pattern as that of draught force.

With respect to tine type, the variation in soil surface roughness between the different tines in this study reflect the effect of tine geometry such as shape and size of tines, which reflects the diversity of purpose. The sweep, chisel and opener tines had different tine widths. Thus, sweep and chisel tines, normally used for weed control, seedbed preparation and tillage operations, produced the greatest soil surface roughness for all studied sites, while the lowest soil surface roughness was found for the opener tine commonly used for planting and fertilising operations at all studied sites. This is mainly due to the amount of soil disturbed by sweep tines being much greater than that displaced by narrow tines. The present finding is supported by Spoor and Godwin (1978) and Hasimu and Chen (2014) who concluded that adding wings to tine increases soil surface roughness and soil disturbance. This also corresponds with draught force for tines which had almost the same rake angle at all studied sites. However, the opener tine showed the opposite pattern with the lowest soil surface roughness with higher draught force. This could be because of the rake angle.

In terms of operating depth, soil surface roughness showed a similar pattern to that presented for draught force at all studied sits. The surface roughness also varied between operating depths for all tines in all studied sites. This is also because the depth variation of soil properties across paddocks at the trial plots (**Table 3.3**). However, soil surface roughness increased for all tines at all sites with increased operating depth. The depth of 75mm achieved the lowest soil surface roughness for all tines in both non-wheeled and wheeled soils for all studied sites, whereas the 125 mm depth obtained the greatest draught force for all tines in both non-wheeled and wheeled soils in all studied sites. This is because the bulk density of soil increased with increased depth. This is consistent with the results of bulk density of soil which were reported in **Table 3.3**. In addition, the amount of soil disturbed increased by increasing the operating depth. The above finding is also consistent with the literature.

In addition, the formation of large soil clods not only requires more intense tillage, it also necessitates greater time and effort to eliminate cloddiness in field. This issue can be eliminated by adopting CTF. However, in no tillage, the performance of narrow point tines can be very different, depending on whether they are behind wheels or between them. In the absence of differential rutting from wheels, the soil surface will also be smoother. Seeding will be more reliable and seed rates might lower because the surface is more level and there is less compaction variation across the drill width (Chamen 2006). These features show that the adoption of CTF can help farmers reduce the cost of grain production and increase profit.

Overall, it can be seen that controlled traffic farming directly and significantly reduced energy requirements by avoiding tilling the wheel track. Furthermore, this had an indirect effect on energy requirements by either reducing the formation of large soil clods or creating favourable soil surface roughness.

4.6. Conclusions

The main conclusions coming from **Chapter 4** are summarised below:

- The results derived from the field work at the Northern region CTF sites (clay soils) in sites showed that wheel traffic significantly increased draught force in clay soils by up to 56% and 38 %, 91 % and 55% (2.08 vs. 3.24 kN) and (2.01 vs. 2.77 kN), (2.33 vs. 4.45 kN) and (2.32 vs. 3.6 kN) for the conservation tillage system (sweep and chisel tines) and no-tillage system (opener tine), for non-wheeled and wheeled soil, at Felton and Pittsworth, respectively, relative to draught force required in non-wheeled soil
- The Southern region CTF sites (loam and sandy soils) also showed that draught force significantly increased by up to 28% (0.95 vs. 1.22 kN) and 25% (1.09 vs. 1.36 kN), and 22% (0.94 vs. 1.18 kN) and 9% (0.97 vs. 1.06 kN), for the conservation tillage system (sweep and chisel tines) and no-tillage system (opener tine), for non-wheeled and wheeled soil, at Swan Hill and Loxton, respectively. in these soils, pre-existing compaction must be removed before the full benefits of CTF can be achieved.
- In wheeled soil, draught force requirements for the conservation tillage system at Northern region sites (clay soils) were up to five times higher compared with the Southern region sites (loam and sandy soils), while No-tillage systems at

the Northern region sites were two times higher than of the Southern region sites.

- The greatest savings in draught were observed at the Northern region sites (clay soils) where CTF is practiced, with savings of up to 60% compared with the non-CTF system, while in the Southern region sites (loam and sandy soils) savings were up to 26% compared to non-CTF. Furthermore, savings in draught were approximately 1.3 times and three times higher on clay soils than on loam and sandy soils, respectively. Generally, savings in draught decreased as the operating depth increased, regardless of soil type. Wheel traffic had a negligible impact on draught force in non-CTF sites such as Kingaroy (QLD) and Waikerie (SA) because the soil of non-CTF sites was affected by historic traffic compaction. Therefore, in non-CTF sites, there were no differences in draught forces measured in wheeled soil and non-wheeled soil. This observation confirmed that most of the compaction damage to the soil likely occurred after the first wheel traffic
- There was little demonstrated energy saving when applying the CTF system with different equipment track widths (incomplete CTF) (Hopetoun site case study). This was also reflected in crop performance at the Hopetoun site. The successful CTF systems use the same track width for all equipment. This was found at full CTF sites such as Felton, Pittsworth, Sawn Hill and Loxton. Therefore, if compaction exists, it has to be removed prior to conversion to CTF
- Draught force increased for all types of tines at all sites with operating depth. This had a strong positive relationship with draught force for all type of tines and the relationship is typically better explained by the exponential model
- Wheel traffic significantly affected soil surface roughness for all sites. Soil surface roughness was highest (37% and 59%) and (23% and 27%) for the no-tillage and conservation tillage systems in Northern region sites and Southern region sites, respectively, relative to the soil surface roughness achieved in non-wheeled soil.

CHAPTER 5

MODELLING OF DRAUGHT FORCE

CHAPTER 5: MODELLING OF DRAUGHT FORCE

5. MODELLING OF DRAUGHT FORCE

5.1. Introduction

The **Chapter 4** discussed the effects of a number of factors such as wheel traffic and operating depth on draught force requirements for different tines in different sites (different soil types) and traffic treatments. This chapter will focus on the modelling and prediction of the draught force reported in **Chapter 4**. First, the chapter will explain the model used to predict draught force. It will investigate the sensitivity of the model based on its input. Then, it will examine the validity of this model by comparing the results of the field draught force with the predicted values.

The objectives of the draught force modelling are summarised below:

- To investigate the sensitivity of the selected model based on its inputs
- To validate the draught tillage force model selected for some Australian soils.

5.2. Prediction of draught force

Accurate prediction of the draught forces of soil-engaging implements is of great value to both implement designers and farmers (Desbiolles et al., 1997). There are several models that can be used to predict the draught force. These models can be grouped into two borad categories: analytical (mathematical) and numerical modelling approaches (Abo Al-Kheer et al. 2011). In this study, the analytical modelling method is selected to quantify and predict the draught force produced by tines.

A number of researchers have developed mathematical models that predict the draught force of tillage tines in soils (e.g. Hettiaratchi & Reece 1967; Godwin and Spoor 1977; Godwin & O´Dogherty, 2007; McKyes & Ali 1977; Perumpral et al. 1983). Most of these models have been reviewed by Grisso et al. (1984). Through these models, the interaction between soil and the soil-engaging tine can be analysed to predict the draught force through operational conditions, soil parameters and the tine itself. The interactions between these different parameters have been further reviewed by Godwin (2007).

The soil parameters are soil mechanical properties, including the cohesion, internal friction angle, adhesion and external friction angle. The tine parameters are mainly its geometry, tine working depth and tine speed (Godwin 2007; Godwin & O'Dogherty 2007; Godwin et al. 2007). For model development, these parameters are used as model inputs to predict the draught force of tines.

Actually, a soil in field is an anisotropic substance (McKyes 1989). Accordingly, soil mechanical properties are variable in field (Cui et al. 2007). This is associated with the complex way in which the ground breaks down, hampering the measurement of the interaction between tines and the acting forces (Machado & Trein 2013).

Therefore, validation of these models is required to choose the one best suited to Australian soil conditions. To this point, such validations have not been conducted.

5.3. Justification for using the Godwin and O'Dogherty model

This model enables draught and vertical forces to be calculated for a wide range of soil engaging implements from the knowledge of tool geometry, operating depth, soil physical properties and the form of the soil disturbance pattern produced by the tines. The effects of soil-tine adhesion are taken into account. To improve the prediction accuracy of draught force, the speed effect was also included in a modified model proposed by Wheeler and Godwin (1996). The final equation for the draught force in the Godwin and O'Dogherty model was given in **Chapter 2** (**Equation 2.5**).

Arguably, this model is the most widely accepted analytical model as it has been applied to a range of tillage tools from simple tines to mouldboard ploughs. Godwin and O'Dogherty further developed a series of Microsoft Excel spreadsheets that incorporated tillage force prediction modules for various farm implements (Godwin & O'Dogherty 2006; Upadhyaya et al. 2009). These spreadsheets can evaluate complex and interdependent expressions involved in tillage calculations. It has been found that despite its simplicity, the model has the ability to predict the draught force within an error bound of ±20%. However, this model has not been validated for Australian soils that typically have a very high clay content (Bennett et al. 2016).

5.4. Materials and methods

5.4.1. Godwin and O'Dogherty model

The model requires the input parameters of soil physical and mechanical properties. These were previously collected and reported in **Chapter 3**. In addition, operating condition parameters and geometry of the tines which include operating depth and ground speed were also reported in **Chapter 3**. The values of all of these parameters, entered into draught force modelling, were presented in **Table 3.5** and **Table 3.6**.

5.4.2. Sensitivity of Godwin and O'Dogherty model

The aim of this section is to study the relationships between the output and input parameters. Sensitivity tests were conducted to investigate and identify which factors may have a major influence on draught force for different soil-engaging implements. Baseline scenarios were dictated by the model input parameters, which included three categories of parameters such as soil physical and mechanical properties, tine parameters and operational conditions. The alternative scenarios were constructed by changing the values of a single input factor while keeping all other input parameters constant. Details were reported in **Chapter 3**, **Section 3.5.2**.

5.4.3. Validation of Godwin and O'Dogherty model

The aim of Godwin and O'Dogherty model validation is to investigate the reliability and accuracy of the model under Australian soil conditions.

5.4.4. Statistical analysis

Statistical analyses (**Appendices A.5.1** and **A5.2**) were undertaken using SPSS (2014). Details of the methods were reported in **Chapter 3**.

5.5. Results

The result of the sensitivity analyses of the Godwin and O'Dogherty model are reported in the following section (**5.5.1**). Validation by comparing measured and predicted results of draught force for all tines for Queensland, and Victorian and South Australian sites is presented in **Section 5.5.2**. An overall discussion is reported in **Section 5.6** which then leads to the conclusions given in **Section 5.7**.

5.5.1. Sensitivity of Godwin and O'Dogherty model

Sensitivity tests were conducted to investigate the changes in the draught force of tine as a result of changes in the variables of soil properties, tine geometry and operating condition. They provide an indication of the effect that these changes can have on the draught force of tines. The maximum and minimum outputs of the model based upon the variables and sensitivity of the model at these variables are presented in **Table 5.2** and **Figure 5.1**. In general, the results from sensitivity tests indicated that the draught force of tine was mostly sensitive to the bulk density, cohesion, width of tine, ground speed, operating depth, soil-metal friction angle and rake angle of the tine. These parameters have a greater effect on draught force than other parameters such as adhesion and internal friction angle. However, the impact of soil surcharge on soil-engaging implement forces can be ignored or is equal to zero in this study (**Table 5.2**). But, the soil surcharge can be considered if there is a heap of soil on the surface. Thus, the soil surcharge with the variation of other parameters must be integrated into the analysis of soil-engaging implement forces.

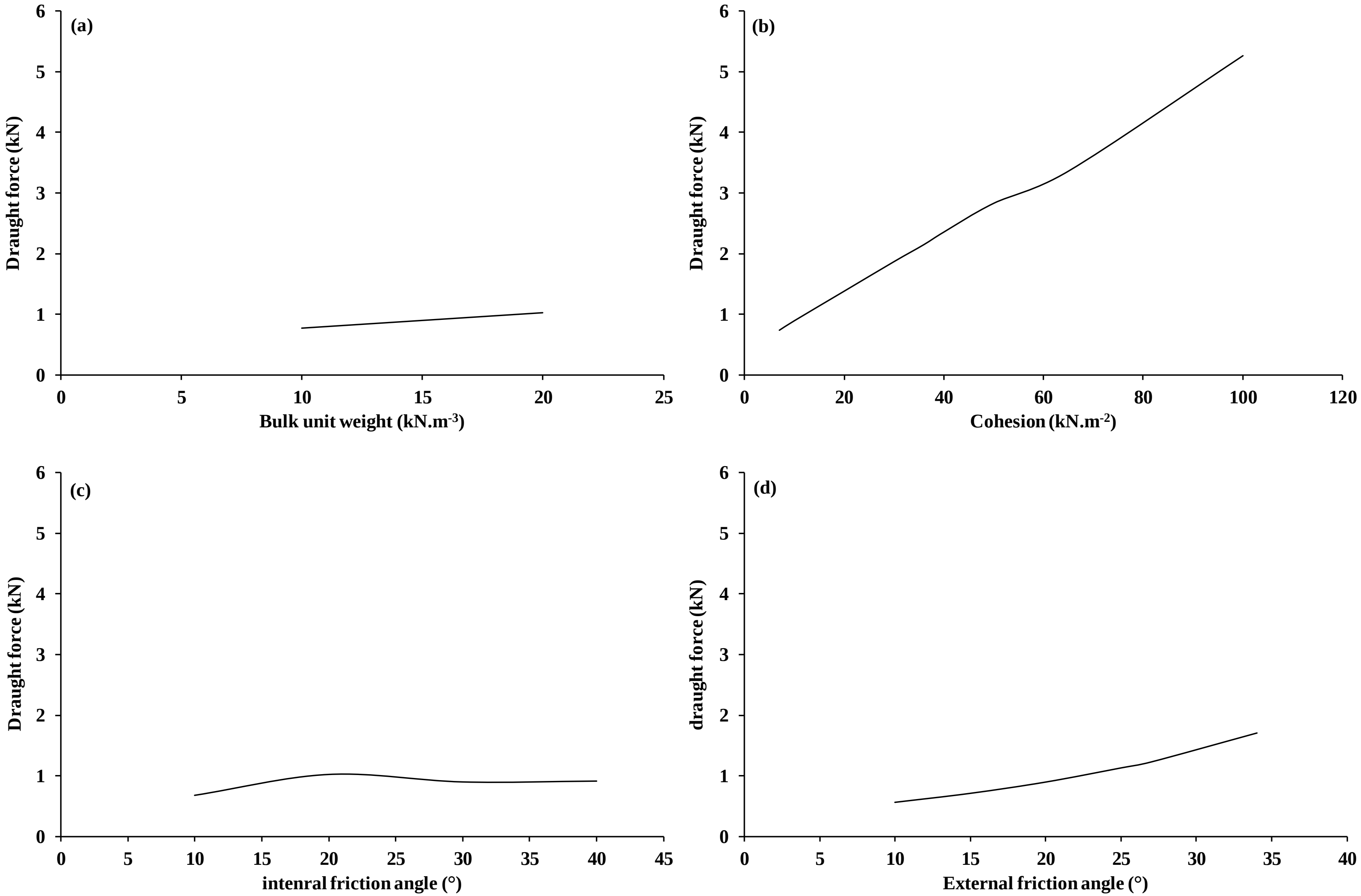
Table 5.1: The effects of input parameter on draught force and sensitivity of model

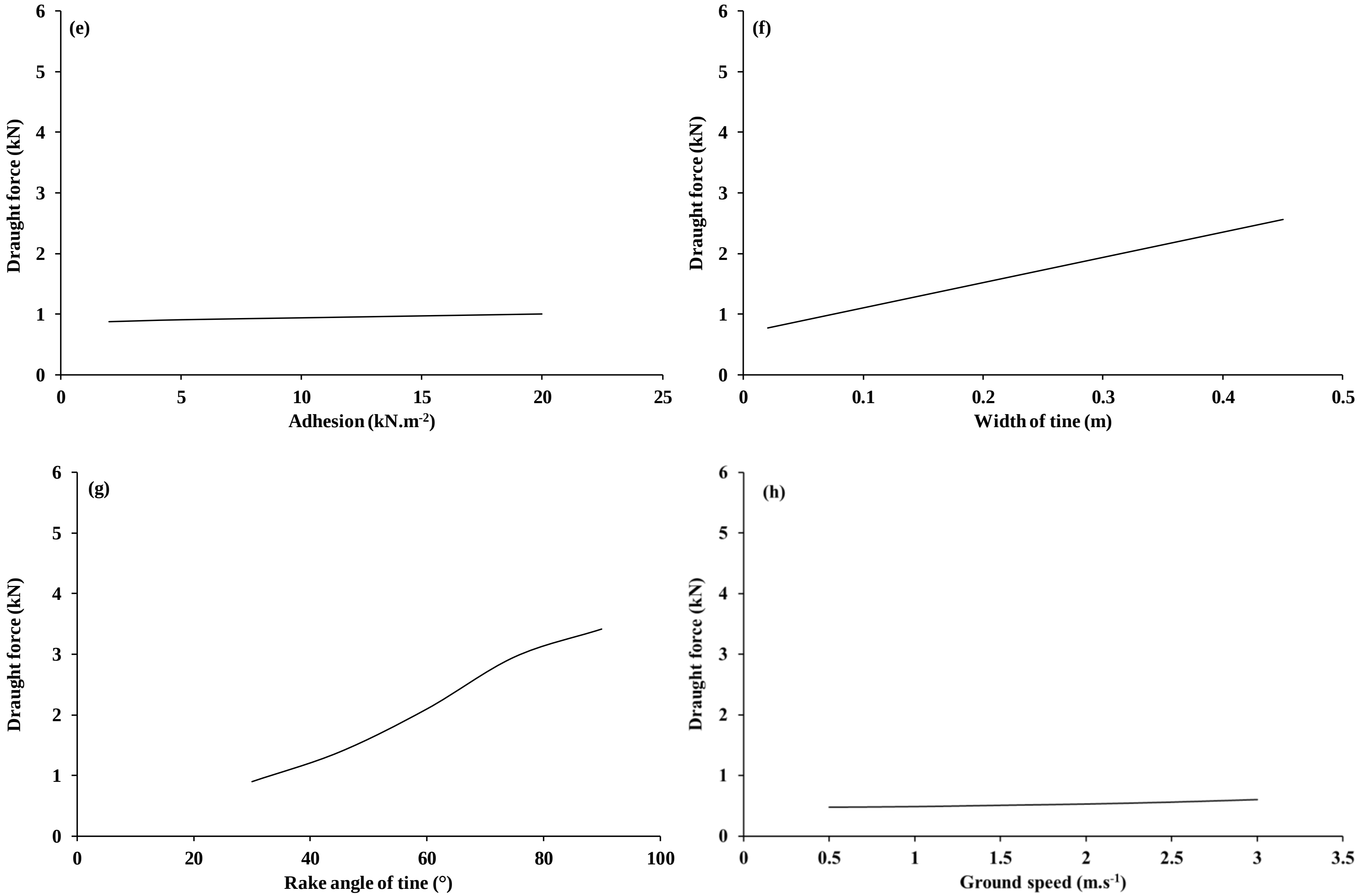
Parameters description	Output of model (draught force (kN))			Sensitivity index
	OP2	OP1	OP avg.	
Bulk unit weight (kN m^{-3}) (γ)	1.2	0.77	0.90	0.72
Cohesion (kN m^{-2}) (C)	5.26	0.74	2.81	0.85
Adhesion (kN m^{-2}) (Ca)	0.88	0.92	0.90	0.03
Internal friction angle (°) (ϕ)	0.91	0.96	0.88	0.09
Soil-metal friction angle (°) (δ)	1.71	0.90	1.20	1.25
Width of the tine (m) (w)	2.56	0.77	1.23	0.42
Rake angle of the tine (°) (α)	3.41	0.76	1.75	1.15
Ground speed (m.s^{-1}) (v)	0.60	0.48	0.53	0.16
Operating depth (m) (d)	1.20	0.12	0.54	1.81
Surcharge (kN m^{-2}) (q)	0.81	0.81	0.81	0

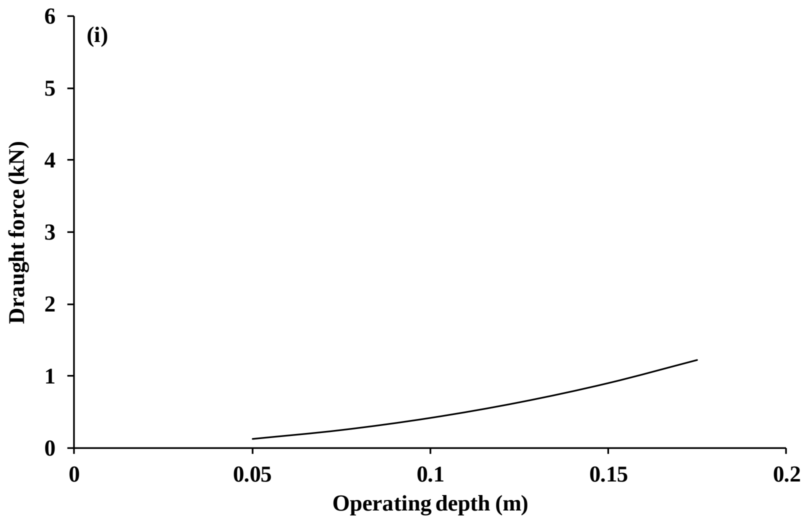
According to results of draught force from the Godwin and O'Dogherty model, as shown in **Figure 5.1**, model parameters, such soil properties, geometry of tine and operating conditions, can all affect the draught force of soil-engaging tine. Among these soil properties, draught force of soil-engaging tine was the most sensitive to bulk unit weight and cohesion (**Figure 5.1a-5.1b**). These figures show that increasing bulk unit weight from 10 kN.m^{-3} (clay soil) to 18 kN.m^{-3} (sandy soil) increased the draught force of tine from 0.77 kN to 1.2 kN resulting in a 56% increase on average. It was expected that the draught force of a soil-engaging implement would increase with bulk density, because the strength of both the soil mass and the aggregates within that mass usually increases with its bulk density as loosening that profile needs more draught and energy (Keller et al. 2007; Chamen et al. 2015). This corresponds with the results of the measured draught force of tines reported in **Chapter 4**.

Figure 5.1b also shows that increasing the cohesion of soil from 7 kN.m^{-2} to 100 kN. m^{-2} increases the draught force of tine from 0.74 kN to 5.26 kN, resulting in six times increase in average. This is caused by increased traction in soils with a high soil cohesion strength (McKyes 1985; Chen et al. 2013). This may be related to Coulomb's equation which was reported in **Chapter 4**. This is also consistent with results of the measured draught force of tines which were reported in **Chapter 4**. Those results showed that the draught force of tines could be greatest in Northern region sites which ususally had a higher cohesion compared to Southern region sites. These results are in agreement with the observations of Abo Al-Kheer et al. (2011) who found that draught force was increased dramatically by increasing the value of cohesion as compared with the impacts of other soil parameters.

In **Figure 5.1d**, it is shown that the soil-metal friction angle also affects the draught force of soil-engaging tine. Increasing the soil-metal friction angle from 10° to 35° increased the draught force of tine from 0.56 kN to 1.71 kN, two times on average. This is compatible with the observations of McKyes (1985). However, **Figures 5.1c**, **5.3e** and **5.1j** show that the effects of the variability of internal friction angle, soil-tine adhesion and surcharge pressure were usually very small compared with the effects of the variability of the other parameters. These results are in agreement with many works reported in the literature (McKyes & Ali 1977; Godwin & O'Dogherty 2007).


(a)
Draught force (kN)
Bulk unit weight (kN.m-3)
(b)
Draught force (kN)
Cohesion (kN.m-2)
(c)
Draught force (kN)
intenral friction angle (°)
(d)
draught force (kN)
External friction angle (°)


(e)
Draught force (kN)
Adhesion (kN.m-2)
(f)
Draught force (kN)
Width of tine (m)
(g)
Draught force (kN)
Rake angle of tine (°)
(h)
Draught force (kN)
Ground speed (m.s-1)



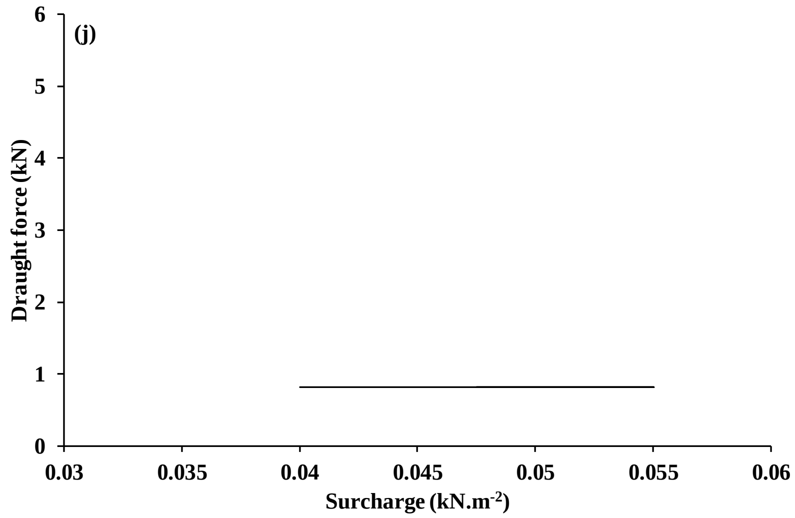


Figure 5.1: The variability of draught forces with respect to input parameters, Figures show: (a) Bulk unit weight, (b) Cohesion (c) Adhesion (d) Internal friction angle (e) Soil-metal friction angle (f) Width of the tine (g) Rake angle of the tine (h) Ground speed (i) Operating depth and (j) Surcharge respectively

Of the geometry of tine parameters, it was observed that the effect of variability of rake angle of tine on draught force of soil-engaging tine was greater than that of other soil-engaging implement parameters. As shown in **Figure 5.1g**, increasing the rake angle of tine from 20° to 90° increased the draught force of tine from 0.76 kN to 3.41 kN, a 3.5 times increase on average. The cause may be the vertical force, which is acting on the tool in a manner to assist or prevent penetration into the soil. Godwin (2007) showed mathematically that the vertical force is a function of the rake angle of the tool and that, the rake angle at about 65-70° for a simple tine, corresponds to a cross-over for the vertical force from a downward to upward force.

Godwin (2007) also found that a lower rake angle tool should be considered in the design of implements because of a reduction in draught and adequate penetration. This was also found to be consistent with results of the measured draught force of tines reported in **Chapter 4**. These results were compatible with the observations of Godwin and O'Dogherty (2007), Manuwa (2009) and Abo Al-Kheer et al. (2011) who all indicted that draught force increased with increased rake angle, as is consistently shown in the literature.

Variability of width of tine showed a similar pattern to that presented for rake angle as shown in **Figure 5.1f**. Increasing the width of tine from 0.02 m to 0.45 m increased the draught force of tine from 0.77 kN to 2.56 kN, resulting in a 2.5 times increase on average. This is mainly due to the amount of soil disturbed by narrow tines which is drastically less than that displaced by wide tines. This was consistent with the results of the measured draught force of tines were reported in **Chapter 4**. These were found to be in agreement with the observation of McKyes (1985) and Manuwa (2009) who indicated that the tine with a wider cutting width requires higher draught force.

With regards to aspect of operating conditions, variability of operating depth shows a similar pattern to those presented for other parameters as shown in **Figure 5.1i**. Increasing the operating depth from 0.05 m to 0.175 m increased the draught force of tine from 0.12 kN to 1.20 kN, resulting in a nine times increase in draught force. The reason for this increase was that at higher depths more soil volume is considered, soil becomes stiffer and denser due to overburden pressure and so strength properties vary (Manuwa 2009). This is consistent with results of the measured draught force of tines reported in **Chapter 4**. These were found to be in agreement with many works reported in the literature (Grisso et al. 1996; Godwin 2007; Manuwa 2009).

Meanwhile the variability ground speed shows a similar pattern to operating depth parameter but, its effects on draught force of tine was very small when compared to the effects of the variability of operating depth parameter as shown in **Figure 5.1h**. Increasing the ground speed from 1 m.s^{-1} to 3 m.s^{-1} increased the draught force of tine from 0.48 kN to 0.60 kN, resulting in 16% increase in draught force. This was caused by the larger force necessary to accelerate the soil at higher tine speeds, and a corresponding increase in the soil shear strength due to an increase in the shear rate (Rowe & Barnes 1961). These results are in agreement with many works reported in the literature (e.g. Rowe & Barnes 1961; Grisso et al. 1996; Wheeler & Godwin 1996).

From the above sensitivity test it can be concluded that only the surcharge pressure can be considered to be a deterministic parameter, and that the variability of the soil-tine adhesion and the other parameters must be integrated into the analysis of tine forces and validation of the Godwin and O'Dogherty model.

5.5.2. The validation of Godwin and O’Dogherty model

In this section, validation of the draught force of soil-engaging tine resulting from this model is verified. The results of experiments carried out in all soil sites for all tines were used in this model. The resultant values of each soil site, tine and operating depth are compared with the values predicted by the Godwin and O’Dogherty model. The statistical analyses were conducted for the data corresponding to the measured and predicted results and are reported in **Appendix A5.1**. In addition, the linear regression of model predicted values against field measured for draught force of tines is presented in **Appendix A5.2**. As shown in the figures below, measured and predicted values of draught force have been compared to each other. The results of validation are presented in two groups of Northern region sites, and Southern region sites sites.

5.5.2.1 Northern region sites

The results of the relationship between measured and predicted draught force for Northern region sites were similar. Thus, results of the Pittsworth (QLD) site is presented in this section to represent all results for the Northern region sites. However, the other sites such as Felton and Gatton (QLD) are reported in **Appendix A5.3**. The relationship between measured and predicted draught force based on the Godwin and O’Dogherty (2007) tillage force prediction model for all tines for the Pittsworth (QLD) site is presented in **Figure 5.2**.

The relationships shown in **Figure 5.2** were found to be significant for all of the tines used at the Pittsworth site: (p-values <0.001) and ($R^2 \leq 0.\ 98$) (**Appendix A5.1** and **A5.2**). **Figure 5.4a** compares the measured and predicted draught force for sweep tine at 75-125 mm operating depth at the Pittsworth site. The measured draught force was taken from **Figure 4.1**. The predicted values were determined based on the Godwin and O’Dogherty (2007) tillage force prediction model. It can be seen that the predicted draught force of sweep tine in this site increased at a higher rate with operating depth compared with measured draught force. However, the Godwin and O’Dogherty model predicted the draught force of sweep tine within an average error 3% compared with measured draught force (**Appendix A5.1**).

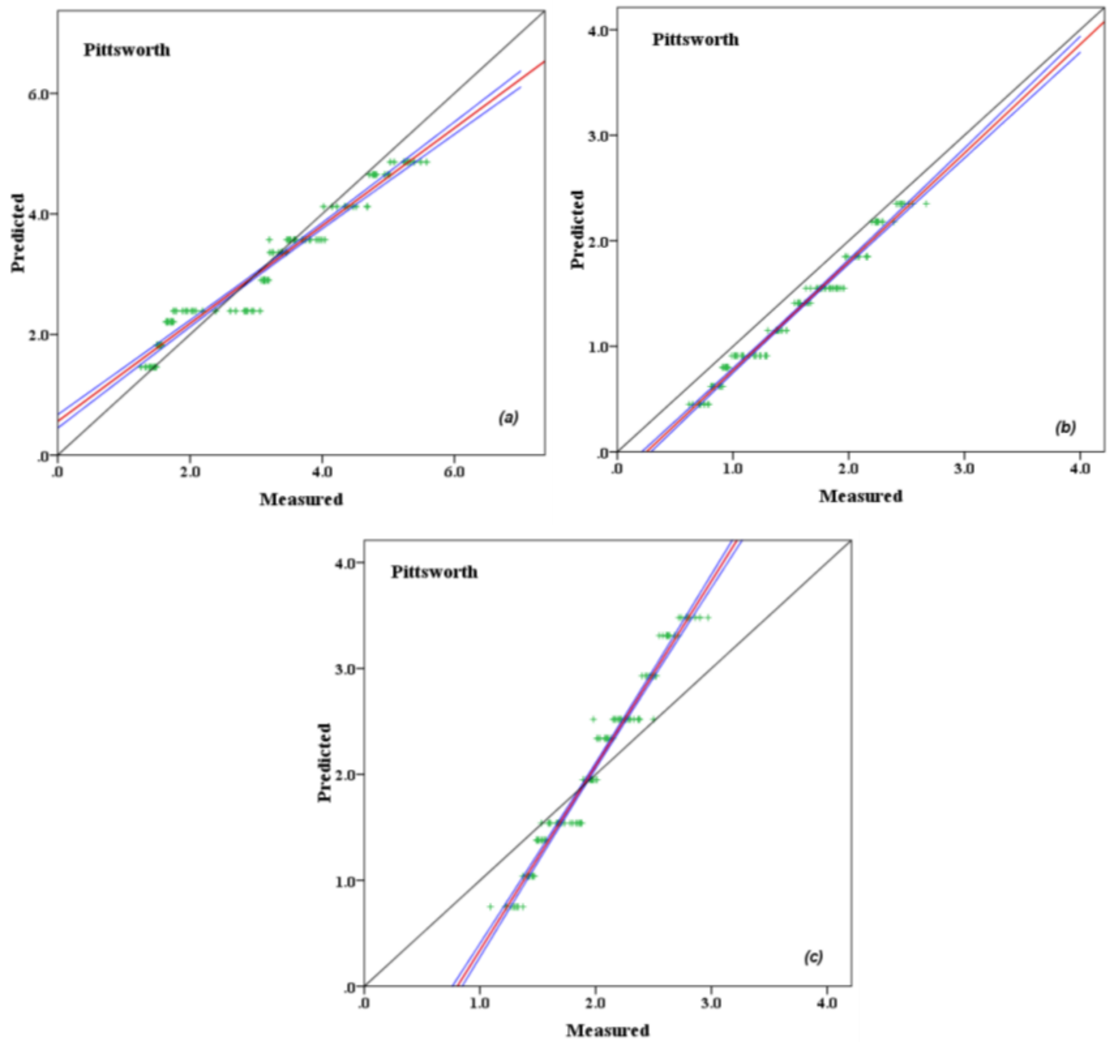


Figure 5.2: Relationship between measured and predicted draught force based on the Godwin and O'Dogherty (2007) tillage force prediction model for Pittsworth (QLD) site. The red line is the relationship between measured and predicted values of draught force. Blue lines show the 95% confidence interval for the linear model fitted to the data, and the black line shows the 1:1 relationship between measured and predicted data. Figures show: (a) Sweep (b) Chisel and (c) Opener, respectively (n=120)

Figure 5.2b also shows the comparison of measured and predicted draught force for chisel tine at 75-125 mm operating depth at the Pittsworth site. The measured draught force was taken from **Figure 4.1**. The calculation of predicted values was also based on the Godwin and O'Dogherty model. This model predicted within -16% of the measured draught force (**Appendix A5.1**). It is important to highlight that there was a variation in the draught force even at the same depth because the measured draught force were conducted in a real farm environment and according to grower practice. In this case, the homogeneity of soil paddock could not be controlled. This had a significant influence on variation of draught force of tines in field measurements.

From the data in **Figure 5.2c**, it is apparent that, the predicted draught force of opener tine in this site compared with measured draught force shows a different pattern to that presented for sweep and chisel tines. The measured draught force was taken from **Figure 4.1**. While the predicted values were determined based on the Godwin and O'Dogherty model. It agreed well at the 100 mm depth; but at the smaller operating depths the prediction of the model was underestimated, while at the greater operating depth the model prediction was overestimated. This could be related to the patterns of the soil-failure. The change in soil failure is related to the operating depth/tine-width ratio, which is postulated a critical depth which separated the distinct soil-failure modes (O'Callaghan and Farrelly 1964).

In very narrow tine such as opener, the soil failure is two-dimensional when the tine works above the critical depth (Spoor and Godwin, 1978), while below the critical depth it is three-dimensional plus two-dimensional (Godwin and O'Dogherty, 2007) therefore, draught force of tine is increased when of working below the critical depth, but draught force of tine is opposite if operating depth is above the critical depth.

The Godwin and O'Dogherty model predicted the draught force of opener tine within an average error 1% compared with measured draught force. In spite of this average error in prediction of draught force of opener tine, was less than that found in the draught force of sweep and chisel trial, but the standard deviation was higher in opener trial (**Appendix A5.1**). This was because the variation of draught was higher in opener tine.

Overall, the general shape and order of magnitude of the predicted curves show a reasonable agreement with the experimental data for draught force. Besides this, the results of draught force perdition based on the Godwin and O'Dogherty model showed that the model has predicted the draught force of all tines within the error range of the model. Godwin and O'Dogherty (2007) concluded that their model has the ability to predict the draught force within error bounds of ±20%. Consequently, it was decided that the prediction of draught force by the Godwin and O'Dogherty model in Northern region sites for sweep and chisel tines was satisfactorily estimated. However, in opener tine, even though the error of prediction was within range of model error, the curve of prediction was systematically unsatisfied. The model is therefore considered valid with chisel and sweep tines during these trials.

5.5.2.2 Southern region sites

As mentioned in **Chapter 4**, the soils in Southern region (Victoria and South Australia) sites are medium-textured and light soils. Consequently, the results of the relationships between measured and predicted draught force for Southern region sites are presented in two groups, Victorian sites and South Australian sites. In the Victorian sites, the relationship between measured and predicted draught force based on the Godwin and O'Dogherty (2007) tillage force prediction model for all tines for Swan Hill site is presented in **Figure 5.3**. The measured draught force for sweep, chisel and opener tines was taken from **Figure 4.2**. There was a significant difference in relationships between the measured and predicted draught force for all tines in at the Swan Hill site (p-values <0.001) and ($R^2 \leq 0.\ 90$) (**Appendix A5.1** and **A5.2**).

The results of the Swan Hill trial demonstrated that the prediction of draught force of sweep tines was greater than the measured draught force (over predicted) (27%), while for chisel and opener tines the prediction was lower than that observed in the field (-13 and -21), respectively. However, the prediction of draught force based on the model for each of tines in Swan Hill site was estimated successfully.

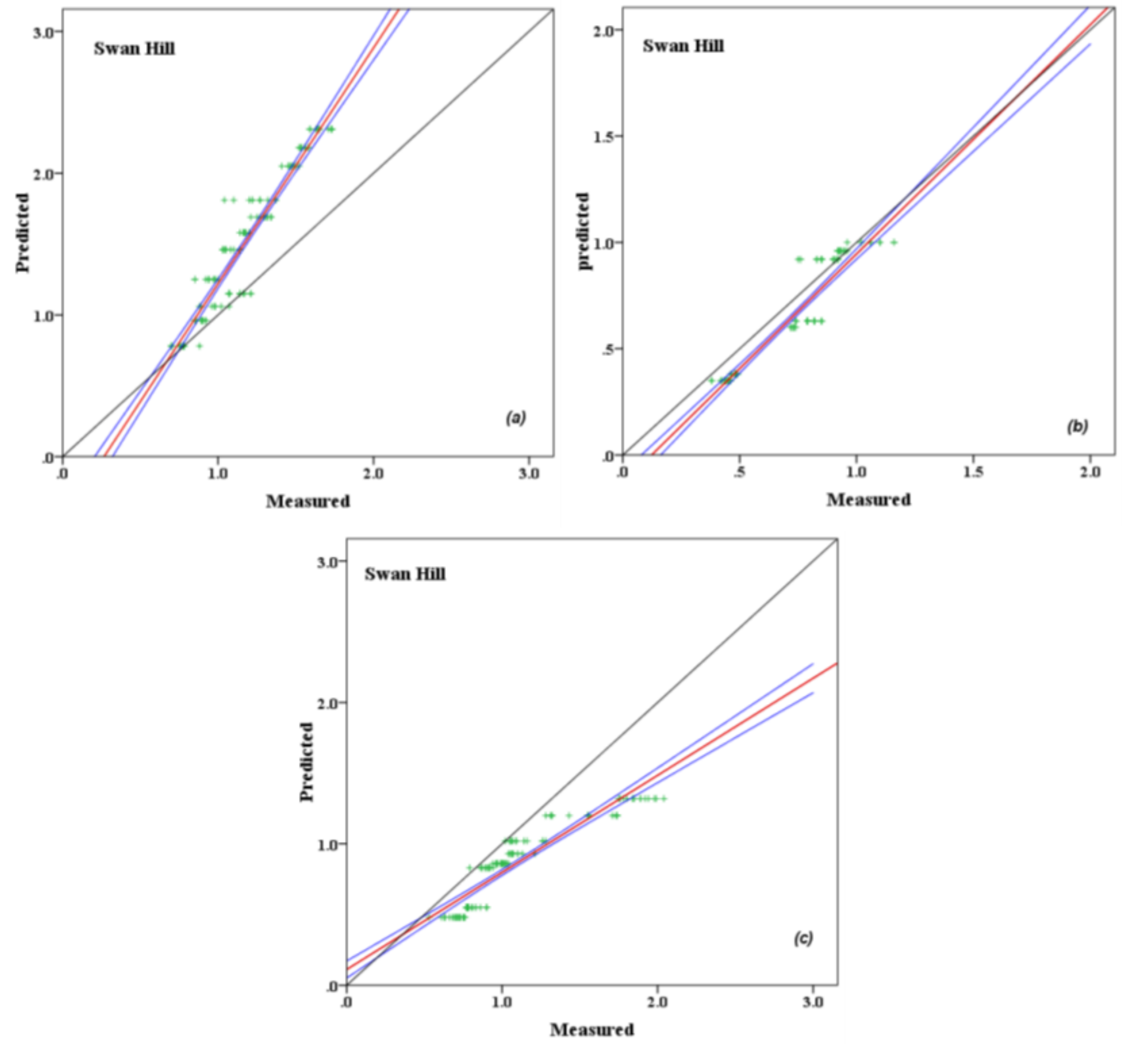


Figure 5.3: Relationship between measured and predicted draught force based on the Godwin and O'Dogherty (2007) tillage force prediction model for Swan Hill (VIC) site. The red line is the relationship between measured and predicted values of draught force. Blue lines show the 95% confidence interval for the linear model fitted to the data, and the black line shows the 1:1 relationship between measured and predicted data. Figures show: (a) Sweep (b) Chisel and (c) Opener, respectively (n=120)

However, at the Hopetoun (VIC) site, the results did not show a similar pattern to those found at the Swan Hill and Northern region sites (**Appendix A5.1** and **Appendix A5.3**). This was expected because of the inhomogeneity of compaction paddock soil compaction. This had a significant effect on variation of draught force of tines in field measurements. This appears to be consistent with the draught force of tines reported for the Hopetoun site in **Chapter 4**. This was also consistent with results of soil penetration resistance, which will be reported in **Chapter 6**. The findings highlight that the prediction of draught force based on the model for each of tines at the Hopetoun site estimated unsuccessfully. These results somewhat contrast with the observations of Godwin and Spoor (1977) and Godwin and O'Dogherty (2007). This is because the condition of soil paddock which was explained at the beginning and in **Chapter 4**.

At the South Australian sites**,** the relationship between measured and predicted draught force based on the Godwin and O'Dogherty model for all tines for Waikerie is presented in **Figure 5.4**. The measured draught force was taken from **Figure 4.2** for sweep, chisel and opener tines. The relationships shown in **Figure 5.4** were found to be significant for each of tines used at the Waikerie site (p-values <0.001) and ($R^2 \leq$ 79) (**Appendix A5.1**). In general, the results of the relationship between measured and predicted draught force show a similar pattern to those reported for Northern region sites, in particular relative to sweep and chisel tines.

However, for opener tines the results showed a better pattern than those reported for Northern region sites. In clay soil (vertsoil), the results of interface and soil internal friction angles were surprisingly higher (21° and 22°, respectively) than for universal clay soils (near zero). And the slope of the soil-rupture plane at the bottom of the tool is governed by the interface and soil internal friction angles (McKyes 1989). These are main effect on the area of soil disturbed by the tine (Plasse et al. 1985). Therefore, the soil failure zone could be affected by these issues. This was clear under the action of narrow tines which in clay soil could be different compared with sand soil at the Waikerie site. This could affect the accuracy of draught force prediction for opener tine in comparison between the sites.

Similarly, at the Loxton **(**SA) site, the results of the relationship between measured and predicted draught force show a similar pattern. The relationships were found to be significant for each of tines used at the Loxton site (p-values <0.001). The relationship between measured and predicted draught force based on the Godwin and O'Dogherty model for all tines for Loxton site is reported in **Appendix A5.3**.

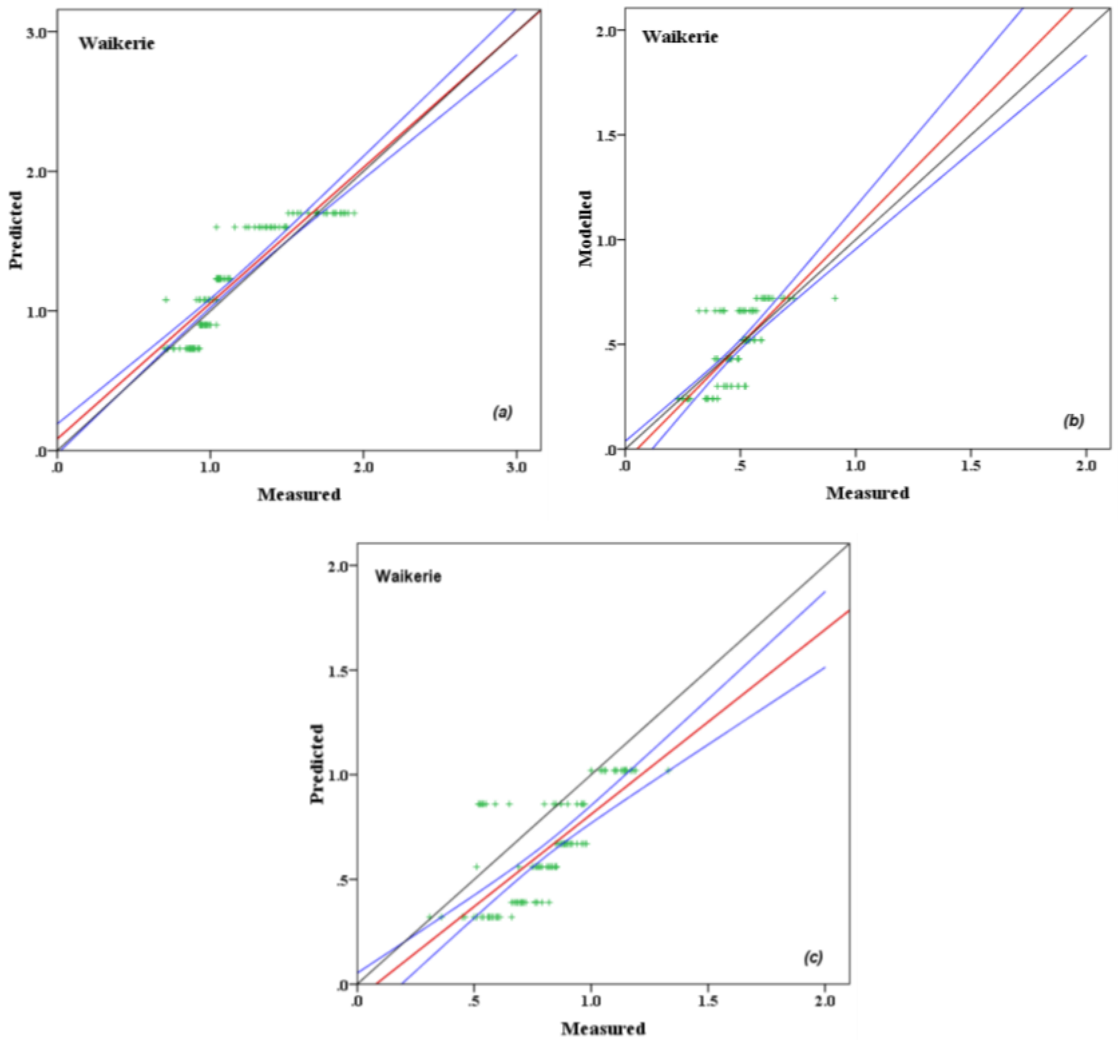


Figure 5.4: Relationship between measured and predicted draught force based on the Godwin and O'Dogherty (2007) tillage force prediction model for Waikerie (SA) site. The red line is the relationship between measured and predicted values of draught force. Blue lines show the 95% confidence interval for the linear model fitted to the data, and the black line shows the 1:1 relationship between measured and predicted data. Figures show: (a) Sweep (b) Chisel and (c) Opener, respectively (n=120)

Finally, the comparison between the measured and predicted draught force has shown that the Godwin and O'Dogherty single model has predicted the draught force within error bounds of ±20%, which was produced by the authors of the model. These findings revealed that the model has the ability to predict the draught force for each of the tines in Southern region sites. Accordingly, the prediction of draught force based on the model for tines has estimated successfully. These results are consistent with the findings by Godwin and O'Dogherty (2007).

5.6. Discussions

The results reported for measured and predicted draught force of various tines tested showed that it is affected by soil property, tine geometry and operating condition parameters. These parameters have been adopted to test the sensitivity and validity of the Godwin and O'Dogherty model. The results of sensitivity testing showed that soil properties including bulk unit weight, cohesion, adhesion, internal and external friction angle (but not surcharge) had a significant effect on the prediction of draught force of soil engaging tine as well as on measured draught force of tines in the field as reported in **Chapter 4**.

Cohesion had a great effect on draught force of soil engaging tine compared with adhesion, which had a very small influence on draught force. This appears to be in agreement with the results obtained by Godwin and Spoor (1977), Godwin and O'Dogherty (2007) and Abo Al-Kheer et al. (2011) who found that draught force increased dramatically by increasing the value of cohesion as compared with the impacts of the variability of the other soil parameters. Similarly, the Northern region sites consistently showed greatest values of measured draught force compared with Southern region sites (**Chapter 4**). This was due to the soil texture in the Northern region sites which were heavy clay soils compare to medium-textured and light soils in Victorian and South Australian (Southern region) sites, respectively (more details in **Chapter 4**).

The results of sensitivity also obtained for geometry of tine parameters showed, in general, an increase in the draught force of tine with an increasing of the rake angle and width of tine. The variability of rake angle had a great influence on draught force of tine compared with the variability of tine width. In this respect, draught force of tine is increased 3.5 times and 2.3 times on average by increasing the rake angle of tine from 20° to 90° and width of tine from 0.02 m to 0.45 m, respectively, as is consistently shown in the literature (Godwin & Spoor 1977; McKyes & Ali 1977; Perumpral et al. 1983; McKyes 1985). This also is consistent with the results of draught force of tines reported in **Chapter 4**. In this respect, McKyes (1985) stated that the volume of soil moving in front of a tool increased with an increase in rake angle. The cause may also be a vertical force, which is acting on the tool in a manner to assist or prevent penetration into the soil (Godwin 2007).

CHAPTER 5: MODELLING OF DRAUGHT FORCE

The reported rate of increase of draught force with rake angle tends to vary as a function of operating conditions and soil properties (Godwin & O'Dogherty 2007). In this regard, the results of sensitivity testing generally showed that operating conditions, including operating depth and ground speed, influence on draught force of tine. It was indicated that increasing the operating depth from 0.05 m to 0.175 m and increasing the ground speed from 1 $m.s^{-1}$ to 3 $m.s^{-1}$ resulted in 9 times and 16% increase in draught force of tine, respectively. With respect to this, operating depth showed higher impact on draught force of tine compared with ground speed. These results were in agreement with the results of measured draught force presented in **Chapter 4**. The reason is, that at higher depths, more soil volume is considered, soil becomes stiffer and denser due to overburden pressure and so strength properties vary (Manuwa 2009). The results of the sensitivity analyses were found to be in close agreement with works reported in the literature.

Overall, the sensitivity testing undertaken, not only provided an indication of the effect of the variabilities of soil properties, tine geometry, and operation conditions on draught force, but it identified changes in draught force of tine as a result of changes in these parameters.

Accordingly, the validation of the Godwin and O'Dogherty model was undertaken based on those parameters. The results of validation of the Godwin and O'Dogherty model were compared the measured and predicted draught force in this study. The study also refers to the linear regression of model predicted values against field measured for draught force of tines for all studied sites. In addition, it highlights the relationship between measured and predicted draught force based on the Godwin and O’Dogherty (2007) tillage force prediction model for all tines in studied sites.

At the Northern region sites, the relationships between measured and predicted draught force based on the Godwin and O’Dogherty model generally showed that model performance was satisfactory within the error bounds of ±20%, which has produced by the authors of the model. At the Felton site, the prediction of draught force by the Godwin and O’Dogherty model was reasonable in most cases. However, the standard deviation of mean difference between predicted and measured draught force for all tines was high (± 24%) (**Appendix A5.1**).

A similar situation was observed at the Pittsworth site where, in most cases the prediction of draught force based on the Godwin and O'Dogherty model was also successful. Nevertheless, the standard deviation of mean difference between predicted and measured draught force for all tines was also high. At the Gatton site, the results of predicted draught force also showed a similar pattern to those reported for the Felton and Pittsworth sites. But, the prediction of draught force was underestimated in sweep and chisel tine. This is because the Gatton soil was tilled prior to the draught force assessment which could affect accuracy of prediction. This is in agreement with the observations of Godwin and Spoor (1977), which found that predictions of draught force for different tines are closer in compacted soil than in loose soil. This was also confirmed by the results of prediction at the Kingaroy site which showed a similar pattern to that presented for other Northern region sites. The prediction of draught force by the Godwin and O'Dogherty model was a fit for chisel tine. These results are in agreement with the observations of Godwin and Spoor (1977) and Godwin and O'Dogherty (2007).

The reason for higher standard deviation is related to where the draught force measurements were taken in a real farm environment and accordingly to grower practice. In this case, the homogeneity of paddock soil could not be controlled. This had a significant influence on variation of draught force of tine in field measurements. In addition, the soil of these fields is clay soil which has higher cohesion. This may be due to the fact that cohesion differed in value with soil depth and soil moisture contents.

This means the tines operate in different soil layers with different cohesion values, which lead to a higher contribution of the soil cohesion. This is consistent with the results of the draught force of tines reported in sensitivity testing. In addition, the authors sought to establish a model that is mathematically based on several and wider assumptions, including that the soil is isotropic and homogeneous. These results are in line with the observations of Abo Al-Kheer et al. (2011) and Al-Halfi et al. (2017).

At the Southern region sites, the relationships between measured and predicted draught force based on the Godwin and O'Dogherty model also showed that model performance was satisfactory within the error bounds of ±20%, which has produced by the authors of the model.

At the Hopetoun (VIC) sites, the draught force prediction results based on the Godwin and O'Dogherty model were unsuccessful in most cases. The larger prediction errors were observed at this site (-39%). This may be explained by potentially significant fluctuations in the condition of paddock soil due to the compaction (more details in **Chapter 4**). At the Swan Hill site, based on the Godwin and O'Dogherty model, the prediction of draught force was satisfactory, but the values of standard deviation showed a similar pattern to those reported in Northern region sites (**Appendix A5.1**).

At the Loxton (SA) site, the results of draught force prediction based on the Godwin and O'Dogherty model compared with measured one, showed a similar pattern to that of the previous two studies (Felton and Pittsworth sites) reported earlier. In spite of this, the prediction of draught force was also reasonable (as in most cases), but the standard deviation of mean difference between predicted and measured draught force for all tines was also high. This is related to where the draught force measurements were taken a in real farm environment and according to grower practice. In this case, the homogeneity of paddock soil could not be controlled. This had a significant influence on the variation of draught force of tine in-field measurements.

At the Waikerie site, based on the Godwin and O'Dogherty model, the prediction of draught force was a fit in most cases. This was a similar pattern to that reported for the Kingaroy site. However, the standard deviation of mean difference between predicted and measured draught force for all tines was high (± 23%) (**Appendix A5.1**). At Kingaroy (QLD) and Waikerie (SA), the paddocks measured for draught force were under non-CTF. The soil, therefore, was compacted as result of random traffic. This is in agreement with observations of Godwin and Spoor (1977), which found that predictions of draught force for different tines are closer in compacted soil than loose soil.

Finally, as highlighted, and based on the Godwin and O'Dogherty (2007) tillage force prediction model, it possible to predict the draught force of different tines in all studied sites except the Hopetoun (VIC) site and opener tine in clay soil (Vertisol) at the Felton (QLD) and Pittsworth (QLD) sites.

5.7. Conclusions

The main conclusions from **Chapter 5** are summarised below:

- The sensitivity tests for the Godwin and O'Dogherty model, indicated that:
    a. The soil properties, which include bulk unit weight, cohesion, adhesion, internal, external friction angle and surcharge, had a significant effect on prediction of draught force of soil engaging tine except for surcharge
        - Variability of cohesion had a great influence on draught force of soil engaging tine, which resulted in six times increase in draught force of tines on average
        - Variability of soil surcharge in this study was unaffected on draught force of soil engaging tine.

    b. The geometry of tine parameters, which include rake angle and width of tine, had a significant influence on the prediction of draught force of soil engaging tine
        - Variability of rake angle of tine had a greater impact on draught force than the variability of width tine. Draught force of tine was increased 3.5 times and 2.3 times on average by increasing the rake angle of tine from 20° to 90° and width of tine from 0.02 m to 0.45 m, respectively.

    c. Operating conditions, which include operating depth and ground speed, had a significant effect on the prediction of draught force of soil engaging tine
        - Operating depth had a greater impact on draught force than ground speed variability. Increasing the operating depth from 0.05 m to 0.175 m resulted in nine times increase in draught force of tine

- The investigation the validity of the Godwin and O'Dogherty (2007) tillage force prediction model indicated that:
    a) In general, the predictions of draught force based on the Godwin and O'Dogherty model have been shown to give useful agreement with the experimental data for different tines in most studied sites except Hopetoun (VIC) site and in clay soil (Vertisol) at Felton and Pittsworth (QLD) sites
    b) In clay soil (Vertisol) (NT, Northern region sites) the investigations showed that the Godwin and O'Dogherty model could predict within

an error range from 3% to %5, -17% to 2%, and -12% to 1% on average the draught forces of sweep, chisel and opener tines, respectively. However, the prediction curve in opener tine did not systematically fit compared with sweep and chisel tines

c) In tilled clay soil (Gatton site), investigations showed that the draught force values estimated from the Godwin and O'Dogherty model were underestimated for sweep, chisel tines within error -16%, -13%, respectively

d) In loam and sand soils (NT, Southern region sites), the prediction of draught force by the Godwin and O'Dogherty model could be estimated within a range from 5% to %26, -13% to -8%, and -21% to -15% on average the draught forces of sweep, chisel and opener tines, for Swan Hill and Loxton sites, respectively

e) In trafficked sand soil (Waikeire (SA) site), the draught force of sweep, chisel and opener tines could be predicted by the Godwin and O'Dogherty model within 5%, -1% and -20% on average, respectively.

CHAPTER 6

MOTION RESISTANCE

6. MOTION RESISTANCE

6.1. Introduction

CTF effects on draught force were discussed in **Chapters 4** and **5**. This chapter examines the CTF impact of motion resistance in reducing energy requirements and improving equipment performance in agricultural systems.

Motion resistance is defined as the force required to move equipment across a horizontal surface (Crossley & Kilgour 1983). On field surfaces motion resistance generally includes two components: internal and external. The internal resistance is due to frictional losses within the ground drive system (wheels or tracks), and is sometimes taken to include drivetrain friction. The external resistance is due to soil deformation (Crossley & Kilgour 1983; Lyasko 2010b). In the case of tyres, the internal energy losses occur in the elastic but non-ideal deformation of the tyre carcass, but in the case of tracks (rubber or steel) it is the friction within the track itself and its drive and idler rollers or sprockets. The external loss is the inelastic and non-recoverable (plastic) deformation of the surface. Friction in the wheel bearings is usually assumed to be negligible (Macmillan 2002) but, when rolling motion resistance is measured by towing farm tractors, it also includes the non-negligible drivetrain friction. Internal resistance is the most significant component of motion resistance on near-rigid road surfaces. But on soft surfaces, external resistance is by far the largest component in terms of energy loss. On field surfaces, deformation also represents soil compaction, and is generally associated with the loss of soil porosity and potential loss of productivity. This study will, therefore focus on external resistance and role of permanent traffic lanes in reducing that resistance.

With accurate and adequate data, some generalisation or extrapolation of these results may also be possible when combined with the validation of the motion resistance models as described in **Chapter 2**. This, together with the draught effects (**Chapter 4**), should provide a more complete picture of CTF impact on energy and fuel requirements, and provide a basis for farmer decisions on CTF adoption. Motion resistance is also an important parameter of trafficability, which in turn affects the timeliness of crop operations, particularly those such as herbicide spraying after rainfall.

The objectives of this work were thus:

- To determine the effects of CTF versus non-CTF on the physical properties and penetration resistance of a range of cropping soils
- To measure equipment motion resistance in CTF versus non-CTF on the same range of cropping soils.

6.2. Materials and methods

6.2.1. Description of sites

Experimental work was conducted in two different Australian regions and a number of sites within each region: Felton, Pittsworth, and Gatton (Northern region sites), Hopetoun, Swan Hill, Loxton and Waikerie (Southern region sites). These are all areas of extensive cropping in which CTF is relatively common (more details in **Chapter 3**).

6.2.2. Details of experiments

Motion resistance experiments were arranged in a complete randomized block design, with three replications. Motion resistance was measured by towing on three surfaces: Permanent Traffic Lanes (PTL) representing CTF, Permanent Crop Beds (PCB), or non-wheeled soil representing non-CTF systems, and on the best available hard surface (e.g., dirt track or road). This latter measurement was intended to assess internal powertrain component friction and energy loss in tyre or track deflection.

All measurements were taken within the range of common ground speeds (2.2, 3.3 and 4.4 m s^{-1}), as these represent those speeds commonly used for conservation tillage, seeding, harvesting and spraying. However, in non-CTF sites the ground speeds were restricted to 0.55 and 0.97 m s^{-1} at Gatton and 2.2, 2.8, 3.3 m s^{-1} at Waikerie by either limitations in field area or towing tractor capacity. The results were measured and compared with predicted results.

Soil properties measured in PTL and PCB included Penetration Resistance (PR), and Moisture Content (MC), at soil depths (0-500 mm), but there was no distinction between PTL and PCB at the non-CTF sites. A more detailed description of the experimental procedures can be found in **Chapter 3**, **Section 3.6**.

6.3. Results and discussion

The effect of the wheel-track on the selected soil physical properties are presented in **Section 6.3.1,** with the effect of CTF on motion resistance in **Section 6.3.2** for Northern region and Southern (Victoria and South Australian) sites. Motion resistance modelling and prediction is covered in **Section 6.3.3** for all sites. Conclusions from these discussions can be found in **Sections 6.4**.

6.3.1. Soil physical properties

The method used for measuring the selected soil parameters in this study were discussed in **Chapter 3**. The results of soil physical properties are presented separately for Northern region sites, and Southern region sites. As stated earlier, the two regions have very different soil characteristics. In the Northern region, sites are heavy clay soil with annual rainfall 600 – 700 mm, but in the Southern region (Victoria and South Australia) sites are medium-textured and light soils, respectively with rainfall 300 – 400 mm.

6.3.1.1 Northern region sites

PR and MC were measured at both CTF and non-CTF sites and reported here, but other soil physical properties of the sites can be seen in **Chapter 3**. The CTF sites were under controlled traffic and no-tillage for up to 15 years. Non-CTF sites such Gatton, a University of Queensland research station, was managed with conventional tillage and cultivated and irrigated before this work was carried out. Statistical analysis of the results is reported in **Appendix A6.1**. Due to the similarity in results of PR and MC in Northern region sites, the results of PR and MC for both PTL and PCB in Pittsworth site are presented in **Figure 6.1**. But, the results of PR and MC for other sites such as Felton and Gatton (QLD) are reported in **Appendix A6.2**.

There were significant differences of PR and MC between permanent traffic lanes and permanent crop beds in CTF sites and wheeled and non-wheeled soil in non-CTF sites for Northern region soil (clay soils) (p-values <0.001) (**Appendix A6.1**). In general, trafficking increased the PR of soils at top surface (**Figure 6.1**). In all cases, PR values showed an increasing trend with soil depths. This is expected because some resistance depends on the weight of soil (overburden) above the depth of measurement (Sands et al. 1979). The highest value observed was on PTL with a mean a 0-150 mm cone index of 2.06 MPa. The least value of PR was obtained on PCB with a mean cone index 0.88

MPa (in this depth range). This was consistent with the results of other physical properties such as bulk density and shear force, as presented in **Table 3.3**, and shows a similar trend, due to the presence or absence of farm machinery traffic in CTF traffic lanes and crop beds. These results are in agreement with Qingjie et al. (2009) which indicated that controlled traffic management of agricultural soil was efficient in improving soil physical conditions. McHugh et al. (2009) also observed a reduced bulk density of 1.40 to 1.25 Mg m^{-3} at depth 0-100 mm in the crop bed after 22 months of traffic control implementation following 30 years of conventional management.

Differences in MC between the two PCB and PTL were significant at all depth intervals (**Figure 6.1**). At the surface, MC values in PTL were higher than MC in PCB, but the opposite pattern occurred in both PTL and PCB at greater depths. The average value for MC in PCB was (25% $w.w^{-1}$) higher than that of PTL (24% $w.w^{-1}$). These findings indicate that PCB stored more soil water (compared with PTL and non-CTF) in the absence of wheel traffic. This observation is also confirmed by results obtained for other soil parameters such as bulk density, shear force and PR (**Table 3.3**). The compacted soil represented by PTL resulted in higher bulk density and PR, and reduced porosity.

Permanent Crop Beds (PCB) represents un-trafficked soil, and the literature suggests that most soils maintain a healthier structure in the absence of traffic (Meek et al. 1988, 1989; Carter et al. 1991). Hussein et al (2017; 2018) found greater water storage in soil of CTF than a non-CTF treatment due to changes in infiltration and hydraulic conductivity, attributed to smaller pores and fewer natural channels in trafficked soils. These observations also agree with studies on clay soil (black Vertisols) dealing with functional relationships between traffic compaction, runoff generation, and traffic effects on soil structure (e.g. Li et al. 2007, 2009).

Therefore, the changes in PR and other soil physical properties due to compaction will be proportionally greater in PTL than in PCB. The changes in PR among sites can be explained in terms of traffic, soil texture and moisture content. The changes were calculated by the difference of PR (at depth 0-150 mm) between the wheeled soil and non-wheeled soil and divided by the PR in non-wheeled soil. In clay soils (Northern region sites) at depth 0-150 mm under CTF no-tillage system, the PR value of the Pittsworth wheel track was greater than that of the crop beds by a factor >2.5 times.

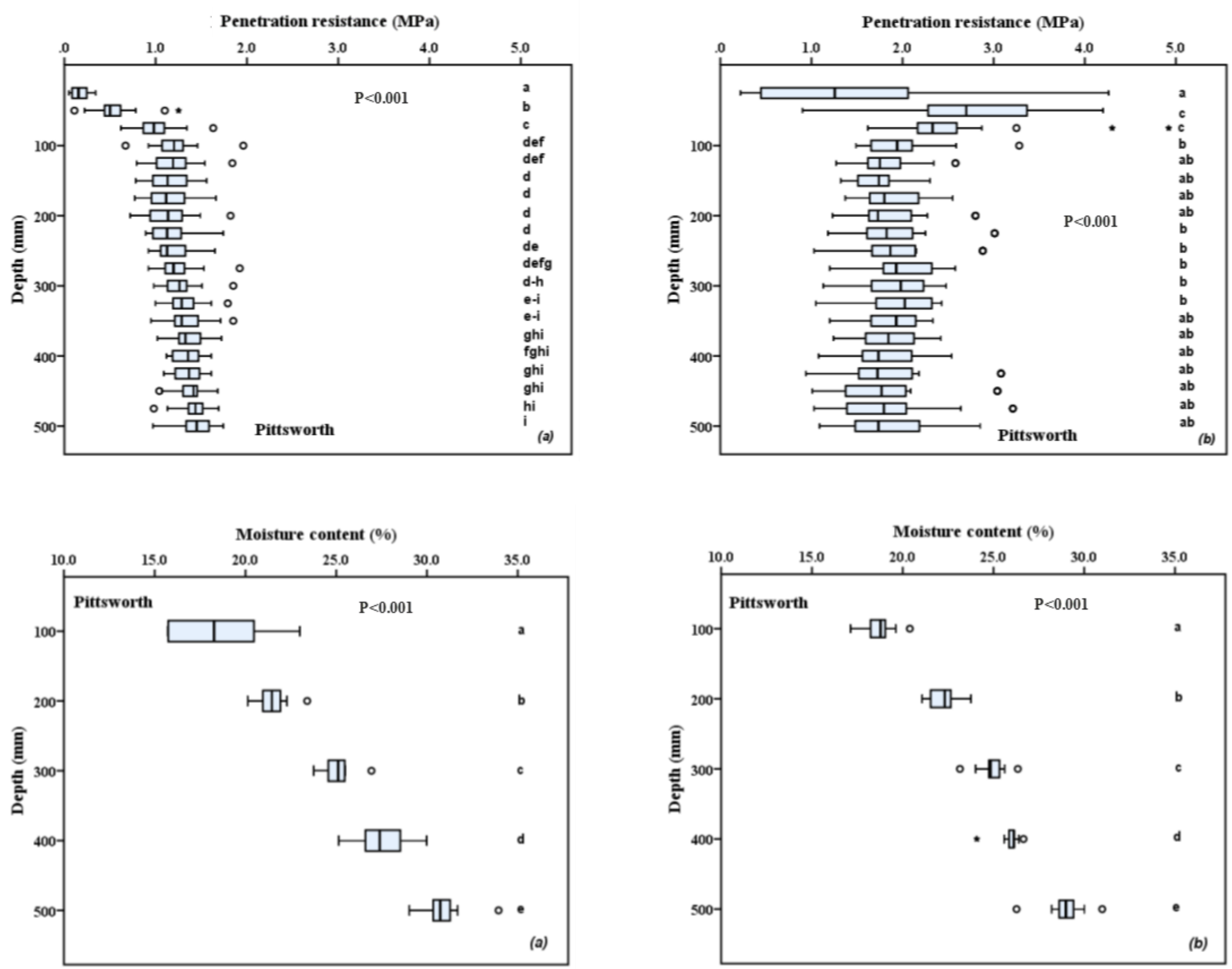


Figure 6.1: Penetration resistance and moisture content of soil as a function of depth (n=20), (n=10), respectively. Box plots show: Min, Q1, Med, Q3 and Max. P < 0.001. The symbols (○) and (*) denote mild and extreme outliers, respectively. Different letters indicate that mean values are significantly different at a 95% confidence interval. Figures show: (a) PCB and (b) PTL; PR (top) and MC (bottom) for Pittsworth (QLD) site

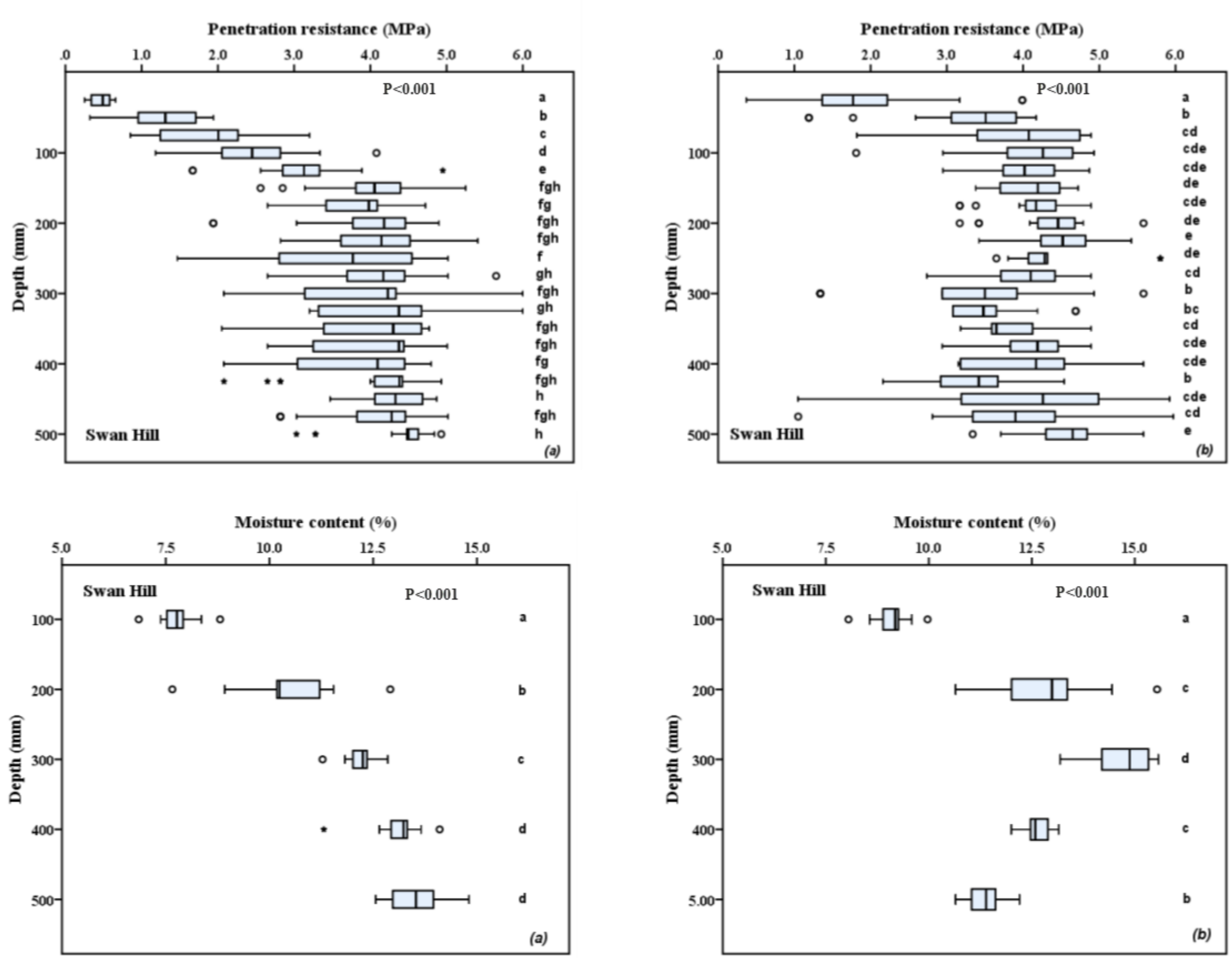


Figure 6.2: Penetration resistance and moisture content of soil as a function of depth (n=20), (n=10), respectively. Box plots show: Min, Q1, Med, Q3 and Max. P < 0.001. The symbols (○) and (*) denote mild and extreme outliers, respectively. Different letters indicate that mean values are significantly different at a 95% confidence interval. Figures show: (a) PCB and (b) PTL; PR (top) and MC (bottom) for Swan Hill (VIC) site

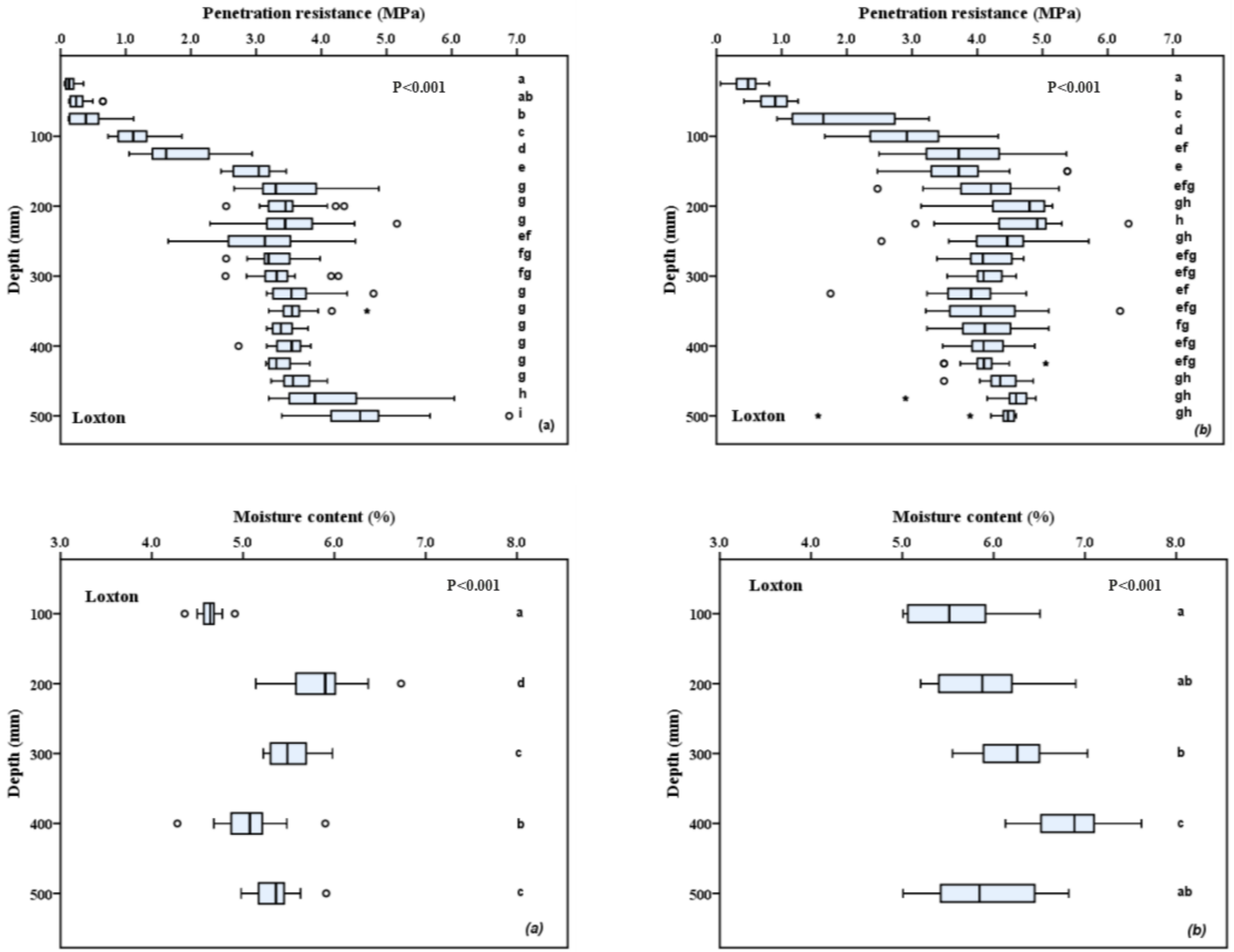


Figure 6.3: Penetration resistance and moisture content of soil as a function of depth (n=20), (n=10), respectively. Box plots show: Min, Q1, Med, Q3 and Max. P < 0.001. The symbols (○) and (*) denote mild and extreme outliers, respectively. Different letters indicate that mean values are significantly different at a 95% confidence interval. Figures show: (a) PCB and (b) PTL; PR (top) and MC (bottom) for Loxton (SA) site

However, in the conventionally tilled soil at Gatton, without CTF, a single wheeling increased PR by a factor >4 times. This probably reflects the weaker structure of the tilled soil, because tillage and agronomic management are important to soil structure, as demonstrated by number of researchers (e.g. Somasundaram et al. 2017).

6.3.1.2 Southern region sites

As mentioned earlier, soils in Southern region (Victoria and South Australia) sites are medium-textured and light soils. Accordingly, the results of PR and MC of soil are presented in two groups. The PR and MC of soils in PTL and PCB at the Swan Hill (VIC) site are presented in **Figure 6.2**. The results obtained for measurements of PR and MC are shown in **Figures 6.3** for PTL and PCB at the Loxton (SA) site. However, the results of PR and MC for rest of sites such as Hopetoun (VIC) and Waikerie (SA) are reported in **Appendix A6.2**.

In general, the results of PR show a similar pattern to that presented for the Northern region CTF sites. The statistical analyses of PR and MC of soil indicated that traffic type, depth and interaction between the factors produce a significant effect (p-values <0.001) (**Appendix A6.1**). However, MC values were lower in the Southern region sites (medium and light-textured soils) than the Northern region sites (clay soils) at both permanent crop beds and permanent traffic lanes in particular, reflecting the role of clay particles in holding more moisture than sand and silt (Martin 1962; Hillel 1980).

In medium-textured soils (Victorian sites) at depth 0-150 mm under CTF no-tillage, the results showed that wheel traffic had a greater effect on PR at Swan Hill (72%), than in the incomplete CTF system at Hopetoun (57%), where occasional wheel traffic had affected the beds. Similarly, in the lighter soils the effects of traffic on PR were much greater at the CTF Loxton site (2 times) than at the non-CTF Waikerie site (70 %).

These results demonstrate that controlled traffic with no-tillage has the potential to improve the selected soil physical properties in permanent crop beds for CTF sites. Effects include reduced bulk density and PR, and increased water storage with greater infiltration and hydraulic conductivity. These factors should not only improve the environment for crop production but also help protect the soil structure from risk of runoff and erosion.

Controlled traffic farming involves the restriction of all wheels to permanent traffic lanes, so compaction in permanent traffic lines is increased, while compaction in traffic lanes improves trafficability and increases tractive efficiency (e.g. Kingwell & Fuchsbichler 2011; Botta et al. 2012). This is beneficial to agricultural activity, improving soil conditions in PCB, which enables reductions in draught force requirements for soil-engaging implements. This is consistent with results of draught force requirements explained in **Chapter 4**. In addition, it is also improving soil conditions in PTL for machinery traffic which will reduce the motion resistance of equipment (explored it in the following section).

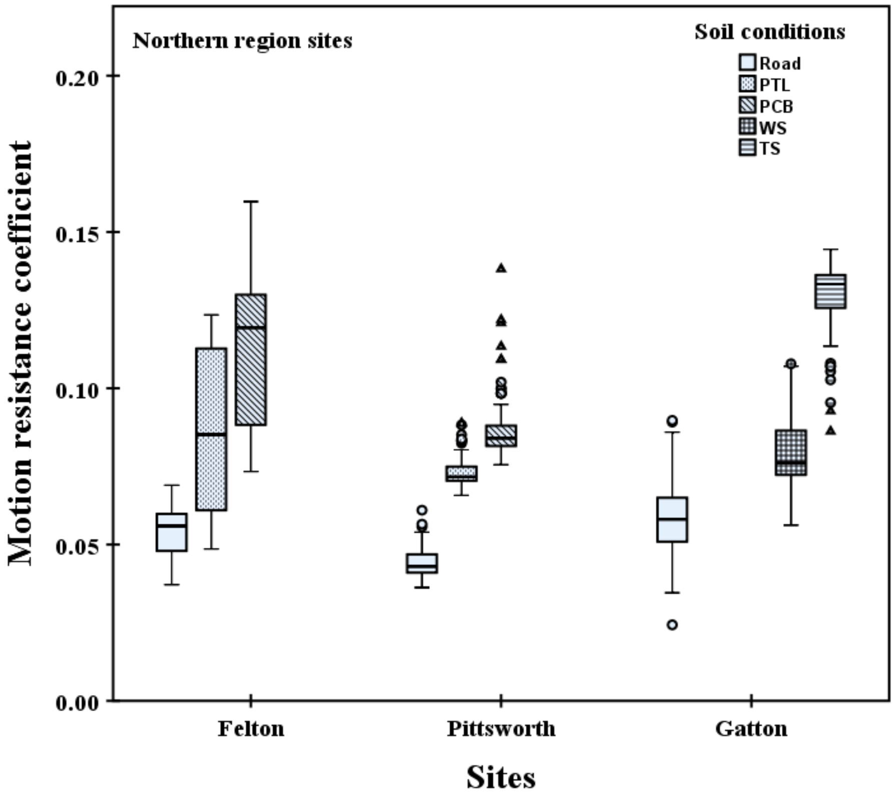
6.3.2. Motion resistance in field

This study's motion resistance measurement methods were discussed in **Chapter 3** and the results of the field measurements of motion resistance for each region are presented separately.

6.3.2.1 Northern region sites

The coefficient of motion resistance (CMR) of tractors at ground speed on road, PTL and PCB in CTF sites, and wheeled soil (WS) and non-wheeled soil (tilled soil (TS)) in non-CTF sites are presented in **Figure 6.4**. The statistical analysis of the results reported in **Appendix A6.3,** demonstrate significant effects of surface traffic and ground speed on the CMR of tractor (p-values <0.001). However, there was a non-significant effect of the interaction between condition and ground speed (p=0.856, 0.522 and 0.114) for Felton, Pittsworth and Gatton sites, respectively.

The average results of motion resistance (MR) of tractors in **Figure 6.4** for Northern region sites are reported in **Appendix A6.4**. At the Pittsworth site, for example, the average motion resistance coefficient of the tractor on road, PTL and PCB was 0.04, 0.07 and 0.09, respectively. The rest of the results show a similar pattern.



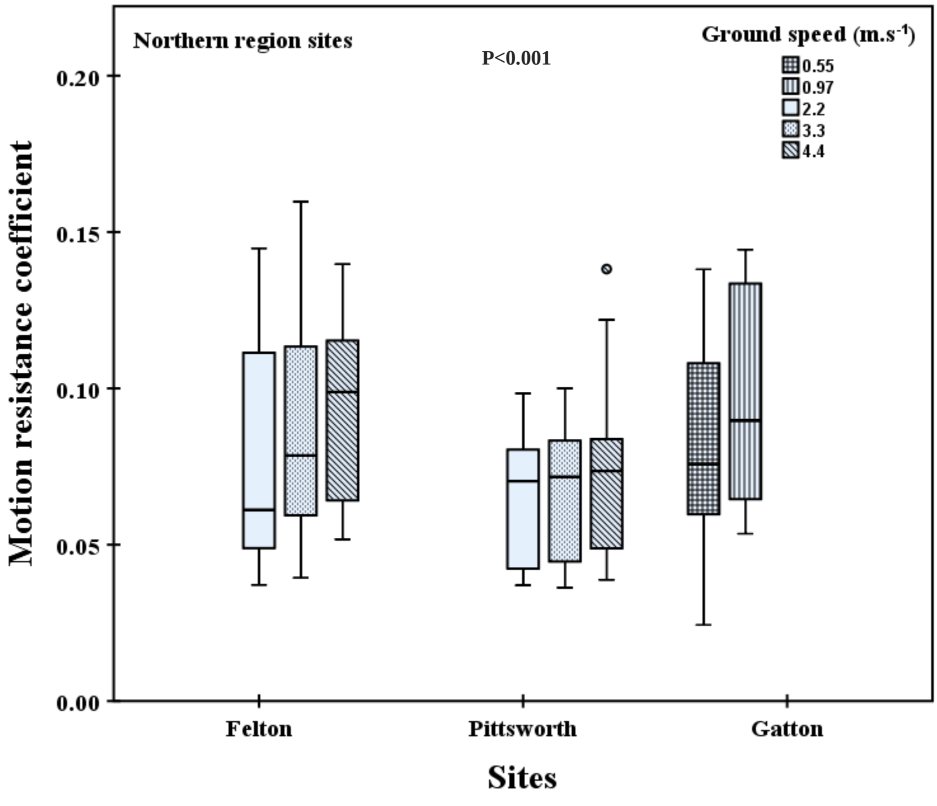


Figure 6.4: The effect of wheel traffic and ground speed on coefficient of motion resistance of tractors for Northern region sites. Box plots show: Min, Q1, Med, Q3 and Max (n=30). P < 0.001. The symbols (○) and (▲) denote mild and extreme outliers, respectively. Figures show: soil conditions (top) and Ground speed (bottom), respectively

MR of tractors on road surfaces (i.e. the internal MR) must be smaller than that on PTL, PCB, WS and TS surfaces (**Appendix A6.4**). However, it is important to demonstrate that MR was less on PTL and WS than PCB and TS for all ground speeds. This coincides with the results of Chen and Yang (2015) who found that MR was closely linked to topsoil compaction and greater soil strength due to wheel traffic resulting in lower motion resistance in one of Chinese CTF farms. This is consistent with the results of PR and other soil properties, which were explained earlier in this chapter and in **Chapter 3**. The highest MR values on PCB soil and TS would have been due to the relatively soft surface soil resulting in higher deformation in the soil tyre interface (**Appendix A6.7**), leading to higher MR because the amount of soil in front of the tyre increased along the run (Wood & Burt 1987; Botta et al. 2012).

Figure 6.4, also shows that increasing ground speed resulted in a significant increase in CMR, which was observed for all conditions tested. It is important to note that the motion resistance increase with ground speed (from 2.2 to 4.4 m.s^{-1}) on PCB (typically 13-16%) was greater than that on PTL surfaces (typically 8-14%). This was not in close agreement particularly on softer surfaces, with the results of Zoz and Grisso (2003) demonstrating the relatively small effect of ground speed on motion resistance. However, the finding was confirmed by results obtained in regression analyse in the current study.

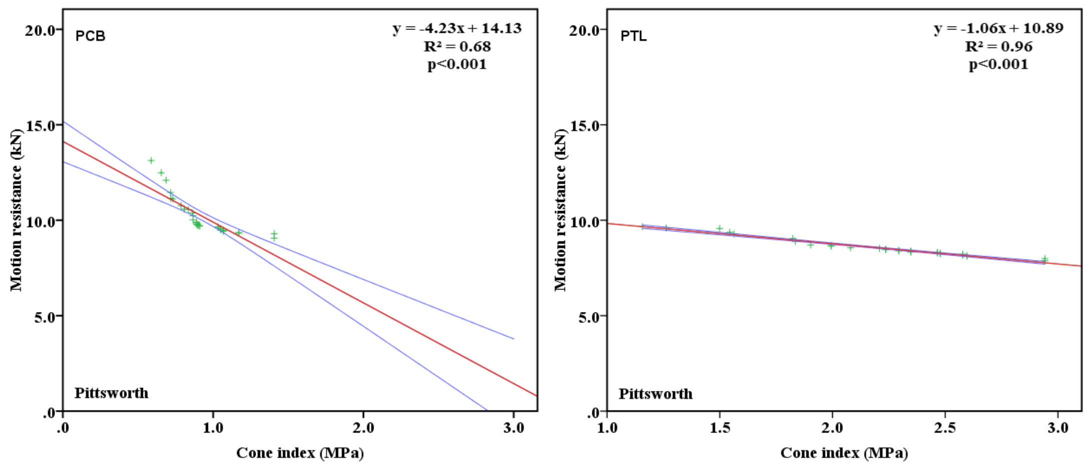


Figure 6.5: Linear regression analyses – relationships between motion resistance and cone index for depth (0-150 mm) for Pittsworth site. The red line is the relationship between motion resistance and cone index. Blue lines show the 95% confidence interval for the linear model fitted to the data. Figures show: PCB soil (left) and PTL soil (right) respectively

The finding highlight that MR is related to soil strength (CI). Thus, **Figure 6.5** illustrates the results of the regression analyses which investigated the relationship between motion resistance and cone index for depth (0-150 mm) for the Pittsworth site. The results showed that the correlation between motion resistance and cone index was significant for **Northern region** sites (p-values <0.001). In general, the R^2 values encountered, indicated acceptable fits for the linear models (≥0.68) (**Appendix A.6.5**).

The results of the regression analyses for the remaining sites, such as Felton and Gatton, are reported in **Appendix A.6.6**. The motion resistance data obtained from all sites generally permit the use of linear functions to describe the relationship with the cone index. This observation is in close agreement with those made by Botta et al. (2012) who indicated that cone index for depth (0-150 mm) in three different soil conditions (ploughed soil, seedbed soil, and direct sowing) had a strong positive relationship to motion resistance in all circumstances, and that the relationship is typically linear and best explained by linear function.

The slope of the regression line decreased with increasing CI, but at lower CI the slope of the regression line was greater than the higher CI. This could be related to the interaction between CI and ground speed. The motion resistance was slightly increased on PTL when the ground speed was increased. However, on PCB, the motion resistance was dramatically increased with increasing ground speed. Increasing ground speed on soft soil lead to increased plastic deformation of soil under tyre (sinkage) (**Appendix A6.7**) (Liu et al. 2010), and increased motion resistance. The observation is in good agreement with some of the previous works on the subject (e.g. Botta et al. 2012).

It is important to highlight that the reduction in motion resistance was calculated based on the results of motion resistance which are reported in **Appendix A6.4**. The reduction in motion resistance due to deformation of the soil under the tyre or belt track was estimated by subtracting the motion resistance on the road surface from that on the field surfaces (PTL and PCB at CTF sites), and (wheeled soil and non-wheeled soil at non-CTF sites). This was to quantify the change in motion resistance produced by deformation of the soil under the tyre or belt track, rather than that being attributable to friction within the drivetrain and deformation of the tyre itself. This might also be reflected in soil compaction (degradation). However, reduction in gross motion resistance was calculated based on the motion resistance on the field surfaces of PTL and PCB at CTF sites, and wheeled soil and non-wheeled soil at non-CTF sites. This was to quantify the impact of wheel traffic on gross motion resistance reduction which is related to the impact of agricultural system applications such as CTF on fuel use.

The effect of PTL and wheeled soil on percentage reductions of motion resistance was calculated. The motion resistance reductions due to PTL in CTF sites and wheeled soil in non-CTF sites are shown in **Table 6.1**. From this, it is apparent that CTF with no-tillage reduced the energy input to soil by an average of 32% and 44 % in clay soil under a no-tillage system at Pittsworth and Felton, respectively (motion resistances were 5.14, 8.58 and 10.21 kN at the Pittsworth site, and 5.81, 9.22 and 11.92 at the Felton site, for road, PTL and PCB, respectively) compared with NT under non-CTF system. This difference could be related to the soil moisture content which was higher at the Felton site compared with the other sites (**Appendix A6.2**), leading to reduced soil strength (PR) and increased plastic deformation of soil under the tyre (sinkage), and increased motion resistance (Ayers & Perumpral 1982; Senatore & Sandu 2011). The observation is in agreement with some of the previous works on the subject.

Table 6.1: Reduction in motion resistance as a result of wheel traffic at range of ground speed for Northern region sites

	Reduction in motion resistance (%)				
	Ground speed (m.s^{-1})	**2.2**	**3.3**	**4.4**	**Mean**
	Gross	23.49	19.85	24.46	**22.65**
Felton	**SD**	± **9.9**	± **7.5**	± **11.7**	± **9.3**
	External	42.79	39.69	49.61	**44.19**
	SD	± **23**	± **16**	± **26**	± **23**
	Ground speed (m.s^{-1})	**2.2**	**3.3**	**4.4**	**Mean**
	Gross	15.88	14.43	17.73	**15.96**
Pittsworth	**SD**	± **2.8**	± **1.9**	± **6.7**	± **3.2**
	External	31.38	29.08	36.24	**32.15**
	SD	± **7**	± **4**	± **10**	± **8**
	Ground speed (m.s^{-1})	**0.55**	**0.97**	**-**	**Mean**
	Gross	27.62	25.36	-	**26.37**
Gatton	**SD**	± **2.6**	± **9**	**-**	± **3.8**
	External	52.34	48.24	**-**	**50.14**
	SD	± **12**	± **10**	**-**	± **11**

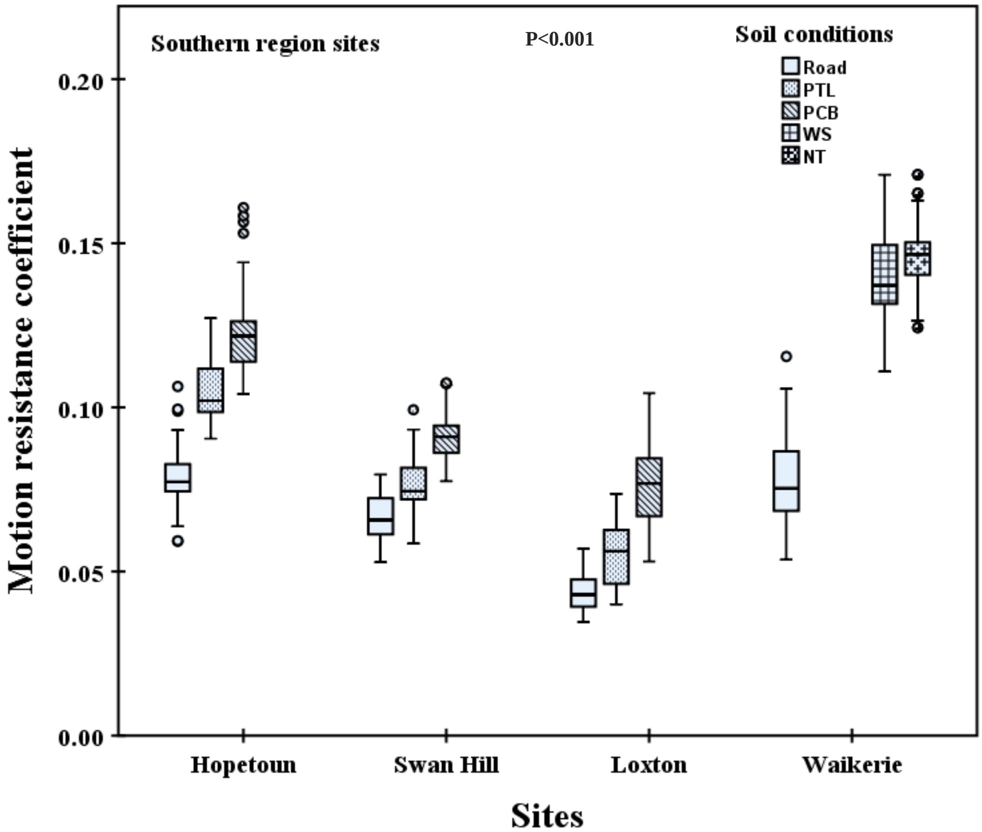
However, in the conventional tillage systems at the Gatton site, the reduction in energy input to soil as result of wheel traffic was on average 50% (3.2, 4.97 and 6.75 kN for road, WS and TS, respectively) compared with non-wheeled soil. It is clear that the Gatton site showed higher energy saving than the other Northern region sites. This is consistent with PR results where the changes in cone index at 0-150 depth as result of traffic, was 4 times higher at the Gatton site compared with the other sites. This occurred because non-wheeled soil at the Gatton site was tilled, leading to greater plastic deformation of soil under the tyre (sinkage) (**Appendix A6.7**). This is in agreement with other findings, which stated that MR is in relation to CI (Botta et al. 2012).

Meanwhile, as demonstrated in **Table 6.1**, CTF with NT decreased the energy input to soil at Pittsworth and Felton. Previous wheeling in CT at the Gatton site reduced the energy input to soil. This term is also directly reflected to fuel saving as a result of wheel traffic. In this regard, CTF can save fuel use based on the deformation of soil under the tyre on average 16%-23% in clay soil under NT at Pittsworth and Felton, respectively, compared with NT in the non-CTF system. However, in CT at the Gatton site, the wheeled soil saved on average 26% of energy compared with non-wheeled soil. It is important to highlight that fuel saving was calculated based only on the total motion resistance on both PTL and PCB in CTF sites and wheeled soil and non-wheeled soil in non-CTF sites.

The data of **Table 6.1** also demonstrates that avoiding wheel traffic effects in both conventional tillage systems and no-tillage systems can reduce energy inputs to soil compaction and degradation. In CT (conventional tillage) the energy saving was higher than in NT, because the weakly aggregated structure of tilled soil is more susceptible to compaction. In no-tillage systems, soil structure is improved in the absence of disturbance, and the additional soil strength can be seen in the cone index value. Therefore, no-tillage and its associated agronomic measures play an important role in reducing compaction effects as indicated by a number of researchers (e.g. Somasundaram et al. 2017).

6.3.2.2 Southern region sites

The results of the motion resistance coefficient for Southern region sites are presented in **Figure 6.6,** and the corresponding mean tractor motion resistance results are reported in **Appendix A6.4**. The statistical analysis has shown that for Southern region sites, the effects of soil condition, ground speed and the interaction between the two parameters were significant at most sites (p-values >0.001), except for Swan Hill (VIC) where p-value > 0.005 for interactions between the two parameters. At the non-CTF **Waikerie** (SA) site, the interactions were statistically insignificant, as were wheeling effects on the motion resistance coefficient (p=0.216). The statistical analysis of these results are reported in **Appendix A6.3**.



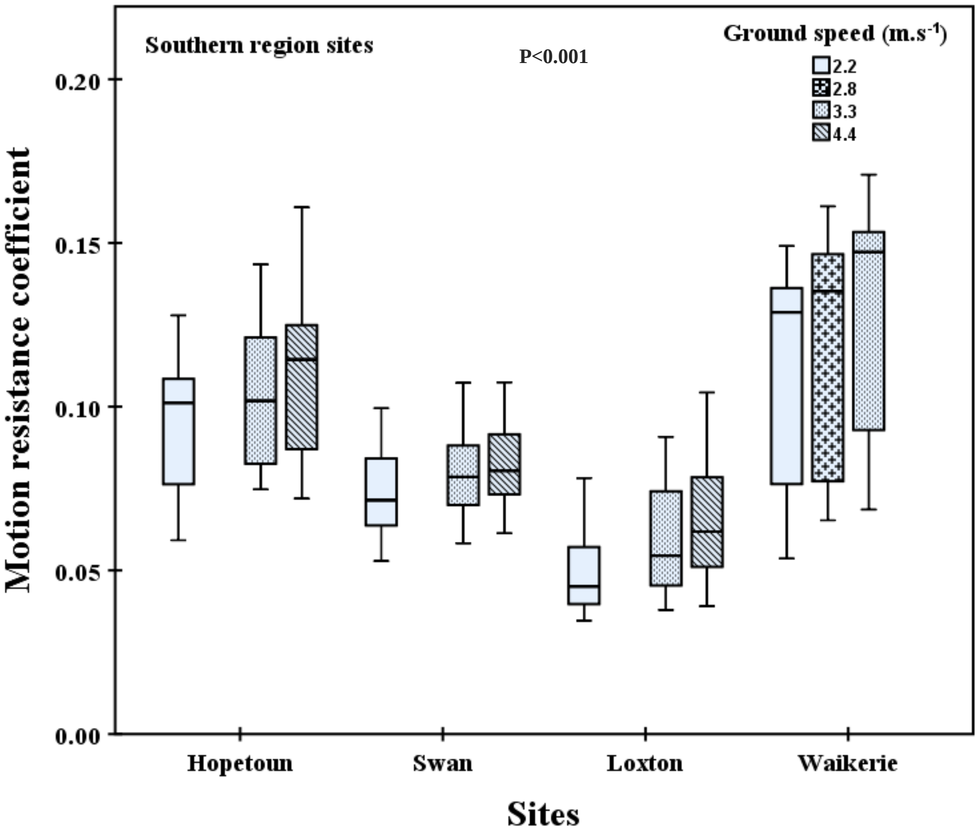


Figure 6.6: The effect of wheel traffic and ground speed on coefficient of motion resistance of tractors for Southern region sites. Box plots show: Min, Q1, Med, Q3 and Max (n=30). P < 0.001. The symbols (○) denote mild outliers. Figures show: soil conditions (top) and Ground speed (bottom), respectively

Generally, the data obtained for motion resistance at Southern region sites, whether in Victoria or South Australia, showed a similar pattern to that presented for Northern region sites. Overall, motion resistance on PTL and WS were significantly lower than PCB at CTF and NT at non-CTF for all ground speed at Southern region sites. These results of CMR were on average (0.10 and 0.12); (0.07 and 0.08); and (0.06 and 0.07) for PTL and PCB at Hopetoun, Swan Hill and Loxton sites, respectively. But on non-CTF sites the results were on average 0.14 and 0.15 for WS and NT at Waikerie site, respectively.

It is interesting to note that motion resistance dramatically increased (typically 18-35%) as the ground speed increased from 2.2 to 4.4 m.s^{-1} in PCB. Whereas, in PTL, motion resistance was slightly increased (typically 9-15%) with increased ground speed for most CTF sites. This finding showed a similar pattern to that presented for Northern region sites. However, at non-CTF such as the Waikerie site, motion resistance increased slightly (13% and15%) in both non-wheeled soil (NT) and WS, respectively. This was because the CI value of the Loxton wheel track was greater than that of the crop beds by a factor ≤ 2 times, but in the NT soil at Waikerie, without CTF, a single wheeling increased motion resistance by 74% compared with non-wheeled soil.

This finding is also confirmed by the results of the regression analyses for Southern region sites. They showed that the changes in motion resistance are related to CI. The regression analyses indicated a significant relationships (p-values <0.001) between cone index for depth (0-150 mm) and motion resistance for the Southern region sites. The results of regression showed a similar trend in the relationship between cone index and motion resistance. **Figure 6.7** shows that motion resistance on PTL was slightly affected, while motion resistance on PCB was dramatically affected.

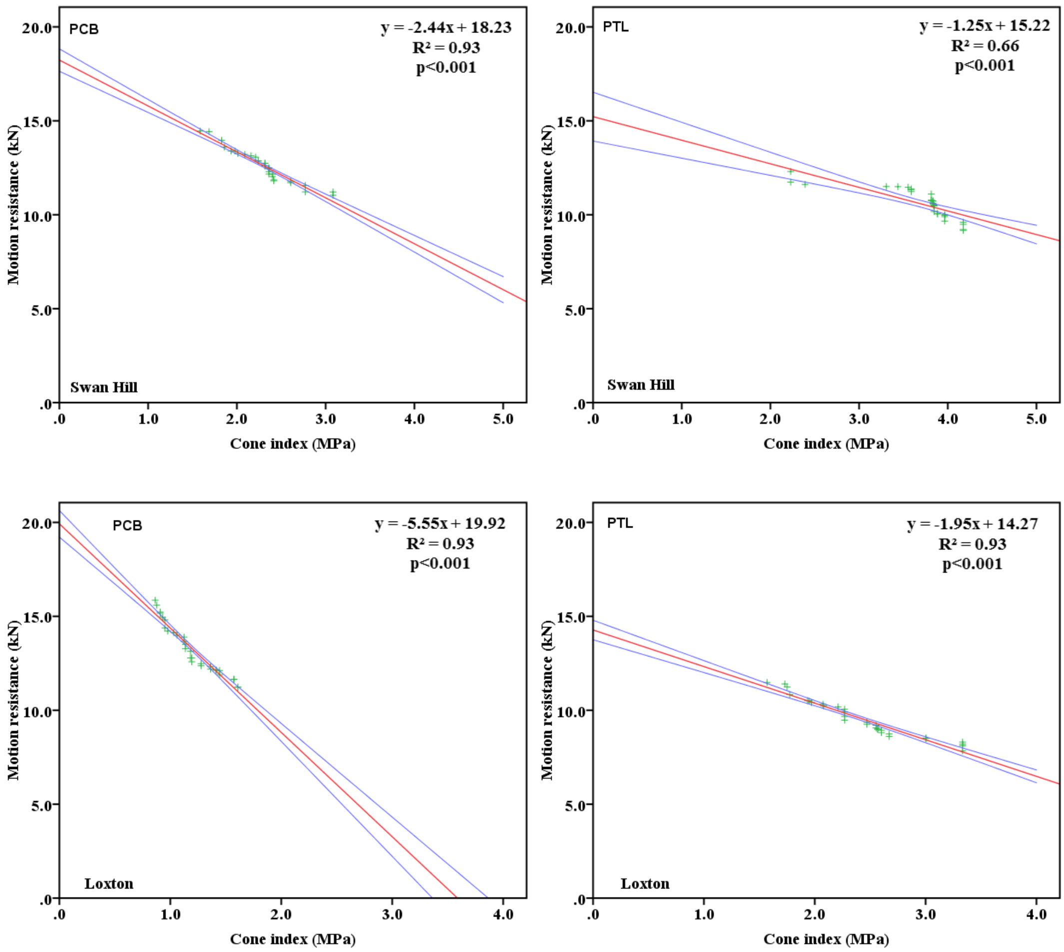


Figure 6.7: Linear regression analyses – relationships between motion resistance and cone index for depth (0-150 mm). The red line is the relationship between motion resistance and cone index. Blue lines show the 95% confidence interval for the linear model fitted to the data. Figures show: PCB soil (left) and PTL soil (right) for Swan Hill (VIC) (top) and Loxton (SA) (bottom), respectively

It important to note that the results of regression reported in **Figure 6.7** are for the Swan Hill (VIC) and Loxton (SA) sites only. The results of regression for sites with compromised controlled traffic Hopetoun (VIC), or random traffic (Waikerie SA) are reported in **Appendix A.6.6**.

Energy savings based on reduction of motion resistance are presented in **Table 6.2**. It can be seen that energy saving in CTF based on soil deformation was 38% and 48% at the Victorian sites (For the Hopetoun and Swan Hill sites, respectively) (For road PTL and PCB, Hopetoun motion resistance was 6.66, 8.95 and 10.39 kN, respectively and Swan Hill motion resistance was 9.24, 10.6 and 11.87 kN, respectively) compared with non-CTF. But, the percentage saving is different for similar soil (medium-textured) at moderate moisture content (**Figure 6.2 and Appendix A6.2**). The reason for the difference between these two sites could be related to soil condition at the Hopetoun site where different track width equipment was used, resulting in a smaller difference between the soil conditions of PTL and PCB, compared with that at Swan Hill.

The data demonstrates that wheel traffic on PTL reduced the energy required to deform the soil, overcome motion resistance and move equipment. This reduction in gross motion resistance should be directly reflected in the fuel saving achieved in CTF by keeping traffic on permanent traffic lanes. This means average fuel saving achieved by CTF in no-tillage systems from the current study could be 11% and 14%, for Swan Hill and Hopetoun sites, respectively, compared with NT under uncontrolled traffic systems.

Table 6.2: Reduction in motion resistance as a results of wheel traffic at range of ground speed for Southern region sites

Site	Reduction in motion resistance (%)				
	Ground speed (m.s^{-1})	**2.2**	**3.3**	**4.4**	**Mean**
	Gross	9.67	15.03	16.49	**13.86**
Hopetoun	**SD**	± **2.06**	± **3.32**	± **4.82**	± **2.34**
	External	27.30	43.09	44.07	**38.61**
	SD	± **4**	± **9**	± **12**	± **12**
	Ground speed (m.s^{-1})	**2.2**	**3.3**	**4.4**	**Mean**
	Gross	10.54	9.34	9.89	**10.70**
Swan Hill	**SD**	± **1.91**	± **2.14**	± **2.22**	± **1.08**
	External	46.27	44.90	43.40	**48.29**
	SD	± **16**	± **6**	± **9**	± **17**
	Ground speed (m.s^{-1})	**2.2**	**3.3**	**4.4**	**Mean**
	Gross	19.60	17.59	22.13	**19.91**
Loxton	**SD**	± **2.07**	± **5.13**	± **3.93**	± **0.90**
	External	50.35	47.31	48.67	**48.66**
	SD	± **6**	± **13**	± **10**	± **12**
	Ground speed (m.s^{-1})	**2.2**	**2.8**	**3.3**	**Mean**
	Gross	4.71	4.75	3.08	**4.11**
Waikerie	**SD**	± **2.55**	± **2.96**	± **2.12**	± **2.35**
	External	9.63	9.49	7.22	**8.74**
	SD	± **5**	± **4**	± **3**	± **4**

In the South Australian sites such as Loxton and Waikerie (light soil), the data obtained for energy saving showed a similar trend as that of saving energy savings at the Victorian sites (**Table 6.2**). However, energy saving in CTF based on soil deformation at the Loxton site was much higher at 49% (7.57, 10.26 and 12.81 for road, PTL and PCB, respectively) than non-CTF. At the Waikerie site, the wheeled soil achieved 9% of energy saving (5.02, 9.09 and 9.48 kN for road, wheeled soil and nonwheeled soil, respectively) compared with non-wheeled soil (**Table 6.2**). The same trend was observed for fuel saving in wheeled soil which was 28% and 4% at the Loxton and Waikerie sites, respectively, compared with non-wheeled soil. This is because the Loxton site was under CTF. Thus, the difference in CI between PTL and PCB was high (171%). However, at the Waikerie site, the difference in CI between wheeled soil and non-wheeled soil was less (74%) because all soil was similarly compacted at the non-CTF site. In addition, the weight of the Loxton tractor was 174 kN while at the

Waikerie site it was 65 kN. The inflation pressure was ≤ 196 kPa at the Waikerie site however, at the Loxton site, a belt track tractor was used (**Appendix A3.9**).

It was also shown that wheel traffic can reduce the motion resistance in all studied wheeled soils compared with non-wheeled soil. The findings in this term suggest that, in general, CTF in heavy clay soils can reduce fuel use by approximately 26% in CT systems compared with the same systems under uncontrolled traffic. In NT systems, the fuel saving can be up to 23% compared with NT in non-CTF. However, in medium-textured and light soil under NT systems, CTF can save 14% and 20%, respectively in fuel use compared with the same system under non-CTF.

In addition to the fuel saving, CTF can also reduce the energy input to compaction of wheeled soil (degradation) by similar proportions in both clay and lighter-textured sites. This average reduction was up to 44% in NT system on clays, and up to 48% and 49% on medium-textured and light soils, respectively.

Overall, regression analyses indicated that cone index for depth (0-150 mm) in different soils (heavy clay soil, medium-textured and light soil) at different conditions (TS, WS, PCB, PTL and NT) showed a strong positive relationship to motion resistance in all circumstances, and the relationship is typically linear and best explained by linear function.

6.3.3. Modelling of motion resistance

In this section, validation of motion resistance resulting from the models are verified. The results of the experiments carried out at all soil sites for all tractors have been developed in these models. The resulting values of motion resistance on non-wheeled and wheeled soils for each site have been compared with the values predicted by the Brixius and Gee-Clough models. As shown in the following figures, measured and predicted values of motion resistance have been compared with each other. It is important to acknowledge that the validation of prediction models was done separately for each site because of the different tractors which were used to conduct the experiment at these sites. The results of validation are presented in two groups: Northern region sites, and Southern region sites.

It is important to note that the measurement of the parameters predicting motion resistance were discussed in **Section 3.6.2**. The linear regression of models predicted values against field measures for the motion resistance of tractors is presented in **Appendix A6.7**.

6.3.3.1 Northern region sites

The relationship between measured and predicted motion resistance based on the Brixius and Gee-Clough models at the Pittsworth (QLD) site is presented in **Figure 6.8**. Due to the similarity in trend of results in most cases, the results of the relationship between measured and predicted motion resistance for other sites such as Felton and Gatton (QLD) are reported in **Appendix A6.8**.

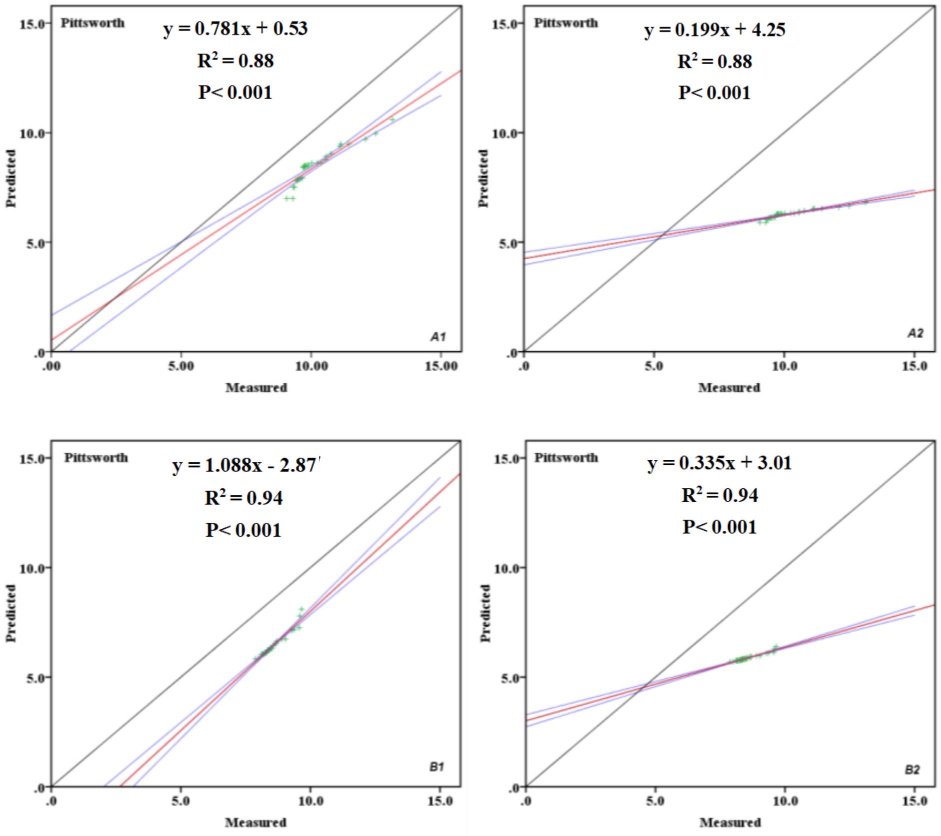


Figure 6.8: Relationship between measured and predicted motion resistance based on Brixius and Gee-Clough models for Pittsworth (QLD) site. The red line is the relationship between measured and predicted values of draught force. Blue lines show the 95% confidence interval for the linear model fitted to the data, and the black line shows the 1:1 relationship between measured and predicted data. Figures show: (top) NT, (bottom) PTL; (left) Brixius model, (right) Gee-Clough model, respectively (n=30)

The results indicate under predictions of motion resistance with both the Brixius model and the Gee-Clough model. However, the percentages of difference between measured and predicted motion resistance were in PTL and NT (31% and 38%) and (25% and 17%) for the Brixius model and the Gee-Clough model, respectively. **Figure 6.8** also shows that prediction of motion resistance in the Brixius model was systematically better than the Gee-Clough model.

However, on TS at the Gatton site, the over-predictions were obtained with both the Brixius and Gee-Clough models (**Table 6.3**). In this regard, it can be seen in the table that the predictions of motion resistance were underestimated when wheel numeric values were greater than 12, while at wheel numeric values less than 12 the over-predictions were obtained. Moreover, the measured motion resistance were 31%, and 38% lower than the predicted values made by the Brixius model and were 25% and 17% lower than the predicted values made by the Gee-Clough model for PTL and NT, respectively. However, for TS at CT site (Gatton), the measured motion resistance were 24% and 25% higher than the predicted values made by the Brixius and Gee-Clough models, respectively.

Table 6.3: Comparison of measured and predicted motion resistance using Gee-Clough and Brixius models at various soil conditions for Northern region sites

Site	Soil conditions	Wheel numeric	Measured (kN)	Predicted (kN)		Percentage difference (%)	
		Cn	MR	Brixius	Gee-Clough	Brixius	Gee-Clough
Felton	PTL	51	9.22	7.56	6.10	22	29
	SD	**± 9**	**± 2.68**	**± 0.31**	**± 0.8**	**± 13**	**± 20**
	NT	33	11.92	9.33	6.43	21	45
	SD	**± 7**	**± 2.28**	**± 1.1**	**± 0.25**	**± 8**	**± 8**
Pittsworth	PTL	68	8.58	6.46	5.89	25	31
	SD	**± 15**	**± 0.59**	**± 0.53**	**± 0.16**	**± 2**	**± 2**
	NT	34	10.21	8.51	6.29	17	38
	SD	**± 7**	**± 1.21**	**± 0.82**	**± 0.21**	**± 3**	**± 4**
Gatton	WS	64	4.97	3.52	3.13	29	32
	SD	**± 4**	**± 0.50**	**± 0.06**	**± 0.02**	**± 4**	**± 5**
	TS	12	6.75	8.47	5.11	24	25
	SD	**± 4**	**± 0.48**	**± 1.92**	**± 0.70**	**± 23**	**± 7**

6.3.3.2 Southern region sites

Due to the similarity in trend of results for most cases at Southern region sites, the result of the relationship between measured and predicted motion resistance in Swan

Hill (VIC) site is presented in **Figure 6.9**. The rest of the site results are reported in **Appendix A6.8**. The results show a similar pattern to that presented for Northern region sites. The predictions of motion resistance were underestimated with both the Brixius and Gee-Clough models. **Table 6.4** summarises the predicted motion resistance and the percentages of difference between the measured and predicted motion resistance for Southern region sites.

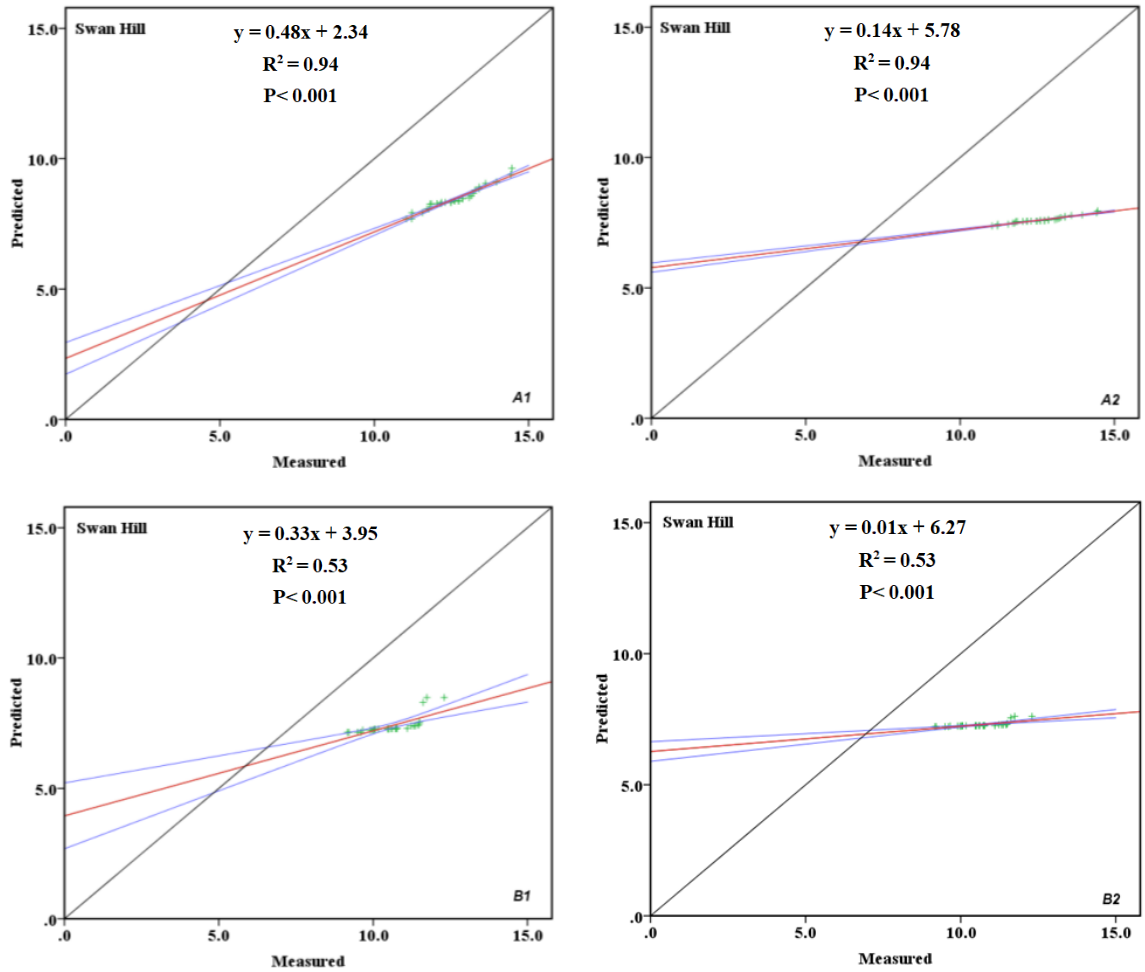


Figure 6.9: Relationship between measured and predicted motion resistance based on Brixius and Gee-Clough models for Swan Hill (VIC) site. The red line is the relationship between measured and predicted values of draught force. Blue lines show the 95% confidence interval for the linear model fitted to the data, and the black line shows the 1:1 relationship between measured and predicted data. Figures show: (top) NT, (bottom) PTL; (left) Brixius model, (right) Gee-Clough model, respectively (n=30)

Table 6.4: Comparison of measured and predicted motion resistance using Gee-Clough and Brixius models at various soil conditions for Southern region sites

Site	Soil conditions	Wheel numeric	Measured (kN)	Predicted (kN)		Percentage difference (%)	
		Cn	MR	Brixius	Gee-Clough	Brixius	Gee-Clough
Hopetoun	PTL	144	8.95	4.32	4.43	43	50
	SD	± 33	± 0.8	± 0.15	± 0.8	± 2	± 3
	NT	81	10.39	5.06	4.66	51	55
	SD	± 24	± 0.99	± 0.54	± 0.25	± 2	± 1
Swan Hill	PTL	104	10.6	8.81	8.19	17	22
	SD	± 18	± 1.16	± 0.35	± 0.10	± 4	± 5
	NT	65	11.87	9.76	8.5	22	32
	SD	± 12	± 0.97	± 0.44	± 0.13	± 2	± 4
Waikerie	WS	32	9.09	6.84	4.97	25	45
	SD	± 6	± 0.86	± 1.12	± 0.47	± 8	± 3
	NT	27	9.48	7.84	5.39	17	43
	SD	± 7	± 0.68	± 1.53	± 0.65	± 12	± 4

Finally, the prediction of motion resistance was underestimated for NT, WS and PTL in all soils (clay, medium and light-textured soils) with both the Brixius and Gee-Clough models. However, at TS in clay soil the over-predictions were obtained with both models. The large discrepancies in these predicted values could be due to the quantitative difference in the tyre dimension characteristics that include the b/d ratio, and δ/h ratio and tyre lug. The tyre dimension characteristics and others were reported in **Table 3.8**. These findings are in close agreement with Elwaleed et al. (2006b, 2006a). Furthermore, in our study the measurements of motion resistance were conducted in a real farm environment (uncontrolled soil conditions), in contrast with Brixius and Gee-Clough which was conducted under controlled soil bin conditions. Therefore, there is a difficulty in controlling the soil properties at the open field, thus the variation of soil properties in our study was high. This shows that both models predicted the motion resistance with a range of error which was acceptable for the uncontrolled soil conditions. This findings are in good agreement with Tiwari et al. (2010).

6.4. Conclusions

The main conclusions coming from **Chapter 6** are:

- The assessment of the field experiments, indicates that:
  - ❖ Control of agricultural traffic was effective in enhancing soil physical and mechanical properties for both PTL and PCB. In Northern region sites (clay soils) under a CTF no-tillage system, the PR value of the Pittsworth wheel track was greater than that of the crop beds by a factor >1.5 times, but in CT at the tilled soil of Gatton, without CTF, a single wheeling increased PR by a factor >4 times (2.14 vs. 0.42 MPa for wheeled soil and non-wheeled soil, respectively) compared with non-wheeled soil. But at Southern region sites (sand soils), in Waikerie site under no-tillage (non-CTF), the results showed that wheel traffic caused changes in PR 21% (0.98 vs. 0.81 MPa for wheeled soil and non-wheeled soil, respectively), relative to PR obtained in non-wheeled soil
  - ❖ As a result of improving soil physical conditions, the energy requirements of cropping was reduced in CTF systems compare with non-CTF systems. The reductions in gross motion in CTF sites were up to 20% and 23% for sandy and clay soils, respectively (motion resistance was ≈ 10.26 versus 12.81kN for sandy soil and 9.22 versus 11.92 for clay soil on PTL and PCB, respectively), compared with non-CTF. This should be reflected in fuel use
  - ❖ The reduction in external motion resistance as a result of PTL was up to 44% and 49% in clay and sandy soils, respectively (motion resistance was ≈ 5.81, 9.22 and 11.92 kN for clay soil, and 7.57, 10.26 and 12.81kN for sandy soil on road, PTL and PCB, respectively). This also reflects the reduction in energy input to soil compaction (degradation) as a result of random traffic
  - ❖ This reduction in motion resistance will also increase paddock accessibility in marginal moisture conditions which will have a positive impact on timeliness, especially when zero-tillage is practised (demonstrated in **Chapter 7**)

- Motion resistance modelling indicates that:
  - The Gee-Clough motion resistance model is not applicable to all studied soil conditions
  - MR increased exponentially with decreasing C_n
  - The Brixius model showed good predictions in most cases when compared with the Gee-Clough model.

Accordingly, the Brixius motion resistance model will be used to predict the mobility number, which is an indicator of the CTF effect on timeliness (demonstrated in **Chapter 7**).

CHAPTER 7

TIMELINESS

7. TIMELINESS

7.1. Introduction

The effects of wheel traffic on soil physical properties were previously discussed. These soil effects can have direct and indirect effects on agricultural operational performance. The direct effects are associated with the energy requirements of cropping which include draught force of soil engaging implements and motion resistance. These have been discussed in previous chapters. However, the indirect effects are associated with timeliness. This is related to the ability to perform various machinery operations such as planting, spraying and harvest at the optimum time.

In non-CTF systems, random traffic produces compacted soil which requires not only more energy (**Chapter 4**), but also more time to prepare a seedbed, and the quality of the seedbed, once prepared can be affected. This may be indicated in measurements of soil surface roughness (**Chapter 4**), (compacted soil as represent non-CTF) producing large clods in clay soil or creating unfavourable soil surface in medium and light-textured soils. These occurred in sweep and chisel tines which are commonly used in conservation tillage systems. Therefore, additional time to resolve these is required. This may influence the timeliness of subsequent operations.

On other hand, soft soil experiences a reduced soil bearing capacity which provides the worst possible access conditions for paddocks, particularly when they are in a wet condition. This may influence the timeliness of various machinery operations such as planting, spraying and harvesting.

However, CTF systems have isolated cropping areas from wheel traffic. This can result in both soft crop beds and compacted traffic lanes at same time. The compacted lanes provide firm conditions conducive to improve wheeled machinery performance by reducing motion resistance. Firm traffic lanes are conducive to improved timeliness, by allowing operations to continue in soil moisture conditions that may inhibit random machinery traffic (Tullberg 2007). CTF systems can provide also timeliness improvements through all of these avenues (working faster (increased speed and/or increased implement width greater capacity), working longer hours (in the day, in the season or after rain), providing comfort to the drivers by using smoother run along firm wheel tracks that can maintain a healthy body posture of the farmers enabling them to work for a longer time and reducing the number of operations required) (McPhee et al. 1995; McPhee et al. 2015). A number of farmers in Australia also claim that improved timeliness is one of the most important characteristics of CTF, but this aspect has not yet been properly investigated (McPhee 2011). Hence this chapter will focus on timeliness improvements by CTF adaption via a mobility/trafficability indicator. Therefore, the specific objectives of this chapter are:

- To determine the mobility number based on the approach reported in the earlier study by Brixius (1987)
- To determine the effects of CTF versus non-CTF on timeliness in terms of the mobility number on a range of cropping soils.

7.2. Materials and methods

The method used for measuring the selected parameters in this chapter were reported and discussed in relevant sections in **Chapter 3**.

7.2.1. Statistical analysis

Statistical analysis has also been reported in the relevant section in **Chapter 3**.

7.3. Results and discussions

Several parameters are used to determine the trafficability classification. This classification can be used to indicate improvements to timeliness. In this study, the mobility number (N), CMR and CI were used to determine timeliness improvement. The latter two were discussed in a previous chapter. The mobility number is discussed in this chapter. A low mobility number indicates poor trafficability (Saarilahti, 2003). **Table 7.1** shows the effect of various soil conditions on mobility numbers.

The statistical analyses showed that soil condition significantly affects the mobility number for all sites ($p<0.001$) except Waikerie ($p=1$) (**Appendix A7.1**). In the Northern region sites, the highest N was 58 which was achieved by PTL (CTF) at the Pittsworth site, while the lowest was 11 which was obtained by TS (CT; non-CTF) at the Gatton site, but at NT in CTF the value of N was in between these two. In the Southern region sites, the mobility number shows a similar pattern to that of the Northern region sites. The highest N was 107 at PTL (CTF) at the Hopetoun site, whereas the lowest was 15 and 18 at WS and NT in the non-CTF system at the Waikerie site.

Table 7.1: Mobility number based on Brixius model for various soil conditions at Northern and Southern region sites

Region	Site	Soil conditions	Cone index (MPa) at 150 mm CI	Coefficient of motion resistance CMR	Mobility number N
Northern	Felton	PTL	1.58	0.09	37
		SD	± **0.14**	± **0.02**	± **11**
		NT	1.04	0.11	24
		SD	± **0.15**	± **0.02**	± **8**
	Pittsworth	PTL	2.18	0.07	57
		SD	± **0.44**	± **0.005**	± **15**
		NT	0.92	0.09	28
		SD	± **0.19**	± **0.01**	± **6**
	Gatton	WS	2.14	0.08	56
		SD	± **0.11**	± **0.01**	± **4**
		TS	0.42	0.13	11
		SD	± **0.14**	± **0.01**	± **4**
Southern	Hopetoun	PTL	3.4	0.10	107
		SD	± **0.51**	± **0.01**	± **21**
		NT	1.91	0.12	60
		SD	± **0.44**	± **0.01**	± **14**
	Swan Hill	PTL	3.68	0.07	77
		SD	± **0.51**	± **0.01**	± **13**
		NT	2.3	0.08	48
		SD	± **0.35**	± **0.01**	± **9**
	Loxton	PTL	2.44	0.05	-
		SD	± **0.50**	± **0.01**	**-**
		NT	1.20	0.08	-
		SD	± **0.23**	± **0.01**	**-**
	Waikerie	WS	0.98	0.14	18
		SD	± **0.18**	± **0.01**	± **6**
		NT	0.81	0.15	15
		SD	± **0.22**	± **0.01**	± **6**

As can be seen from table, the mobility number increased by increasing the CI and decreasing the CMR. This is also confirmed by the MR results. The compacted soils do provide better support to farm equipment than loose soils (McKyes 1989). This also confirmed by the regression analyses, which shows that the mobility number decreases exponentially with an increase in the motion resistance ratio (**Figure 7.1**). These findings are in close agreement with Gee-Clough (1978a), Crossley et al. (2001), and Elwaleed et al. (2006b) .

It is important to highlight that the summary of regression analysis of the relationships between the motion resistance coefficient and mobility number for all studied sites are reported in **Appendix A7.2**. The advantage of CTF on the motion resistance ratio was pronounced. Therefore, the permanent traffic lanes in CTF systems provide firm conditions conducive to greater tractive efficiency and trafficability improvement by increasing N and reducing MR.

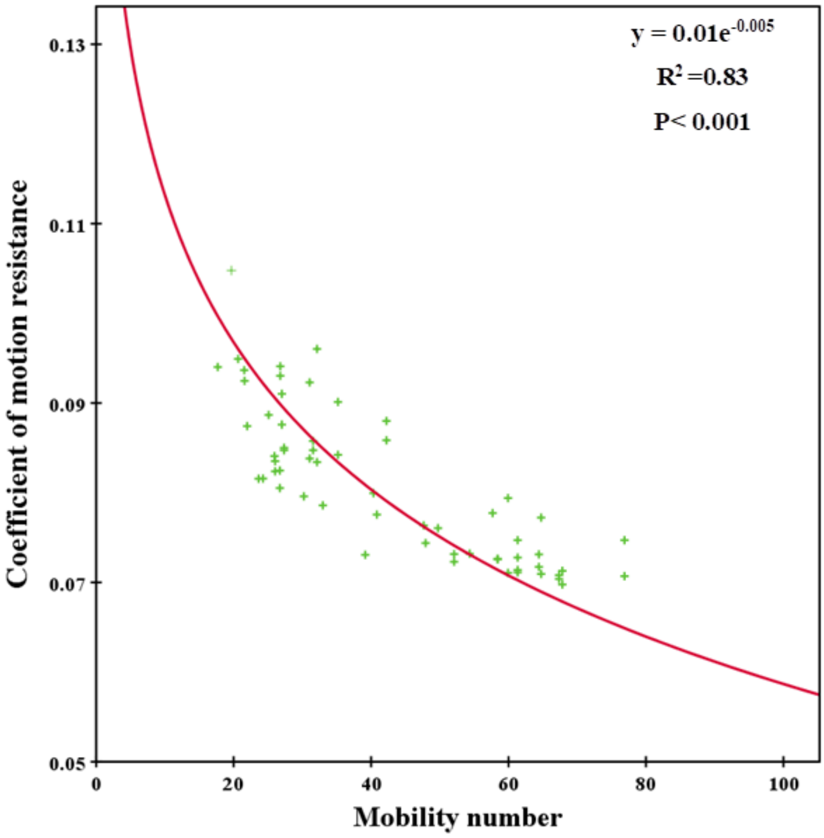


Figure 7.1: Regression analyses – relationships between motion resistance coefficient and mobility number for Pittsworth site in Northern region

It is important to note that during the calculations of the mobility number, an increased mobility number was associated with an increased tyre diameter. Therefore, increasing the diameter of tyres is another solution to improving the mobility of equipment, and reducing the compaction of soil. This finding was also confirmed by Antille et al. (2013, 2016).

The results in table 7.1 show that, PTL in CTF and WS in non-CTF increase the mobility number therefore, CTF can improve trafficability by 80% in CT, and 50% in NT for clay soil. While in medium and light textured soils, CTF can improve trafficability by 38%. These results are confirmed by the results of MR which were reported in the previous chapter.

Controlled traffic farming played an essential role in improving the mobility of equipment hence, the improvement of trafficability. This improvement will allow operations to continue in soil moisture conditions that may restrict the number of workable days in non-CTF. Increased timeliness makes early planting possible, which often results in yield increases. Meanwhile, delay in planting and harvesting usually costs between 0.5% and 2% yield loss for every day lost. Furthermore, the improvement could allow more timely spraying, particularly in no tillage cropping where it is essential (Tullberg 2007). Finally, this increase in the timeliness of operations can provide significant direct yield benefits and many indirect benefits such as improved herbicide weed control particularly in NT systems.

7.4. Conclusions

The main conclusions coming from Chapter 7 are:

- The mobility number increased for all soils tested by increasing the CI and tyre diameter
- Controlled traffic farming improved trafficability by 80% in CT, and 50% in NT for clay soil, while a 38% improvement was experienced in NT for medium and light textured soils.

CHAPTER 8

GENERAL DISCUSSION

8. GENERAL DISCUSSION

8.1. Introduction

This chapter discusses the results reported in previous chapters. These results were obtained from the field experiments and modelling works. It also refers to some elements such as traffic farming systems and their role in reducing energy requirements and improving equipment performance which subsequently improve the timeliness of field works. The purpose of this chapter is to integrate the outcomes of this study in a holistic manner to address the overall aim and objectives of the research. A synthesis of how the chapters relate to the objectives and to each other, as first mentioned in **Chapter 1**, can be found in **Figure 8.1**.

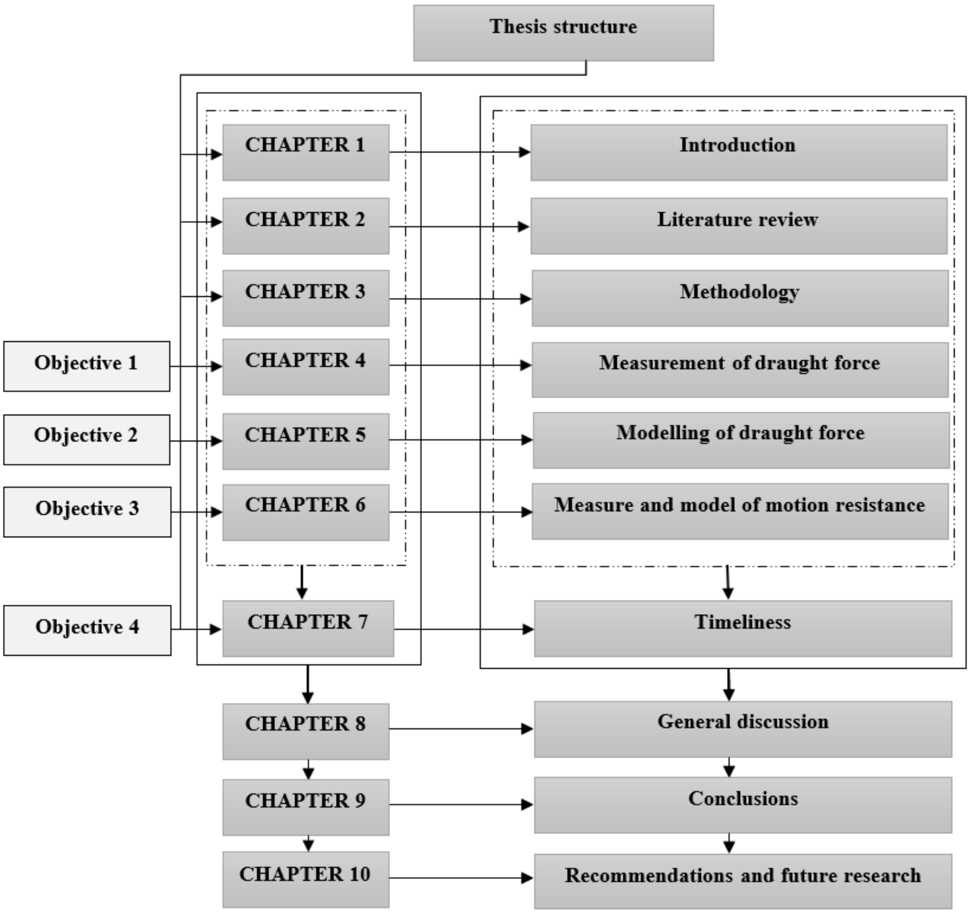


Figure 8.1: Schematic showing the chapters of this study and how they relate to the objectives

8.2. Controlled traffic farming

Extensive traffic causes major problems for agricultural production due to the increased compaction of soil. Soil compaction is one of the major problems facing modern agriculture (Hamza & Anderson 2005). In addition, soil compaction is considered to be a multi-disciplinary problem in which machine, soil and crop interactions play an essential role. It is also seen as a major cause of physical land degradation worldwide, (e.g. Al-Gaadi 2013) and a threat to agricultural productivity.

The controlled traffic farming system provides a number of advantages in terms of increasing yields (Williford 1980; Smith et al. 2014; Hussein et al. 2017, 2018) and reducing production costs relative to non-CTF systems (Tullberg 2007). CTF was used on 22% of Australian grain production area in 2016 (ABS 2017), and adoption is increasing rapidly.

CTF systems are an effective means of managing compaction by isolating cropping zones from the damaging effects of compaction by concentrating traffic in permanent laneways where compaction will improve motion resistance and trafficability. The isolated cropping zones in CTF not only enhance both soil properties and crop productivity, they also reduce the energy requirements of soil engaging implements. These have not been deeply investigated to the extent addressed in this work.

The research reported in this thesis was based upon the need to further quantify the benefits associated with the use of CTF, specifically with regards to the energy requirements of cropping. Therefore, this research determined the effects of controlled and non-controlled traffic of farm machinery on the energy requirements of cropping. This includes determining the effects of wheel traffic on the draught force of soil engaging implements, motion resistance and mobility/timeliness in a range of cropping soils. This was achieved through a combination of field-scale experiments and modelling approaches, as highlighted in the four objectives stated in **Section 1.2.3**. Accordingly, the discussion of study is divided into five main topics, namely:

1. Effect of CTF on soil physical properties
2. Wheel traffic effects on draught force of soil engaging implements
3. Effect of permanent traffic lanes on motion resistance
4. Modelling of energy requirements of cropping
5. Effect of field traffic on mobility/timeliness.

8.2.1. Effect of CTF on soil physical properties

Soil compaction is inevitable, and potentially damaging compaction is unavoidable due to the intensive use of farm machinery in different farm operations (Hamza et al. 2011). The literature and research conducted here, suggest that CTF is an effective approach for managing compaction and soil physical conditions efficient and for improving the efficiency of both plant and equipment. Significant differences in soil physical properties such as PR, MC bulk density and shear strength were observed on PTL compared with PCB. The PTL resulted in higher PR, bulk density and shear strength for all soils, and lower MC particularly in soil with high clay content. However, PR, bulk density, and shear strength were all lower under PCB (zero traffic) for all field experiments.

In this study, soil PR was consistent with soil bulk density and shear strength in all field experiments. This study's MC was chosen based on grower practice in Northern and Southern region sites. The samples of PR were determined at moisture contents ranging from 15-25% 19-28% and 26-39% (w/w) in clay soils for Gatton, Pittsworth and Felton in Northern region sites, respectively. These MC values were generally within the average value of the Optimum Moisture Content for compaction (OMC) (21.4%) based on the Proctor test which was determined by Bennett et al. (2017). The Proctor density value obtained in that work (1.57 Mg m^{-3}) suggests that soil susceptibility to traffic compaction may be highest at moisture contents in the range of 20% to 35% (w/w) in clay soils. Therefore, the risk of soil damage in these sites due to compaction will be proportionally increased when traffic occurs at MC above plastic limit (Kirby 1991; Bennett et al. 2017). Soil penetration resistance increases with decreasing MC (Lipiec, 2002).

In Southern regions sites the samples of PR in PCB were determined at moisture contents ranging from 7-18%, 8-14, 4-6% and 5-7% (w/w) in loam and sandy soils for Hopetoun, Swan Hill Loxton, and Waikerie sites, respectively. The MC values of medium-textured soil were below the range of the OMC (17%) reported by Hillel (1982). The maximum density value was also reported (1.78 Mg.m^{-3}). Rab et al. (2005) suggested that soil susceptibility to traffic compaction may be highest at moisture contents in the range of 17% to 22% (w/w) in medium-textured soil. Therefore, the risk of soil damage in these sites due to compaction will be proportionally reduced when traffic occurs at MC below plastic limit (Kirby 1991; Cresswell et al. 2016).

In PTL, as mentioned earlier, PR, bulk density and shear strength were significantly increased at all site soils. There were variations in the changes in PR and other soil physical properties among sites. This can be explained in terms of changes in MC and soil texture due to traffic. In clay soils (Northern region sites) at depth 0-150 mm under CTF no-tillage system, the PR value of the Pittsworth wheel track was greater than that of the crop beds by a factor >1.5 times. Furthermore, the change in bulk density due to PTL was 36%. However, in medium-textured soils (Southern region sites) the change in bulk density was 15%. In addition, the results showed that wheel traffic increased PR by 57% at Hopetoun. The MC in Northern region sites under farmer practice was greater than in Southern region sites. The reason was that the PTL was commonly planted in Southern region sites to reduce the risk of erosion.

However, in non-CTF, in the conventionally tilled soil at Gatton site (clay soil), a single wheeling increased PR by a factor >4 times. But, in the light soil at the Waikerie site under no-tillage (non-CTF), the results showed that wheel traffic caused a change in PR of 70%. The main reason for this change is probably that the tilled soil has a weakly aggregated structure which is more susceptible to compaction. But in the no-tillage system, an aggregated structure of soil is improved due to the avoidance of soil disturbance for a given crop, and leaving the remaining crop to cover the soil. Therefore, no-tillage sites with agronomic measures play important role in reducing compaction effects. These have been indicated by number of researches (e.g. Somasundaram et al. 2017).

The MC results in both Northern and Southern regions sites demonstrate that, in the non-CTF case, the risk of soil damage due to compaction will be proportionally harmful if traffic occurs at MC which is the practice selected by growers in this study, particularly for clay soils. This confirmed that >93% of potential compaction for the investigated Vertisols (clay soil) occurred at MC of 21.37%, as found by Bennett et al. (2017). They suggested that traffic should occur at moisture contents much less than the plastic limit in order to limit compaction.

Conversely, the MC was chosen based on grower practice in our study, which is related to strength of soil and the relative ease of cultivation of the soil. Besides this, the precompression stress (which defines the magnitude of stress a soil has been subjected to prior to traffic and refers to the maximum stress the soil can undergo without any irreparable compression) from Kirby (1991) was found to be 99.3 kPa in soil similar to the current study's soils (Australian Vertisols). This suggests that irreparable damage should be expected with current wheel loads (more than 500 Kpa) (Bennett et al. 2017). But, lighter machines and lower pressures did not seem to prevent soil degradation in terms of raised bulk density and penetration resistance which built up with repeated passes (Voorhees et al. 1986; Jorajuria et al. 1997; Zhang et al. 2007;). It could be argued that this compaction can be rectified quickly by deep tillage but, as has been highlighted, deep tillage is energy-intensive, expensive, and often ineffective particularly when soil settles again very rapidly; or has negative effects where an unfriendly subsoil layer is mixed with the topsoil (Tullberg 2018). Deep tillage can also make the soil more vulnerable to compaction and often to greater depths in the profile (Schäfer-Landefeld et al. 2004; Chamen et al. 2015). This reconfirms the concerns about the effects of non-CTF practice reported in the literature. It is also confirms that avoidance of traffic is the best solution to limiting risk, which supports controlled traffic farming approaches.

The PCB is un-trafficked soil in CTF. Both the literature and this study suggest that most soils can maintain a healthy structure in the absence of traffic (Carter et al. 1991; Meek et al. 1988, 1989). Bulk density, of which play a major role in water storage in soil profile, was lower under PCB (zero traffic). Hussein et al (2017; 2018) found that water storage in the soil of CTF treatment was higher than in non-CTF treatment. This due to reduced infiltration and hydraulic conductivity resulting from changes in bulk density and porosity. These observations agree with studies dealing with functional relationships between traffic compaction, runoff generation, and their effects on soil structure (e.g. Li et al. 2007, 2009).

Finally, the results of soil physical properties including bulk density and shear strength were reported in **Chapter 3** (**Table 3.3**), while PR and MC were reported in **Chapter 6** and **Appendix A6.2.** These results demonstrated that controlled traffic has the potential to reduce PR, soil bulk density and shear strength in permanent crop beds. This can create, not only the best environment for crop production, but also protect soil structure from risk of runoff and erosion. These results were in agreement with Qingjie et al. (2009) and McHugh et al. (2009) which indicated that isolation of traffic in no-till systems was efficient in improving soil physical conditions. This translates into reducing the energy requirements of soil engaging implements, which is discussed in **Section 8.2.2**.

However, permanent traffic lanes significantly increased PR, bulk density and shear strength at all sites. As mentioned earlier, CTF isolates traffic by restricting all wheels to permanent traffic lanes. Accordingly, the compaction in permanent traffic lines is increasing. A higher soil compaction in the vehicle tracks improves traffic conditions and increases the tractive efficiency (e.g. Kingwell & Fuchsbichler 2011; Botta et al. 2012). This will be discussed in **Section 8.2.3**.

8.2.2. Wheel traffic effects on draught force of soil of soil engaging implements.

As discussed in the previous section, the outcomes of CTF system and non-CTF system over different soil types in different conditions reveal that soil physical conditions were improved under CTF. This translates into reducing the energy requirements of cropping; an important consideration for the use of soil engaging implements. The other consideration is motion resistance; both contribute to energy requirements. This section discusses the outcomes of CTF in reducing the energy requirements of soil engaging implements.

The results presented in **Chapter 4** highlighted a number of factors such as wheel traffic, operating depth and tine type effects on energy requirements. Wheel traffic on soft soil had the direct effect of increasing the draught force requirements of subsequent soil-disturbing operations. Wheel impact on soil surface profile can also be important. Draught force requirement, **Figure 4.1** and **Figure 4.2,** showed that wheel traffic had a significant effect on the draught force of all tines at most CTF sites for the Northern and Southern region sites, respectively. Although the operating depth of tine in wheeled soil is lower than non-wheeled soil as a result of soil sinkage, but this showed that draught force was significantly greater in wheeled than non-wheeled soil for all tines at CTF sites for both Northern and Southern regions.

The difference between draught in wheeled and non-wheeled soil found in this study was similar though greater than those reported in earlier work by Tullberg (2000). These results however, do not closely agree with those reported by Burt et al. (1994) and Arslan et al. (2015). In Burt's case, the use of "draught control" implements probably ensured little difference in draught between treatments, because tillage depth in non-trafficked soil was greater than that in trafficked soil. In Arslan's case, tine tillage draught differences were not significant and they found no traffic system differences in no-till seeder draught. This might be because measurements of whole planter draught include that due to motion resistance of depth and press wheels, which would be expected to increase in softer soils.

In non-CTF sites, such as Kingaroy and Waikerie, the wheel traffic did not significantly effect draught force of tines. These results also show that even one pass by a tractor with a weight of 69 kN and 65 kN at Kingaroy and Waikerie, respectively could cause significant damage in soil that has already been compacted. In this regard, once soil is compacted, there is only a small effect from repeating the same compaction input. Up to 85% compaction damage occurs in the first pass wheeled soil. This could have affected the capability to compact the soil by one pass. This is in close agreement with Jorajuria and Draghi (1997) who demonstrated that the first pass of a tractor caused a greater increase in the soil bulk density compared to five times passing.

However, in non-CTF tilled soil at the Gatton site, wheel traffic had a significant effect on draught force of all tines. This because Gatton was used as a research station for the University of Queensland under non-controlled traffic and conventional tillage. The site had been deep cultivated and irrigated before the experiment was conducted. Therefore, the compactability of soil is related to pre-existing soil bulk density. Soane et al. (1980 a & b) reported that loose soils undergo greater deformation than soils with a high bulk density. In other word, the higher bulk density, the lower the soil deformation and the soil susceptibility to compaction.

In general, the CTF Northern region sites achieved by far the greatest draught force compared to CTF at the Victorian and South Australian sites. The draught force in non-wheeled soil as example for Northern region sites was two times higher than in Southern region sites for conservation tillage systems (sweep and chisel tines), while for no-tillage systems (opnere tine) the draught force was 1.5 times higher at the Northern region sites than at the Southern region sites (**Chapter 4**). This is due to the lower clay content in Southern region sites compared to Queensland sites. This is caused by increased friction in soils with a high content of clay particles, high soil cohesion strength, high moisture content, and possibly adhesion (McKyes 1985; Chen et al. 2013). Kiss and Bellow (1981) and Van Bergeijk et al. (2001) demonstrated that the clay content in soil has a strong influence on draught force. Their results from two years of experiments showed that the range of specific draught force was 30 kN m^{-2} to 50 kN m^{-2} when the range of clay content was 6% to 22%.

This study also found that, in draught saving, the CTF sites in the Northern region obtained the highest draught saving compared to CTF sites in the Southern region. However, in Hopetoun (VIC) site and in non-CTF sites such as Kingaroy (QLD) and Waikerie (SA), the draught saving was negligible. This showed that, on average, draught saving was two times higher in CTF at Northern region sites (clay soil) compared with Southern region sites (medium and light-textured). This was because the MC in Northern region sites was the greatest and within range of OMC for compaction. Additionally, susceptibility of soils to compaction varies with the soil texture. Frictionless, i.e cohesive clay soils, are the soil type most susceptible to compaction, and silt soils and cohesion-less sand soils the least at critical soil moisture (Horn et al. 1995). Unsurprisingly, the draught force of soil engaging implements increases with increasing operating depth (Da Rocha Junior et al. 2016).

However, draught saving decreased with increasing operating depth for all sites in most cases. As result of wheel traffic, the increase in the soil bulk density decreased with depth as greater deformation of soil occurs in soil surface layer. This is supported by Jorajuria et al. (1997) who showed that the axle load of 2.3 Mg produced a maximum change in bulk density of 19% at depth 0-50 mm compared to 12% and 15% at depths 100-500 mm and 300-350 mm, respectively. The current result conforms to that of Chen and Yang (2015) who found that the tine opener resistance reduced by 30% and 22% at soil operating depth 50 mm and 100 mm.

It has been indicated that the relationship between draught force and operating depth is exponential (Godwin 2007; Manuwa 2009) but this is very dependent on the operating depth (Kiss & Bellow 1981). If the operating depth is less than 70 mm, the relationship to draught force is linear (Collins & Fowler 1996). The relationship between draught force and operating depth reported for all tines in studies sites was in agreement with the previous works on the subject. In most circumstances, the draught force data presented did not permit the use of linear and polynomial functions to describe its relationship with increasing operating depth. For the operating depth investigated, that relationship was better explained by exponential function and it was also shown that the R^2 values indicated acceptable fits of exponential model, additionally the standard error of estimate (SE) was the lowest compared to polynomials and linear models.

CHAPTER 8: GENERAL DISCUSSION

Wheel traffic on soft soil had the direct effect of increasing the draught force requirement of subsequent soil-disturbing operations. Furthermore, increasing the formation of large soil clods and creating unfavourable soil surface roughness was as result of tractor wheel traffic. As has been reported in the earlier chapters, **Figure 4.3** and **Appendix A4.4** and **Appendix A4.5**, tillage of wheeled soil resulted in a significantly greater surface roughness compared to non-wheeled traffic for both the Northern region sites and Southern region sites. For example, at the Pittsworth site, tillage of wheeled soil resulted in significant greater surface roughness of 48% compared to 27% in non-wheeled traffic which is unsurprising when traffic-induced compaction increases the bulk density and strength of the aggregates within the soil mass (Chamen et al. 2015) to produce a more cloddy surface. This is consistent with the work of Lyles and Woodruff (1961), Voorhees et al. (1978) and Lehrsch et al. (1987) who also point towards a clod density that was markedly higher following wheel traffic than after no traffic.

In terms of operating depth (Pittsworth site), soil surface roughness was significantly different among the depths. The soil surface roughness was consistently lowest at a depth 75 mm (30%), while the highest value was at a depth 125 mm (44%). This is because the bulk density of soil increases with increased depth. This is consistent with the results of bulk density of soil which were reported in **Table 3.3**. In addition, the amount of soil disturbed increase by increasing the operating depth. The above finding is also consistent with the literature (Da Rocha Junior et al. 2016).

With regards to tine types, soil roughness was significantly lowest in opener tine (30%) compared to sweep tines which obtained the highest values (43%), while the average soil roughness was observed in chisel tine (36%). It was expected that a wider tine would generate the greatest surface roughness. This is mainly due to the amount of soil disturbed by sweep tines being much greater than that displaced by narrow tines. The present finding is also support by Spoor and Godwin (1978) and Hasimu and Chen (2014) which concluded that adding wings to tines increases soil surface roughness and soil disturbance as well as draught force.

For all sites, this study has showed that, generally, wheel traffic has a significant effect on draught force and soil surface roughness in CTF sites. In this aspect, the CTF directly reduced the draught force by avoiding tillage of the wheeled soil. This can indirectly reduce the energy requirements by avoiding either increasing clods population, which happened in Queensland and Victorian sites, or creating unfavourable soil surface roughness, which happened at the South Australian sites as result of tilling the wheeled soil.

Finally, the wheel traffic on soft soil had the direct and indirect effect of increasing the draught force requirement of subsequent soil-disturbing operations, but this phenomenon is itself a consequence of the increased motion resistance of wheels when driving over soft soil. This is explained with further details in the next section.

8.2.3. Effect of permanent traffic lanes on motion resistance.

As discussed in previous sections, in a CTF system, the crop zone and the traffic lanes are distinctly and permanently separated. Accordingly, the soil in permanent traffic lanes is heavily compacted, which improves the conditions for machinery traffic. This, in turn, reduces the motion resistance of the equipment.

Figure 6.4 and **Figure 6.6** showed significant effects of surface conditions and ground speed on CMR of tractors for both Northern region and Southern region sites, respectively. The CMR values were less on PTL and WS than PCB, TS and NT for all ground speeds at Northern region and Southern region sites. These finding were confirmed by Chen and Yang (2015) who found that MR was closely linked to topsoil compaction; greater soil strength due to wheel traffic resulted in lower motion resistance in Chinese CTF farms. This is consistent with results of soil physical properties, which were explained earlier in this chapter. However, the highest CMR values on PCB soil TS and NT may have been due to the relatively soft surface soil resulting in higher deformation in the soil tyre interface (**Appendix A6.7**), and leading to higher MR because the amount of soil in front of the tyre increased along the run (Wood & Burt 1987; Botta et al. 2012).

Ground speed was selected for study at both Northern and Southern region sites. The CMR was much higher in soft soil (PCB, TS and NT) than firm soil (Road, PTL, WS) as the ground speed increased. This was not in close agreement with Zoz and Grisso (2003) particularly on softer surfaces. They demonstrated a relatively small effect of ground speed on MR. On the other hand, evidence coming from the regression analysis in the current study indicated that CI had a strong positive relationship to motion resistance in all circumstances. Therefore, increasing ground speed on soft soil leading to increased plastic deformation of soil under the tyre (sinkage) (**Appendix A6.7**) (Liu et al. 2010) and increased motion resistance. The observation is in good agreement with some of the previous works on the subject.

Interestingly, both Northern and Southern region sites showed that CTF with NT and CT can decrease the energy input to soil based on reduction of MR. This term is directly reflected to fuel saving and soil deformation as a results of wheel traffic. As demonstrated in **Tables 6.1** and **6.2**, CTF leads to a greater reduction in MR which is due to greater soil strength as a result of wheel traffic. This can save fuel use ((20% and 26% for NT and CT in clay soil, respectively) and (12% and 20% for NT in medium and light-textured soil, respectively)) in farm activities of Northern region and Southern region sites, respectively. The current results conform with those of Taylor (1983) who demonstrated that the first pass across relatively soft soil brought with it high motion resistance and poor tractive efficiency. However, with following passes, efficiency had risen from less than 50% to close to 75% on a Decatur silty loam, with very similar results for a sandy loam and a clay soil.

In clay soils, the CTF can secure the soil from the risk of compaction by up to 38% in NT systems. However, in CT systems, CTF can save the soil from risk of compaction nearly 50% as high as it was in the NT. But, in medium-textured and light soils, the CTF in NT can reduce energy input to soil (compaction) up to 43% and 49%, respectively. The reason for this difference is related to soil strength (CI). In CT, the main reason probably reflects the weaker structure of the tilled soil, because tillage and agronomic management are important to soil structure, as demonstrated by number of researchers (e.g. Somasundaram et al. 2017). Therefore, no-tillage sites with agronomic measures play an important role in reducing compaction effects. This corresponded well with data reported in **Chapters 3** and **6** on soil physical properties.

The experimental data in **Chapters 4** and **6**, which have been discussed in previous sections, were used to calibrate and validate the draught and motion resistance models at each site. The outcome of experimental and modelled data were used as the basis for a broader exploration of CTF effects in timeliness. Therefore, the following section reviews the results obtained in modelling studies for energy requirements of cropping including draught force and motion resistance.

8.2.4. Modelling of energy requirements of cropping

As mentioned previously, the energy requirements of cropping are associated with two components: are draught force of soil engaging implements and motion resistance. In draught force of soil-engaging implements, collecting data under various field conditions is an expensive and time-consuming work. Thus, prediction of draught requirements of soil-engaging implements is of importance to designers and operators of cultivation equipment to achieve the best results when implementing size matching of tractor power. Therefore, accurate prediction of the draught forces of soil-engaging implements is of great value to both implement designers and farmers.

The model used to predict the draught force of soil-engaging implements was the Godwin and O'Dogherty (2007) integrated tillage force prediction model. The results of the validation of the Godwin and O'Dogherty model was reported earlier in **Chapter 5**. The linear regression of model used to highlight the relationship between measured draught force, reported in **Chapter 4,** predicted draught force based on the Godwin and O'Dogherty (2007) tillage force prediction model for all tines in studied sites.

For both Northern and Southern region sites (clay soils, and medium and light-textured soils, respectively), the results of the regression analyses showed that the model predicts the draught requirements of tillage and seeding implements within an error bounds of less than ±20 %, if one extreme case is ignored (Hopetoun site). However, the standard deviation of mean difference between predicted and measured draught force for all tines was high (3%), especially in the Northern region sites (clay soils) compared with Southern region sites, except for the Hopetoun site (**Appendix A5.1**). The standard deviation range is acceptable when considering the variation in soil strength factors. Furthermore, the variations in soil strength characteristics even in the same field can produce a variation of ±18% (**Appendix A5.1**). It would be difficult to obtain meaningful cohesion and internal friction angle data and implement a prediction model which would be any more accurate (Payne 1956; Q'Callaghan & Farrelly 1964; Hettiaratchi & Reece 1967; Godwin & Spoor, 1977).

Based on the Godwin and O'Dogherty (2007) tillage force prediction model, it is possible to predict the draught force of different tines in all studied sites except the Hopetoun (VIC) site.

For motion resistance, two models were used to predict it for different tractors on varying soil conditions. The resultant values of motion resistance on PTL and NT in CTF sites and non-wheeled soil and wheeled soil in non-CTF sites of ground speed (**Chapter 6**) have been compared with the values predicted by the Brixius model and the Gee-Clough model. It is important to acknowledge that the validation of prediction models was done separately for each site because of the different tractors which were used to conduct the experiments at these sites.

The prediction of motion resistance was underestimated (up to 55%) for NT, WS and PTL at all studied soil, clay, medium and light-textured soils, with both the Brixius and Gee-Clough models. However, at TS in clay soil over-predictions (up to 25%) were obtained with both models. The large discrepancies in these predicted values could be due to the quantitative difference in the tyre dimensional characteristics that includes the b/d ratio (tyre section width/overall unloaded tyre diameter), and δ/h ratio (tyre deflection/tyre section height) and tyre lug characteristics. The tyre dimensional characteristics were reported in **Table 3.8**. This is in close agreement with Elwaleed et al. (2006b). Finally, the Brixius model showed good predictions when compared with the Gee-Clough model. Accordingly, the Brixius motion resistance model was used to predict the mobility number, which used as an indicator of the CTF effect on timeliness.

8.2.5. Effect of field traffic on mobility/timeliness

Controlled traffic farming improved the mobility of equipment, hence improvement of trafficability. The results of this study on clay soils showed that CTF can improve trafficability by 80% in CT, and by 50% in NT. While in medium and light textured soils, CTF can improve trafficability by 38%. These results also confirmed by the reduction in MR which reported in **Chapter 6**.

This improvement will allow operations to continue in soil moisture conditions that may restrict the number of workable days in non-CTF. Increased timeliness makes early planting possible, which often results in yield increases. Meanwhile, delay in planting and harvesting cost is usually between 0.5% and 2% yield loss for every day. Furthermore, the improvement could allow more timely spraying particularly in no-tillage cropping as an essential component of effective no-tillage cropping (Tullberg 2007). Finally, this increase in timeliness of operations can provide significant direct yield benefits, and many indirect benefits such as improved herbicide weed control particular in NT systems.

This chapter has discussed the findings from **Chapters 4**, **5**, **6**, and **7**. It has addressed the overall aim and objectives stated in **Chapter 1**. The overall conclusions coming from this research will be summarised in **Chapter 9**. These conclusions allow the making a set of recommendations for future work that can be done in relation to controlled traffic farming systems and the energy requirements of cropping (**Chapter 10**).

CHAPTER 9

CONCLUSIONS

9. CONCLUSIONS

This chapter summarises the overall conclusions of this study. Based on the research aims and objectives outlined in **Chapter 1**, the conclusions below were drawn. Detailed conclusions corresponding to the field assessment of draught force, modelling work of draught force and field assessment of motion resistance with modelling work can be found in **Chapter 4**, **Chapter 5**, and **Chapter 6,** respectively. The overall conclusions relating to timeliness are outlined in **Chapter 7**. Based on these conclusions, a set of recommendations is provided in **Chapter 10**.

9.1. Conclusions of the field studies

Controlled traffic farming offers fundamental advantages in terms of trafficability, and therefore timelines and energy use, by allowing machinery to move along compacted traffic lanes. The main conclusions derived from this part of the work are summarised below:

9.1.1. Soil physical and mechanical properties

- At Northern region sites, controlled traffic farming improved soil physical properties with the results showing that soil penetration resistance (PR), soil bulk density (BD) soil moisture content (MC) and shear strength (SS) at a depth of 0-150 mm were higher 1.58 MPa, 1.19 Mg m^{-3}, 38 % (w/w) and 0.19 MPa, respectively and 2.18 MPa, 1.6 Mg m^{-3}, 22% (w/w) and 0.31 MPa, respectively on permanent traffic lanes (PTL) for the Felton and Pittsworth sites, respectively, compared with permanent crop lanes (PCB), where the results were lower 1.04 MPa, 1.08 Mg m^{-3}, 36%(w/w) and 0.06 MPa, respectively and 0.93 MPa, 1.17 Mg m^{-3}, 22%(w/w), and 0.08 MPa, respectively, for the Felton and Pittsworth sites, respectively.
- At Southern region sites, the results also showed that PR, BD, MC and SS were higher 3.4 MPa, 1.66 Mg m^{-3}, 11% (w/w) and 0.21 MPa, respectively, 3.68 MPa, 1.75 Mg m^{-3}, 13% (w/w) and 0.28 MPa, respectively and 2.44 MPa, 1.67 Mg m^{-3}, 6% (w/w) and 0 MPa, respectively, on PTL for Hopetoun (VIC), Swan Hill (VIC) and Loxton(SA), respectively, compared with PCB where the results were lower 1.91 MPa, 1.44 Mg m^{-3}, 10%(w/w) and 0.09 MPa, respectively, 2.3 MPa, 1.32 Mg m^{-3}, 8%(w/w) and 0.13 MPa, respectively and

1.20 MPa, 1.54 Mg m^{-3}, 5% (w/w) and 0 MPa, respectively for Hopetoun (VIC), Swan Hill (VIC) and Loxton (SA), respectively

- At Northern region sites in non-CTF (clay soils), in the conventionally tilled soil at Gatton, a single wheeling increased PR by a factor >4 times (2.14 vs. 0.42 MPa for wheeled soil and non-wheeled soil, respectively), compared to non-wheeled soil. But at the Southern region sites (sand soils) in Waikerie site under no-tillage (non-CTF), the results showed that wheel traffic had changes in PR 21% (0.98 vs. 0.81 MPa for wheeled soil and non-wheeled soil, respectively), relative to PR obtained in non-wheeled soil
- At Northern region sites, the change in bulk density due to PTL was up to 36% compared with PCB. However, at Southern region sites the change in bulk density was up to 15% compared to PCB.

9.1.2. Field assessment of draught force

- The results derived from the field work at the Northern region sites (clay soils) in CTF sites showed that wheel traffic significantly increased draught force in clay soils by up to 56% and 38 %, 91 % and 55% (2.08 vs. 3.24 kN) and (2.01 vs. 2.77 kN), (2.33 vs. 4.45 kN) and (2.32 vs. 3.6 kN) for conservation tillage systems (sweep and chisel tines) and the no-tillage system (opener tine), for non-wheeled and wheeled soil, at Felton and Pitsworth, respectively, relative to draught force required in non-wheeled soil
- The Southern region sites (loam and sand soils) in CTF also showed that the draught force significantly increased by up to 28% (0.95 vs. 1.22 kN) and 25% (1.09 vs. 1.36 kN), and 22% (0.94 vs. 1.18 kN) and 9% (0.97 vs. 1.06 kN), for conservation tillage systems (sweep and chisel tines) and the no-tillage system (opener tine), for non-wheeled soil and wheeled soil, at Swan Hill and Loxton, respectively, compared to draught force required in non-wheeled soil
- The greatest savings in draught were observed on the Northern region sites (clay soils) where CTF is practiced, with savings of up to 60% compared to the non-CTF system, while in the Southern region sites (loam and sand soils) savings were up to 26% compared to non-CTF. In addition, savings in draught were approximately 1.3 times and three times higher on clay soils than on loam and sand soils, respectively. Generally, savings in draught decreased as

operating depth increased, regardless of soil type. Wheel traffic had a negligible impact on draught force in non-CTF such as the Kingaroy (QLD) and Waikerie (SA) sites because the soil of non-CTF sites was affected by historic traffic compaction. Therefore, in non-CTF sites, there were no differences in draught forces measured in wheeled soil and non-wheeled soil. This observation confirmed that most of the compaction damage to the soil likely occurred after the first wheel traffic

- Draught force increased for all types of tine at all sites with operating depth. Operating depth had a strong positive relationship to draught force for all types of tine and the relationship is typically better explained by the exponential model
- Wheel traffic significantly affected soil surface roughness for all sites. Soil surface roughness was highest (37% and 59%) and (23% and 27%) for the no-tillage system and conservation tillage system in Northern region and Southern region sites, respectively, relative to the soil surface roughness achieved in non-wheeled soil.

9.1.3. Field assessment of motion resistance

- The results derived from the field assessment showed that the coefficient of motion resistance (CMR) was less on permanent traffic lanes (PTL) and wheeled soil (WS) than permanent crop beds (PCB), tilled soil (TS) and no-tillage (NT) for all ground speeds at both the Northern and Southern region sites
- The CMR was higher in soft soil (NT) up to 13% in Northern region sites (clay soils), when ground speed increased by 2.2 m s^{-1} to 4.4 m s^{-1}, compared to firm soil (PTL) (11%). While in Southern region sites the CMR was higher up to 15% and 35% in NT as ground speed increased, for loam and sandy soils, respectively, compared with firm soil (PTL) (12% and 31%) for loam and sandy soils, respectively
- The reductions in gross motion in CTF sites were up to 20% and 23% for sandy and clay soils, respectively (motion resistance was ≈ 10.26 vs. 12.81kN for sandy soil and 9.22 vs. 11.92 for clay soil on PTL and PCB, respectively), compared with non-CTF. This is also reflected in differences in fuel use

- The reduction in external motion resistance as a result of PTL was up to 44% and 49% in clay and sandy soils, respectively (motion resistances were ≈ 5.81, 9.22 and 11.92 kN for clay soil, and 7.57, 10.26 and 12.81kN for sandy soil on road, PTL and PCB, respectively). This also reflects a need to secure the soil from compaction as a result of random traffic
- Regression analyses indicated that cone index for depth (0-150 mm) in different soils (heavy clay soil, medium-textured and light soil) at different conditions (TS, WS, PCB, PTL and NT) had a strong positive relationship to motion resistance in all circumstances, and the relationship was explained by a linear function.

9.2. Conclusions of the modelling study

The results derived from modelling draught force are:

- The integrated soil tillage force prediction model of Godwin and O'Dogherty (2007) can be satisfactorily applied to predict draught force of a range of tines for the different Australian soils tested in this study. In clay soils, predicted draught force for sweep, chisel and opener tines were within an average error of ±16%, ±13% and ±26%, respectively. In medium- and light-textured soils, model predictions of draught force were within an average error of ±15%, ±11% and ±18% for sweep, chisel and opener tines, respectively. The model proposed by Godwin and O'Dogherty is less complex in terms of input parameters and can be satisfactorily used to predict of draught force for a range tines for different Australian soils.

The results derived from modelling of motion resistance showed:

- Gee-Clough resistance models are not applicable to all studied soil conditions
- The Brixius model showed good predictions when compared with the Gee-Clough model for most experimental data of motion resistance
- Motion resistance increases exponentially with decreasing wheel numeric (dimensionless number for tyre moving in a given soil) (C_n).

The results derived from modelling of mobility (timeliness) are:

- The mobility number increased by increasing the Cone Index (CI) and tyre diameter for all soils tested in this study

- At Northern region sites (clay soils) showed that CTF can improve trafficability by 80% in CT (conventional tillage), and by 50% in NT. While at Southern region sites (medium and light textured soils), CTF can improve trafficability by 38%. These results were also confirmed by the reduction in MR as a results of CTF.

The results of this study confirmed the hypotheses formulated prior to this research (*The separation of traffic lanes and crop bed under CTF reduces draught (energy) requirements and machinery motion resistance. Reducing machine motion resistance improves trafficability, field access and timeliness of field operations*) and, therefore, are supportive of an increased adoption of CTF in Australia. Based on the field assessments at industry and regional scale level, the research undertaken was able to draw recommendations for increasing adoption of CTF as discussed in the next chapter.

CHAPTER 10

RECOMMENDATIONS AND FUTURE RESEARCH

CHAPTER 10: FUTURE RESEARCH AND RECOMMENDATIONS

10. RECOMMENDATIONS AND FUTURE RESEARCH

Mechanisation systems which enable the avoidance of soil compaction allow for significant savings in energy needed for both its creation and repair while delivering positively to improved soil structure, crop yields and crop production efficiency:

- The moisture content (MC) value particularly in Northern region sites was up to 25% (w/w) based on grower practice in our study. This value was within the average value of the soil moisture content at which the maximum dry density is achieved based on the Proctor test. Furthermore, the risk of soil damage due to compaction will be proportionally harmful if traffic occurs at MC which is the practice selected by growers in this study. Therefore, to limit traffic compaction, field operation in non-CTF systems should occur at moisture contents less than the soil moisture content at which the maximum dry density is achieved based on the Proctor test
- The Godwin and O'Dogherty (2007) model was validated by this study for a range of Australian soils and conditions and it may be readily applied to predict draught force of a range tines for different Australian soils. There is a need to extend the modelling study presented in this work to further investigate the prediction of draught force of soil engaging implements in wheeled soil
- There is also a need to extend the modelling study of opener tines in no-tillage soil, particularly in clay soils, and to investigate the effectiveness of other soil tillage force prediction approaches. For example, the application of the Discrete Element Method (DEM) should be considered in future soil tillage research for predicting draught. Recent research in South Australia on sandy soils (Barr et al. 2017; Barr et al. 2018) (e.g., Barr et al, 2017, 2018) showed the suitability of DEM for predicting opener forces and soil disturbance characteristics. This would help to provide explanations into soil failure patterns
- This research also showed that PTL in CTF can reduce motion resistance and improve timeliness, while PCBs decrease the energy requirements of soil engaging implements. There is a need to measure mobility and tafficability per day to estimate the number of extra working days for the sites. There is a need

to further extend this study to investigate the effect of timeliness improvement on agronomic aspects under CTF systems and its impact on overall system efficiency and costs compared with non-CTF systems.

REFERENCES

Abo Al-Kheer, A, Kharmanda, MG, Hami, AE & Mouazen, AM 2011, 'Estimating the variability of tillage forces on a chisel plough shank by modeling the variability of tillage system parameters', *Computers and Electronics in Agriculture*, vol. 78, no. 1, pp. 61-70.

ABS 2017, *Land Management and Farming in Australia, 2016-17'*, Australian Bureau of Statistics, Cat. no. 4627.0.

Adem, HH & Tisdall, JM 1984, 'Management of tillage and crop residues for double-cropping in fragile soils of south-eastern Australia', *Soil and Tillage Research*, vol. 4, no. 6, pp. 577-89.

AGF 2018, *Tillage radish*, Australian Grain & Forage Seeds, 10/8/2018, <https://agfseeds.com.au/cover-crops/#tillage-radish>.

Ahmad, N, Hassan, F & Belford, R 2009, 'Effect of soil compaction in the sub-humid cropping environment in Pakistan on uptake of NPK and grain yield in wheat (Triticum aestivum): I. Compaction', *Field crops research*, vol. 110, no. 1, pp. 54-60.

Al-Gaadi, KA 2013, 'Assessment of soil compaction under center pivot irrigation systems and its effect on crop performance', *American Journal of Agricultural and Biological Sciences*, vol. 8, no. 1, p. 54.

Al-Halfi, K, Bennett, JM & Jensen, T 2017, 'Investigating the validity of the Godwin and O'Dogherty single tine model for a red ferrosol clay soil - Queensland', in *The First MoHESR and HCED Iraqi Scholars Proceedings of the The First MoHESR and HCED Iraqi Scholars* Melbourne, Australia.

Al-Hamed, SA, Grisso, RD, Zoz, FM & Von Bargen, K 1994, 'Tractor performance spreadsheet for radial tires', *Computers and Electronics in Agriculture*, vol. 10, no. 1, pp. 45-62.

Al-Janobi, A & Al-Suhaibani, SA 1998, 'Draft of primary tillage implements in sandy loam soil', *Applied Engineering in Agriculture*, vol. 14, no. 4, p. 343.

Alakukku, L, Weisskopf, P, Chamen, WCT, Tijink, FGJ, van der Linden, JP, Pires, S, Sommer, C & Spoor, G 2003, 'Prevention strategies for field traffic-induced subsoil compaction: a review: Part 1. Machine/soil interactions', *Soil and Tillage Research*, vol. 73, no. 1, pp. 145-60.

Alcock, R 1986, 'Traction', in *Tractor-Implement Systems*, Springer, pp. 44-58.

Alvarez, R & Steinbach, HS 2009, 'A review of the effects of tillage systems on some soil physical properties, water content, nitrate availability and crops yield in the Argentine Pampas', *Soil and Tillage Research*, vol. 104, no. 1, pp. 1-15.

Anken, T, Holpp, M & Weisskopf, P 2016, 'Controlled Traffic Farming improves soil physical parameters', in *CIGR-AgEng conference*: *Proceedings of the CIGR-AgEng conference* Aarhus, Denmark, pp. 1-8.

Ansorge, D 2005, 'Comparison of soil compaction below wheels and tracks', MSc by research thesis, Cranfield University, Silsoe, England, UK.

Ansorge, D 2007, 'Soil reaction to heavily loaded rubber tracks and tyres', PhD thesis, Cranfield University, Silsoe, England.

REFERENCES

Ansorge, D & Godwin, RJ 2007, 'The effect of tyres and a rubber track at high axle loads on soil compaction, Part 1: Single axle-studies', *Biosystems Engineering*, vol. 98, no. 1, pp. 115-26.

Antille, DL, Bennett, JM & Jensen, TA 2016, 'Soil compaction and controlled traffic considerations in Australian cotton-farming systems', *Crop and Pasture Science*, vol. 67, no. 1, pp. 1-28.

Antille, DL, Ansorge, D, Dresser, ML & Godwin, RJ 2013, 'Soil displacement and soil bulk density changes as affected by tire size', *Transactions of the ASABE*, vol. 56, no. 5, pp. 1683-93.

Antille, DL, Chamen, WCT, Tullberg, JN & Lal, R 2015, 'The potential of controlled traffic farming to mitigate greenhouse gas emissions and enhance carbon sequestration in arable land: A critical review', *Transactions of the ASABE*, vol. 58, no. 3, pp. 707-31.

Arslan, S, Misiewicz, P, Smith, E, Underhill, T, Franklin, K, White, D & Godwin, R 2015, 'The effect of tire tracks on draft force requirements of soil tillage and field traffic systems', in *2015 ASABE Annual International Meeting*: *Proceedings of the 2015 ASABE Annual International Meeting* ASABE, St. Joseph, Mich., pp. 1-8.

Arvidsson, J 1999, 'Nutrient uptake and growth of barley as affected by soil compaction', *Plant and Soil*, vol. 208, no. 1, pp. 9-19.

Arvidsson, J 2001, 'Subsoil compaction caused by heavy sugarbeet harvesters in southern Sweden: I. Soil physical properties and crop yield in six field experiments', *Soil and Tillage Research*, vol. 60, no. 1, pp. 67-78.

Arvidsson, J & Keller, T 2010, 'Draught Requirement During Tillage', in AP Dedousis & T Bartzanas (eds), *Soil Engineering*, Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 3-17.

Arvidsson, J, Keller, T & Gustafsson, K 2004, 'Specific draught for mouldboard plough, chisel plough and disc harrow at different water contents', *Soil and Tillage Research*, vol. 79, no. 2, pp. 221-31.

ASABE 2005, *Terminology and definitions for doil tillage and soil-tool relationships*, American Society of Agricultural and Biological Engineers, 2950 Niles Road, St. Joseph, MI 49085-9659, USA, http://elibrary.asabe.org/abstract.asp?aid=44185&t=2>.

ASABE 2009, *Terminology and Definitions for Agricultural Tillage Implements*, American Society of Agricultural and Biological Engineers, 2950 Niles Road, St. Joseph, MI 49085-9659, USA, http://elibrary.asabe.org/abstract.asp?aid=44205&t=2>.

ASABE 2013a, *Soil cone penetrometer*, S313.3 FEB1999ED (R2013), American Society of Agricultural and Biological Engineers, 2950 Niles Road, St. Joseph, Ml 49085-9659, USA.

ASABE 2013b, *Procedures for using and reporting data obtained with the soil cone penetrometer*, EP542 FEB1999 (R2013), American Society of Agricultural and Biological Engineers, 2950 Niles Road, St. Joseph, Ml 49085-9659, USA.

ASABE 2015, 'Agricultural wheeled tractors - Rear-mounted three-point linkage - Categories 1N, 1, 2N, 2, 3N, 3, 4N and 4', p. 1.

REFERENCES

Australia, SAO 1976, *Determination of the particle size distribution of a soil: an analysis by sieving in combination with hydrometer analysis*, Standards Association of Australia, Australia.

Ayers, PD 1987, 'Moisture and Density Effects on Soil Shear Strength Parameters for Coarse Grained Soils', *Transactions of the ASAE*, vol. 30, no. 5, p. 1282.

Ayers, PD & Perumpral, JV 1982, 'Moisture and density effect on cone index', *Transactions of the ASAE*, vol. 25, no. 5, pp. 1169-72.

Baan, CD, Grevers, MCJ & Schoenau, JJ 2009, 'Effects of a single cycle of tillage on long-term no-till prairie soils', *Canadian journal of soil science*, vol. 89, no. 4, pp. 521-30.

Bai, Y, He, J, Li, H, Wang, Q, Chen, H, Kuhn, N, Hikel, H, Chen, F & Gong, Y 2009, 'Soil structure and crop performance after 10 years of controlled traffic and traditional tillage cropping in the dryland Loess Plateau in China', *Soil science*, vol. 174, no. 2, pp. 113-9.

Bakker, DM & Barker, TM 1998, 'Soil structure assessment and 3-dimensional visualisation of a Vertosol under controlled traffic', *Soil Research*, vol. 36, no. 4, pp. 603-20.

Barger, EL, Carleton, WM, Mckibben, EG & Bainer, R 1967, *Tractors and Their Power Units*, Second edn, John Wiley and Sons, Inc., The United States of America.

Barr, J, Fielke, J & Desbiolles, J 2017, 'A New Method of Quantifying Discrete Element Method Predicted Furrow Profiles of Narrow Point Openers', in *2017 ASABE Annual International Meeting*: *Proceedings of the 2017 ASABE Annual International Meeting* ASABE, St. Joseph, Mich., p. 1-10.

Barr, J, Ucgul, M, M A Desbiolles, J & Fielke, J 2018, 'Simulating the effect of rake angle on narrow opener performance with the discrete element method', *Biosystems Engineering*, ', vol. 171, pp. 1-15.

Barr, JB, Desbiolles, JMA & Fielke, JM 2016, 'Minimising soil disturbance and reaction forces for high speed sowing using bentleg furrow openers', *Biosystems Engineering*, vol. 151, pp. 53-64.

Batey, T 2009, 'Soil compaction and soil management – a review', *Soil use and management*, vol. 25, no. 4, pp. 335-45.

Beard, FR, McClendon, RW & Manor, G 1995, 'Comparing Widespan Equipment with Conventional Machinery Systems for Soybean Production', *Applied Engineering in Agriculture*, vol. 11, no. 6, pp. 795-800.

Becker, F 2003, *Site for tractors stuck in mud*, Yesterday's Tractor Co., viewed 6/5/2017, <http://www.yesterdaystractors.com/cgi-bin/viewit.cgi?bd=ttalk&th=327323>.

Bennett, JM, Jensen, T, Antille, D & Baillie, C 2016, *An impact assessment framework for harvesting technologies in cotton: management considerations for the John Deere 7760*, University of Southern Queensland, National Centre for Engineering in Agriculture, Toowoomba, Australia. http://eprints.usq.edu.au/id/eprint/30015>.

Bennett, JM, Woodhouse, NP, Keller, T, Jensen, TA & Antille, DL 2015, 'Advances in cotton harvesting technology: a review and implications for the John Deere round baler cotton picker', *Journal of Cotton Science*, vol. 19, no. 2, pp. 225-49.

REFERENCES

Bennett, JM, Roberton, SD, Jensen, TA, Antille, DL & Hall, J 2017, 'A comparative study of conventional and controlled traffic in irrigated cotton: I. Heavy machinery impact on the soil resource', *Soil and Tillage Research*, vol. 168, pp. 143-54.

Bennie, ATP & Botha, FJP 1986, 'Effect of deep tillage and controlled traffic on root growth, water-use efficiency and yield of irrigated maize and wheat', *Soil and Tillage Research*, vol. 7, no. 1, pp. 85-95.

Bezborodova, G, Kosharny, N & Zadorozhny, V 1968, 'Determination of rolling resistance of multi-axle automobiles on deformable soils', *Automobile Transport*, vol. 5, no. 1.

Blackwell, P 2007, ' Development of controlled traffic in WA and future directions integrated with precision agriculture.', in *5th Australian Controlled Traffic and Precision Agriculture*: *Proceedings of the 5th Australian Controlled Traffic and Precision Agriculture* University of Western Australia, Perth, pp. 16-22.

Blackwell, P, Ward, M, Lefevre, R & Cowan, D 1985, 'Compaction of a swelling clay soil by agricultural traffic; effects upon conditions for growth of winter cereals and evidence for some recovery of structure', *European Journal of Soil Science*, vol. 36, no. 4, pp. 633-50.

Blake, GR 1965, 'Bulk density', in CA Black (ed.), *Methods Of Soil Analysis Part1*, American Society of Agronomy, Madison, Wisconsin, USA, pp. 374-90.

Bochtis, DD, Sørensen, CG, Green, O, Moshou, D & Olesen, J 2010, 'Effect of controlled traffic on field efficiency', *Biosystems Engineering*, vol. 106, no. 1, pp. 14-25.

Bögel, T, Osinenko, P & Herlitzius, T 2016, 'Assessment of soil roughness after tillage using spectral analysis', *Soil and Tillage Research*, vol. 159, no. Supplement C, pp. 73-82.

Botta, GF, Jorajuria, D & Draghi, LM 2002, 'Influence of the axle load, tyre size and configuration on the compaction of a freshly tilled clayey soil', *Journal of Terramechanics*, vol. 39, no. 1, pp. 47-54.

Botta, GF, Becerra, AT & Melcona, FB 2009, 'Seedbed compaction produced by traffic on four tillage regimes in the rolling Pampas of Argentina', *Soil and Tillage Research*, vol. 105, no. 1, pp. 128-34.

Botta, GF, Jorajuria, D, Rosatto, H & Ferrero, C 2006, 'Light tractor traffic frequency on soil compaction in the Rolling Pampa region of Argentina', *Soil and Tillage Research*, vol. 86, no. 1, pp. 9-14.

Botta, GF, Tolon-Becerra, A, Tourn, M, Lastra-Bravo, X & Rivero, D 2012, 'Agricultural traffic: Motion resistance and soil compaction in relation to tractor design and different soil conditions', *Soil and Tillage Research*, vol. 120, pp. 92-8.

Bouwman, LA & Arts, WBM 2000, 'Effects of soil compaction on the relationships between nematodes, grass production and soil physical properties', *Applied Soil Ecology*, vol. 14, no. 3, pp. 213-22.

Boydell, B & Boydell, C 2003, 'A decade of directions: trials and tribulations of precision agriculture and controlled traffic at ‘Marinya’. Keynote address.', in *the International Soil Tillage Research Organisation 16th Triennial conference*: *Proceedings of the the International Soil Tillage Research Organisation 16th Triennial conference* Brisbane, Australia pp. 196-207.

REFERENCES

Braunack, M, McPhee, J & Reid, D 1995, 'Controlled traffic to increase productivity of irrigated row crops in the semi-arid tropics', *Australian Journal of Experimental Agriculture*, vol. 35, no. 4, pp. 503-13.

Braunack, MV & McGarry, D 2006, 'Traffic control and tillage strategies for harvesting and planting of sugarcane (Saccharum officinarum) in Australia', *Soil and Tillage Research*, vol. 89, no. 1, pp. 86-102.

Brixius, W 1987, 'Traction prediction equations for bias ply tires', *ASAE Paper*, vol. 87, no. 1622, p. 8.

Burt, E, Reeves, D & Raper, R 1994, 'Energy utilization as affected by traffic in a conventional and conservation tillage system', *Transactions of the ASAE*, vol. 37, no. 3, pp. 759-62.

Burt, EC, Taylor, JH & Wells, LG 1986, 'Traction Characteristics of Prepared Traffic Lanes', *Transactions of the ASAE*, vol. 29, no. 2, pp. 393-401.

Cannell, RQ 1977, 'Soil aeration compaction in relation to root growth and soil management', *Applied biology*, vol. 2, pp.1-36.

Carter, LM 1985, 'Wheel Traffic is Costly', *Transactions of the ASAE*, vol. 28, no. 2.

Carter, LM, Meek, BD & Rechel, EA 1991, 'Zone production system for cotton: Soil response', *Transactions of the ASAE*, vol. 34, no. 2, pp. 354-0360.

Chamen, WCT 2013, 'An overview of Controlled Traffic Farming (CTF) systems in Northern Europe', in *First International CTF Conference, 25-27 February 2013*, Toowoomba, Australia.

Chamen, WCT 2006, *'Controlled traffic' farming: Literature review and appraisal of potential use in the UK*, Agriculture and Horticulture Development Board, Warwickshire, UK.

Chamen, WCT 2011, 'The effects of low and controlled traffic systems on soil physical properties, yields and the profitability of cereal crops on a range of soil types', thesis thesis, Cranfield University, Silsoe, England.

Chamen, WCT, Alakukku, L, Pires, S, Sommer, C, Spoor, G, Tijink, F & Weisskopf, P 2003, 'Prevention strategies for field traffic-induced subsoil compaction: a review: Part 2. Equipment and field practices', *Soil and Tillage Research*, vol. 73, no. 1, pp. 161-174.

Chamen, WCT & Audsley, E 1993, 'A study of the comparative economics of conventional and zero traffic systems for arable crops', *Soil and Tillage Research*, vol. 25, no. 4, pp. 369-96.

Chamen, WCT & Cavalli, R 1994, 'The effect of soil compaction on mole plough draught', *Soil and Tillage Research*, vol. 32, no. 4, pp. 303-11.

Chamen, WCT & Longstaff, DJ 1995, 'Traffic and tillage effects on soil conditions and crop growth on a swelling clay soil', *Soil use and management*, vol. 11, no. 4, pp. 168-76.

Chamen, WCT, Audsley, E & Holt, JB 1994a, 'Economics of Gantry- and Tractor-based Zero-Traffic Systems', in BD Soane & C van Ouwerkerk (eds), *Developments in Agricultural Engineering*, Elsevier, vol. 11, ch 24, pp. 569-95.

Chamen, WCT, Vermeulen, GD, Campbell, DJ & Sommer, C 1992a, 'Reduction of traffic-induced soil compaction: a synthesis', *Soil and Tillage Research*, vol. 24, no. 4, pp. 303-18.

REFERENCES

Chamen, WCT, Watts, CW, Leede, PR & Longstaff, DJ 1992b, 'Assessment of a Wide Span Vehicle (Gantry), and Soil and Cereal Crop Responses to Its Use in a Zero Traffic Regime', *Soil & Tillage Research*, vol. 24, no. 4, pp. 359-80.

Chamen, WCT, Dowler, D, Leede, PR & Longstaff, DJ 1994b, 'Design, Operation and Performance of a Gantry System: Experience in Arable Cropping', *Journal of agricultural engineering research*, vol. 59, no. 1, pp. 45-60.

Chamen, WCT, Chittey, ET, Leede, PR, Goss, MJ & Howse, KR 1990, 'The effect of tyre/soil contact pressure and zero traffic on soil and crop responses when growing winter wheat', *Journal of agricultural engineering research*, vol. 47, no. 1, pp. 1-21.

Chamen, WCT, Moxey, AP, Towers, W, Balana, B & Hallett, PD 2015, 'Mitigating arable soil compaction: A review and analysis of available cost and benefit data', *Soil and Tillage Research*, vol. 146, Part A, pp. 10-25.

Chancellor, WJ 1976, *Compaction of soil by agricultural equipment*, vols., University of California, Division of Agricultural Sciences, Davis, CA, USA.

Chancellor, WJ & Schmidt, RH 1962, 'Soil deformation beneath surface loads', *Transactions of the ASAE*, vol. 5, no. 2, pp. 240-0246.

Chen, H & Yang, Y 2015, 'Effect of controlled traffic system on machine fuel saving in annual two crops region in North China Plain', *Soil and Tillage Research*, vol. 153, pp. 137-44.

Chen, H, Bai, Y, Wang, Q, Chen, F, Li, H, Tullberg, JN, Murray, JR, Gao, H & Gong, Y 2008, 'Traffic and tillage effects on wheat production on the Loess Plateau of China: 1. Crop yield and SOM', *Soil Research*, vol. 46, no. 8, pp. 645-51.

Chen, Y, Munkholm, LJ & Nyord, T 2013, 'A discrete element model for soil–sweep interaction in three different soils', *Soil and Tillage Research*, vol. 126, pp. 34-41.

Collins, BA & Fowler, DB 1996, 'Effect of soil characteristics, seeding depth, operating speed, and opener design on draft force during direct seeding', *Soil and Tillage Research*, vol. 39, no. 3, pp. 199-211.

Cox, SWR 1988, *Farm electronics*, BSP Professional Books, Oxford.

Craig, RF 1997, *Soil mechanics*, 6th edn, E & FN Spon.

Cresswell, HP & Hamilton, GJ 2002, 'Bulk density and pore space relations', in N McKenzie, et al. (eds), *Soil physical measurement and interpretation for land evaluation,* CSIRO, Collingwood, Victoria, Australia ch Chapter 3 pp. 35-58.

Cresswell, HP, Abbott, B, Antille, DL, Macdonald, BCT, Thomas, M & Rattray, D 2016, *Origin Energy LNG soil management and reinstatement*, CSIRO, Brisbane, Australia.

Crossley, CP, Kibiwot, VN, Reynolds, AJ & Rickson, RJ 2001, 'SW—Soil and water: Rut formation and rolling resistance on earth roads', *Journal of agricultural engineering research*, vol. 78, no. 1, pp. 99-107.

Crossley, P & Kilgour, J 1983, *Small farm mechanization for developing countries*, John Wiley and Sons.

Cui, K, Défossez, P & Richard, G 2007, 'A new approach for modelling vertical stress distribution at the soil/tyre interface to predict the compaction of cultivated soils by using the PLAXIS code', *Soil and Tillage Research*, vol. 95, no. 1, pp. 277-87.

REFERENCES

da Rocha Junior, PR, Bhattarai, R, Alves Fernandes, RB, Kalita, PK & Vaz Andrade, F 2016, 'Soil surface roughness under tillage practices and its consequences for water and sediment losses', *Journal of soil science and plant nutrition*, vol. 16, pp. 1065-74.

DeJong-Hughes, J 2015, *Tires, traction and compaction*, University of Minnesota extension, viewed 11/10/2015, <https://www.extension.umn.edu/agriculture/soils/tillage/tires-traction-and-compaction/>.

DeJong-Hughes, J, Moncrief, JF, Voorhees, W & Swan, J 2001, *Soil compaction: Causes, effects and control*, St. Paul, MN: University of Minnesota Extension Service, Minnesota, USA.

Demmel, MR, Kirchmeier, H, Brandhuber, R, Kupke, S & Blumental, B 2015, 'Controlled traffic farming in Germany - technical and organizational realization and results', in *2015 ASABE Annual International Meeting*: *Proceedings of the 2015 ASABE Annual International Meeting* ASABE, St. Joseph, MI, p. 1.

Derpsch, R, Sidiras, N & Roth, CH 1986, 'Results of studies made from 1977 to 1984 to control erosion by cover crops and no-tillage techniques in Paraná, Brazil', *Soil and Tillage Research*, vol. 8, pp. 253-63.

Desbiolles, JMA, Godwin, RJ, Kilgour, J & Blackmore, BS 1997, 'A Novel Approach to the Prediction of Tillage Tool Draught using a Standard Tine', *Journal of agricultural engineering research*, vol. 66, no. 4, pp. 295-309.

Dickson, JW & Ritchie, RM 1996, 'Zero and reduced ground pressure traffic systems in an arable rotation: 1. Cultivation power requirement', *Soil and Tillage Research*, vol. 38, no. 1-2, pp. 71-88.

Douglas, JT, Campbell, DJ & Crawford, CE 1992, 'Soil and crop responses to conventional, reduced ground pressure and zero traffic systems for grass silage production', *Soil & Tillage Research*, vol. 24, no. 4, pp. 421-39.

Dwyer, MJ 1983, 'Soil dynamics and the problems of traction and compaction', *Agricultural engineer*, vol. 38, no. 3, pp. 62-8.

Edwards, J, Umbers, A & Wentworth, S 2012, *GRDC farm practices survey report 2012*, Grains Research and Development Corporation, Australia. http://grdc.com.au/Resources/Publications/2012/11/GRDC-Farm-Practices-Survey-2012>.

Elwaleed, AK, Yahya, A, Zohadie, M, Ahmad, D & Kheiralla, AF 2006a, 'Net traction ratio prediction for high-lug agricultural tyre', *Journal of Terramechanics*, vol. 43, no. 2, pp. 119-39.

Elwaleed, AK, Yahya, A, Zohadie, M, Ahmad, D & Kheiralla, AF 2006b, 'Effect of inflation pressure on motion resistance ratio of a high-lug agricultural tyre', *Journal of Terramechanics*, vol. 43, no. 2, pp. 69-84.

Evans, MD, Clark, RL & Manor, G 1991, 'An Improved Traction Model for Ballast Selection', *Transactions of the ASAE*, vol. 34, no. 3, pp. 773-80.

Fan, R, Zhang , X, Liang , A, Shi, X, Chen, X, Bao, K, Yang, X & Jia, S 2012, 'Tillage and rotation effects on crop yield and profitability on a Black soil in northeast China', *Canadian journal of soil science*, vol. 92, no. 3, pp. 463-70.

Flocker, WJ, Vomocil, JA & Vittum, MT 1958, 'Response of winter cover crops to soil compaction1', *Soil Science Society of America Journal*, vol. 22, no. 2, pp. 181-4.

REFERENCES

Flowers, MD & Lal, R 1998, 'Axle load and tillage effects on soil physical properties and soybean grain yield on a mollic ochraqualf in northwest Ohio', *Soil and Tillage Research*, vol. 48, no. 1–2, pp. 21-35.

Forristal, D 2003, 'Machinery, tyres and the soil', in *National Tillage Conference*, Teagasc, Ireland, pp. 83-99.

Freitag, DR 1965, *A dimensional analysis of the performance of pneumatic tires on soft soils*, DTIC Document.

Freitag, DR 1970, *Performance evaluation of wheels for lunar roving vehicles*, U.S. Army Engineer Waterways Experiment Station, DTIC Document.

Galambošová, J, Macák, M, Rataj, V, Antille, DL, Godwin, RJ, Chamen, WCT, Žitnák, M, Vitázková, B, Dudák, J & Chlpík, J 2017, 'Field Evaluation of Controlled Traffic Farming in Central Europe Using Commercially Available Machinery', *Transactions of the ASABE*, vol. 60, no. 3, p. 657.

Gamache, P 2013, *Controlled Traffic Farming Alberta project*, Canda. http://controlledtrafficfarming.org/index.php/ctf-plot-reports > 5/11/2016.

Gardner, WH 1965, 'Water content', in CA Black (ed.), *Methods of soil analysis*, American Society of Agronomy, Madison, Wisconsin, USA, pp. 82-127.

Gasso, V, Sørensen, CAG, Oudshoorn, FW & Green, O 2013, 'Controlled traffic farming: A review of the environmental impacts', *European journal of agronomy*, vol. 48, pp. 66-73.

Gee-Clough, D 1978a, 'The effect of wheel width on the rolling resistance of rigid wheels in sand', *Journal of Terramechanics*, vol. 15, pp. 161-84.

Gee-Clough, D 1978b, 'A comparison of the mobility number and Bekker approaches to traction mechanics and recent advances in both methods at the NIAE', in *Proc. 6th Internat. Conf. Internat. Soc. Terrain-Vehicle Systems*.

Gee-Clough, D 1980, 'Selection of tyre sizes for agricultural vehicles', *Journal of agricultural engineering research*, vol. 25, no. 3, pp. 261-78.

Ghildyal, B & Tripanthi, R 1987, *Soil physics*, New York, USA.

Giarola, NFB, da Silva, ÁP, Tormena, CA, Guimarães, RML & Ball, BC 2013, 'On the Visual Evaluation of Soil Structure: The Brazilian experience in Oxisols under no-tillage', *Soil and Tillage Research*, vol. 127, pp. 60-4.

Gill, WR & Vanden Berg, GE 1968, *Soil dynamic in tillage and traction*, U. S. Government Printing Office, Washington.

Godwin, R 2009, 'Precision management of soil compaction and alternative approaches', in *R&D Conference" Precision in arable farming: current practice and future potential", Grantham, Lincolnshire, UK, 28th-29th October 2009*, HGCA, pp. 116-26.

Godwin, RJ, Misiewicz, PA, Smith, EK, Millington, WA, White, DR, Dickin, ET & Chaney, K 2017, 'Summary of the effects of three tillage and three traffic systems on cereal yields over a four-year rotation', in *2017 ASABE Annual International Meeting*: *Proceedings of the 2017 ASABE Annual International Meeting* ASABE, St. Joseph, MI, pp. 1-7.

REFERENCES

Godwin, R, Misiewicz, P, White, D, Smith, E, Chamen, T, Galambošová, J & Stobart, R 2015, 'Results from recent traffic systems research and the implications for future work', *Acta Technologica Agriculturae*, vol. 18, no. 3, pp. 57-63.

Godwin, RJ 2007, 'A review of the effect of implement geometry on soil failure and implement forces', *Soil and Tillage Research*, vol. 97, no. 2, pp. 331-40.

Godwin, RJ 2016, *Potential of "No-till" Systems for Arable Farming*, The Worshipful Company of Farmers. London, Soil and Water Management Centre, Harper Adams University, Shropshire, UK. viewed 20/5/2016, <https://cdn.harper-adams.ac.uk/document/project/Potential-of-No-till-Systems-for-Arable-Farming-Report.pdf>.

Godwin, RJ & Spoor, G 1977, 'Soil failure with narrow tines', *Journal of agricultural engineering research*, vol. 22, no. 3, pp. 213-28.

Godwin, RJ & O'Dogherty, MJ 2006, 'Tillage dynamics-Spreadsheet models for the prediction of soil tillage implement forces', *Landwards*, vol. 61, no. 1, pp. 8-11.

Godwin, RJ & O'Dogherty, MJ 2007, 'Integrated soil tillage force prediction models', *Journal of Terramechanics*, vol. 44, no. 1, pp. 3-14.

Godwin, RJ, Spoor, G & Soomro, MS 1984, 'The effect of time arrangement on soil forces and disturbance', *Journal of agricultural engineering research*, vol. 30, no. C, pp. 47-56.

Godwin, RJ, O'Dogherty, MJ, Saunders, C & Balafoutis, AT 2007, 'A force prediction model for mouldboard ploughs incorporating the effects of soil characteristic properties, plough geometric factors and ploughing speed', *Biosystems Engineering*, vol. 97, no. 1, pp. 117-29.

Godwin, RJ, Misiewicz, PA, Smith, EK, Millington, WA, White, DR, Dickin, ET & Chaney, K 2017, 'Summary of the effects of three tillage and three traffic systems on cereal yields over a four-year rotation', in *2017 ASABE Annual International Meeting: Proceedings of the 2017 ASABE Annual International Meeting* ASABE, St. Joseph, MI, p. 1.

GRDC, 2009, *Deep ripping fact-sheet*, Grains Research and Development Corporation (GRDC), viewed 20/10/2015, <https://grdc.com.au/resources-and-publications/all-publications/factsheets/2009/06/grdc-fs-deepripping>.

Grisso, RD & Perumpral, JV 1985, 'Review of models for predicting performance of narrow tillage tool', *Transactions of the ASAE*, vol. 28, no. 4, pp. 1062-7.

Grisso, RD, Perumpral, JV & Desai, CS 1980, 'A soil-tool interaction model for narrow tillage tools', ASAE, St. Joseph, MI, p. 20.

Grisso, RD, Yasin, M & Kocher, MF 1996, 'Tillage implement forces operating in silty clay loam', *Transactions of the ASAE*, vol. 39, no. 6, pp. 1977-82.

Guerif, J 1994, 'Effect of compaction on soil strength parameters', in BD Soane & C Van Ouwerkerk (eds), *Soil compaction in crop production* Elsevier Science, Amsterdam, Netherlands, ch 9, pp. 191-214.

Gupta, CP & Surendranath, T 1989, 'Stress field in soil owing to tillage tool interaction', *Soil and Tillage Research*, vol. 13, no. 2, pp. 123-49.

REFERENCES

Gutu, D, Hůla, J, Kovaříček, P & Novák, P 2015, 'The influence of a system with permanent traffic lanes on physical properties of soil, soil tillage quality and surface water runoff', *Agronomy research*, vol. 13, no. 1, pp. 63-72.

Håkansson, I, Voorhees, WB & Riley, H 1988, 'Vehicle and wheel factors influencing soil compaction and crop response in different traffic regimes', *Soil and Tillage Research*, vol. 11, no. 3, pp. 239-82.

Hamza, MA & Anderson, WK 2003, 'Responses of soil properties and grain yields to deep ripping and gypsum application in a compacted loamy sand soil contrasted with a sandy clay loam soil in Western Australia', *Australian Journal of Agricultural Research*, vol. 54, no. 3, pp. 273-82.

Hamza, MA & Anderson, WK 2005, 'Soil compaction in cropping systems: A review of the nature, causes and possible solutions', *Soil and Tillage Research*, vol. 82, no. 2, pp. 121-45.

Hamza, MA, Al-Adawi, SS & Al-Hinai, KA 2011, 'Effect of combined soil water and external load on soil compaction', *Soil Research*, vol. 49, no. 2, pp. 135-42.

Harrigan, TM & Rotz, CA 1995, 'Draft relationships for tillage and seeding equipment', *Applied Engineering in Agriculture*, vol. 11, no. 6, pp. 773-83.

Hasimu, A & Chen, Y 2014, 'Soil disturbance and draft force of selected seed openers', *Soil and Tillage Research*, vol. 140, pp. 48-54.

Hassan, FU, Ahmad, M, Ahmad, N & Abbasi, MK 2007, 'Effects of subsoil compaction on yield and yield attributes of wheat in the sub-humid region of Pakistan', *Soil and Tillage Research*, vol. 96, no. 1–2, pp. 361-6.

He, J, McHugh, AD, Li, HW, Wang, QJ, Li, WY, Rasaily, RG & Li, H 2012, 'Permanent raised beds improved soil structure and yield of spring wheat in arid north-western China', *Soil Use and Management*, vol. 28, no. 4, pp. 536-43.

Hefner, M, Labouriau, R, Nørremark, M & Kristensen, HL 2019, 'Controlled traffic farming increased crop yield, root growth, and nitrogen supply at two organic vegetable farms', *Soil and Tillage Research*, vol. 191, pp. 117-30.

Hegazy, S & Sandu, C 2013, 'Experimental investigation of vehicle mobility using a novel wheel mobility number', *Journal of Terramechanics*, vol. 50, no. 5–6, pp. 303-10.

Henning, T 2018, Henning, Tyrone, viewed 10/2/2018, <https://www.facebook.com/groups/1292198200824881/?ref=gs&tn-str=*F&fref=gs&dti=1292198200824881&hc_location=group_dialog>.

Hettiaratchi, DRP & Reece, AR 1967, 'Symmetrical three-dimensional soil failure', *Journal of Terramechanics*, vol. 4, no. 3, pp. 45-67.

Hettiaratchi, DRP & Reece, AR 1974, 'The calculation of passive soil resistance', *Géotechnique*, vol. 24, no. 3, pp. 289-310.

Hillel, D 1982, *Introduction to soil physics*, Academic Press, Orlando, Fla.

Hillel, D 2007, *Soil in the environment: crucible of terrestrial life*, Elsevier.

Horn, R & Lebert, M 1994, 'Soil Compactability and Compressibility', in BD Soane & C van Ouwerkerk (eds), *Developments in Agricultural Engineering*, Elsevier, vol. 11, ch Chapter 3, pp. 45-69.

REFERENCES

Horn, R, Domżżał, H, Słowińska-Jurkiewicz, A & van Ouwerkerk, C 1995, 'Soil compaction processes and their effects on the structure of arable soils and the environment', *Soil and Tillage Research*, vol. 35, no. 1, pp. 23-36.

Horn, R, Fleige, H, Peth, S & Peng, X (eds) 2006, *Soil management for sustainability*, vol. 38, in Advances in Geoecology, Schweizerbart and Borntraeger, Catena Verlag, Reiskirchen, Germany.

Hulugalle, NR & Lal, R 1986, 'Root growth of maize in a compacted gravelly tropical alfisol as affected by rotation with a woody perennial', *Field crops research*, vol. 13, pp. 33-44.

Hulugalle, NR, Lal, R & Ter Kuile, CHH 1986, 'Amelioration of soil physical properties by Mucuna after mechanized land clearing of a tropical rain forest', *Soil science*, vol. 141, no. 3, pp. 219-24.

Hussein, MA, Antille, D, Chen, G, Kodur, S & Tullberg, JN 2018, Agronomic performance of sorghum (*Sorghum bicolor* L. Moench) and fertilizer use efficiency as affected by controlled and non-controlled traffic of farm machinery', , in 2017 ASABE Annual International Meeting: Proceedings of the 2018 ASABE Annual International Meeting ASABE, St. Joseph, MI, pp. 1-13.

Hussein, MA, Antille, DL, Chen, G, Luhaib, AAA, Kodur, S & Tullberg, JN 2017, 'Agronomic performance of wheat (Triticum aestivum L.) and fertiliser use efficiency as affected by controlled and non-controlled traffic of farm machinery', in *2017 ASABE Annual International Meeting*: *Proceedings of the 2017 ASABE Annual International Meeting* ASABE, St. Joseph, MI, pp. 1-9.

Iler, G & Stevenson, C 1991, 'The effects of soil compaction on the production of processing vegetables and field crops', *A review. Ridgetown College of Agricultural Technology, Ontario*, pp. 0-57.

Inns, F & Kilgour, J 1978, 'Agricultural tyres: Principle of off highway mobility', *Dunlop Limited*, pp. 26-36.

Isbell, R 2002, *The Australian soil classification*, Revised edn, CSIRO publishing, Collingwood, Victoria, Australia.

Isbister, B, Blackwell, P, Riethmuller, G, Davies, S, Whitlock, A & Neale, T 2013, *Controlled traffic farming technical manual*, Northern Agricultural Catchments Council, Western Australia.

Ishaq, M, Hassan, A, Saeed, M, Ibrahim, M & Lal, R 2001, 'Subsoil compaction effects on crops in the Punjab, Pakistan I. Soil physical properties and crop yield.', *Soil and Tillage Research*, vol. 59, no. 1-2, pp. 57-65.

Jensen, HG, Jacobsen, L-B, Pedersen, SM & Tavella, E 2012, 'Socioeconomic impact of widespread adoption of precision farming and controlled traffic systems in Denmark', *Precision Agriculture*, vol. 13, no. 6, pp. 661-77.

Jorajuria, D & Draghi, L 1997, 'The Distribution of Soil Compaction with Depth and the Response of a Perennial Forage Crop', *Journal of agricultural engineering research*, vol. 66, no. 4, pp. 261-5.

Jorajuria, D, Draghi, L & Aragon, A 1997, 'The effect of vehicle weight on the distribution of compaction with depth and the yield of Lolium/Trifolium grassland', *Soil and Tillage Research*, vol. 41, no. 1, pp. 1-12.

REFERENCES

Kang, BT, Reynolds, L & Atta-Krah, AN 1990, 'Alley Farming', *Advances in Agronomy*, vol. 43, pp. 315-59.

Karmakar, S, Ashrafizadeh, SR & Kushwaha, RL 2009, 'Experimental validation of computational fluid dynamics modeling for narrow tillage tool draft', *Journal of Terramechanics*, vol. 46, no. 6, pp. 277-83.

Kayombo, B & Lal, R 1993, 'Tillage systems and soil compaction in Africa', *Soil and Tillage Research*, vol. 27, no. 1, pp. 35-72.

Keller, T 2004, 'Soil compaction and soil tillage – studies in agricultural soil mechanics', Doctoral thesis, Swedish University of Agricultural Sciences, Uppsala, Sweden.

Keller, T, Arvidsson, J & Dexter, AR 2007, 'Soil structures produced by tillage as affected by soil water content and the physical quality of soil', *Soil and Tillage Research*, vol. 92, no. 1–2, pp. 45-52.

Khan, SR, Abbasi, MK & Hussan, AU 2012, 'Effect of induced soil compaction on changes in soil properties and wheat productivity under sandy loam and sandy clay loam soils: A greenhouse experiment', *Communications in soil science and plant analysis*, vol. 43, no. 19, pp. 2550-63.

Kingwell, R & Fuchsbichler, A 2011, 'The whole-farm benefits of controlled traffic farming: An Australian appraisal', *Agricultural Systems*, vol. 104, no. 7, pp. 513-21.

Kirby, J 1991, 'Critical-state soil mechanics parameters and their variation for Vertisols in eastern Australia', *Journal of Soil Science*, vol. 42, no. 3, pp. 487-99.

Kiss, G & Bellow, D 1981, 'An analysis of forces on cultivator sweeps and spikes', *Canadian Agricultural Engineering, Saskatoon*, vol. 23, no. 2, pp. 77-83.

Koger, JL, Burt, EC & Trouse, ACJ 1985, 'Multiple Pass Effects of Skidder Tires on Soil Compaction', *Transactions of the ASAE*, vol. 28, no. 1, p. 11.

Komandi, G 1999, 'An evaluation of the concept of rolling resistance', *Journal of Terramechanics*, vol. 36, no. 3, pp. 159-66.

Komatsuzaki, M & Ohta, H 2007, 'Soil management practices for sustainable agro-ecosystems', *Sustainability science*, vol. 2, no. 1, pp. 103-20.

Koolen, A & Kuipers, H 1983, *Agricultural soil mechanics. Advances Series in Agricultural Sciences 13*, Springer-Verlag, Berlin, Germany.[Links].

Koolen, AJ, Lerink, P, Kurstjens, DAG, van den Akker, JJH & Arts, WBM 1992, 'Prediction of aspects of soil-wheel systems', *Soil and Tillage Research*, vol. 24, no. 4, pp. 381-96.

Košutić, S, Filipović, D, Gospodarić, Z, Husnjak, S, Kovačev, I & Čopec, K 2005, 'Effects of different soil tillage systems on yield of maize, winter wheat and soybean on albic luvisol in north-west slavonia', *Journal of central European agriculture*, vol. 6, no. 3, pp. 241-8.

Kroulík, M, Kumhála, F, Hůla, J & Honzík, I 2009, 'The evaluation of agricultural machines field trafficking intensity for different soil tillage technologies', *Soil and Tillage Research*, vol. 105, no. 1, pp. 171-5.

Kurjenluoma, J, Alakukku, L & Ahokas, J 2009, 'Rolling resistance and rut formation by implement tyres on tilled clay soil', *Journal of Terramechanics*, vol. 46, no. 6, pp. 267-75.

REFERENCES

Kushwaha, RL, Chi, L & Shen, J 1993, 'Analytical and numerical models for predicting soil forces on narrow tillage tools', *CANADIAN AGRICULTURAL ENGINEERING*, vol. 35, no. 3, p. 183.

Laguë, C, Agnew, J & Khelifi, M 2003, Theoretical evaluation On The feasibility of controlled-Traffic Farming (CTF) using Wide-Span Implement Carriers (WSIC) for Canadian agriculture, CSAE/SCGR, 03-233.

Laker, M & Du Preez, C 1982, 'investigation into the accuracy of hydrometers for soil particle size determinations', *Agroplantae*, no. 14, pp. 17-22.

Lal, R 1989, 'Conservation Tillage for Sustainable Agriculture: Tropics Versus Temperate Environments', *Advances in Agronomy*, vol. 42, pp. 85-197.

Lamers, JG, Perdok, UD, Lumkes, LM & Klooster, JJ 1986, 'Controlled traffic farming systems in the Netherlands', *Soil and Tillage Research*, vol. 8, no. 0, pp. 65-76.

Lehrsch, GA, Whisler, FD & Römkens, MJM 1987, 'Soil surface roughness as influenced by selected soil physical properties', *Soil and Tillage Research*, vol. 10, no. 3, pp. 197-212.

Li, YX, Tullberg, JN & Freebairn, DM 2001, 'Traffic and residue cover effects on infiltration', *Soil Research*, vol. 39, no. 2, pp. 239-47.

Li, YX, Tullberg, JN, Freebairn, D, McLaughlin, N & Li, H 2008, 'Effects of tillage and traffic on crop production in dryland farming systems: I. Evaluation of PERFECT soil-crop simulation model', *Soil and Tillage Research*, vol. 100, no. 1-2, pp. 15-24.

Li, YX, Tullberg, JN & Freebairn, DM 2007, 'Wheel traffic and tillage effects on runoff and crop yield', *Soil and Tillage Research*, vol. 97, no. 2, pp. 282-92.

Li, YX, Tullberg, JN, Freebairn, DM & Li, HW 2009, 'Functional relationships between soil water infiltration and wheeling and rainfall energy', *Soil and Tillage Research*, vol. 104, no. 1, pp. 156-63.

Lipiec, J & Hatano, R 2003, 'Quantification of compaction effects on soil physical properties and crop growth', *Geoderma*, vol. 116, no. 1-2, pp. 107-36.

Lipiec, J, Arvidsson, J & Murer, E 2003, 'Review of modelling crop growth, movement of water and chemicals in relation to topsoil and subsoil compaction', *Soil and Tillage Research*, vol. 73, no. 1-2, pp. 15-29.

Lipiec, J 2002, 'Impact of soil compaction on crop productivity-Polish experience', In: Canarache, A., Dimitru, E., Enache, R. (Eds.) *Proceedings of the 3rd Workshop, Inco Copernicus Concerted Action Experiences with the Impact of Subsoil Compaction on Soil Nutrients, Crop Growth and Environment, and Ways to Prevent Subsoil Compaction*, Research Institute for Soil Sciences and Agrochemistry, Bucharest, Romania, pp. 229-233.

Liu, K, Ayers, P, Howard, H & Anderson, A 2010, 'Influence of soil and vehicle parameters on soil rut formation', *Journal of Terramechanics*, vol. 47, no. 3, pp. 143-50.

Llewellyn, RS & D'Emden, F 2010, *Adoption of no-till cropping practices in Australian grain growing regions*, Australia. http://www.grdc.com.au/uploads/documents/GRDC_adoption_of_no-till.pdf>.

REFERENCES

López Bravo, E, Herrera Suárez, M, González Cueto, O, Iglesias Coronel, C & Ramon, H 2016, 'Effect of Moisture and Soil Compaction on Tillage Operations', *Revista Ciencias Técnicas Agropecuarias*, vol. 25, no. 1, pp. 32-7.

Lyasko, MI 2010a, 'How to calculate the effect of soil conditions on tractive performance', *Journal of Terramechanics*, vol. 47, no. 6, pp. 423-45.

Lyasko, MI 2010b, 'Multi-pass effect on off-road vehicle tractive performance', *Journal of Terramechanics*, vol. 47, no. 5, pp. 275-94.

Lyles, L & Woodruff, N 1961, 'Surface soil cloddiness in relation to soil density at time of tillage', *Soil Sci*, vol. 91, no. 3, pp. 178-82.

Machado, ALT & Trein, CR 2013, 'Draft prediction models for soil engaging tines in two soils of Rio Grande do Sul, Brazil', *Engenharia Agrícola*, vol. 33, pp. 167-75.

Maclaurin, E 1981, 'The effect of tread pattern on the field performance of tyres', in *Proc. 7th Int. Conf. ISTVS, Calgary*.

Maclaurin, E 1997, 'The use of mobility numbers to predict the tractive performance of wheeled and tracked vehicles in soft cohesive soils', in *Proceedings of the 7th European ISTVS Conference, Ferrara, Italy*, pp. 8-10.

Macmillan, RH 2002, *The mechanics of tractor-implement performance: theory and worked examples: a textbook for students and engineers*, Melbourne, University of Melbourne, .

Mak, J & Chen, Y 2014, 'Simulation of Draft Forces of a Sweep in a Loamy Sand Soil Using the Discrete Element Method', *Canadian Biosystems Engineering*, vol. 56.

Manuwa, SI 2009, 'Performance evaluation of tillage tines operating under different depths in a sandy clay loam soil', *Soil and Tillage Research*, vol. 103, no. 2, pp. 399-405.

Martin, RT 1962, 'Adsorbed water on clay: A review', in E Ingerson (ed.), *Clays and Clay Minerals*, Pergamon, pp. 28-70.

Materechera, SA & Mloza-Banda, HR 1997, 'Soil penetration resistance, root growth and yield of maize as influenced by tillage system on ridges in Malawi', *Soil and Tillage Research*, vol. 41, no. 1, pp. 13-24.

Mathers, AC, Lotspeich, FB, Laase, GR & Wilson, GC 1966, 'Strength of compacted amarillo fine sandy loam as influenced by moisture, clay content, and exchangeable cation1', *Soil Science Society of America Journal*, vol. 30, no. 6, pp. 788-91.

McAllister, M 1983, 'Reduction in the rolling resistance of tyres for trailed agricultural machinery', *Journal of agricultural engineering research*, vol. 28, no. 2, pp. 127-37.

McHugh, AD, Tullberg, JN & Freebairn, DM 2009, 'Controlled traffic farming restores soil structure', *Soil and Tillage Research*, vol. 104, no. 1, pp. 164-72.

McKibben, E & Davidson, J 1940, 'Transport wheels for agricultural machines III. Effect of inflation pressure on the rolling resistance of pneumatic implement tires', *Agricultural Engineering*, vol. 21, no. 1, pp. 25-6.

McKyes, E 1985, *Soil cutting and tillage*, Elsevier, Amsterdam, Netherlands.

McKyes, E 1989, *Agricultural engineering soil mechanics*, vol. 10, Elsevier, Amsterdam ;.

McKyes, E & Ali, OS 1977, 'The cutting of soil by narrow blades', *Journal of Terramechanics*, vol. 14, no. 2, pp. 43-58.

REFERENCES

McKyes, E & Desir, FL 1984, 'Prediction and field measurements of tillage tool draft forces and efficiency in cohesive soils', *Soil and Tillage Research*, vol. 4, no. 5, pp. 459-70.

McPhee, J 2011, *The benefits of controlled traffic farming to assist adaptation to climate change for Australian crop production industries. Submission to House Standing Committee on Primary Industries and Resources*.

McPhee, JE & Aird, PL 2013, 'Controlled traffic for vegetable production: Part 1. Machinery challenges and options in a diversified vegetable industry', *Biosystems Engineering*, vol. 116, no. 2, pp. 144-54.

McPhee, JE, Neale, T & Aird, PL 2013, 'Controlled traffic for vegetable production: Part 2. Layout considerations in a complex topography', *Biosystems Engineering*, vol. 116, no. 2, pp. 171-8.

McPhee, JE, Aird, PL, Hardie, MA & Corkrey, SR 2015, 'The effect of controlled traffic on soil physical properties and tillage requirements for vegetable production', *Soil and Tillage Research*, vol. 149, no. 0, pp. 33-45.

McPhee, JE, Braunack, MV, Garside, AL, Reid, DJ & Hilton, DJ 1995, 'Controlled traffic for irrigated double cropping in a semi-arid tropical environment: Part 3, timeliness and trafficability', *Journal of agricultural engineering research*, vol. 60, no. 3, pp. 191-9.

Meek, BD, Rechel, EA, Carter, LM & DeTar, WR 1988, 'Soil Compaction and its Effect on Alfalfa in Zone Production Systems1', *Soil Science Society of America Journal*, vol. 52, no. 1, pp. 233-6.

Meek, BD, Rechel, EA, Carter, LM & DeTar, WR 1989, 'Changes in Infiltration Under Alfalfa as Influenced by Time and Wheel Traffic', *Soil Science Society of America Journal*, vol. 53, no. 1, pp. 238-41.

Meek, BD, Rechel, E, Carter, LM & DeTar, WR 1992, 'Bulk density of a sandy loam: traffic, tillage, and irrigation-method effects', *Soil Science Society of America Journal*, vol. 56, no. 2, pp. 562-5.

Melland, AR, Antille, DL & Dang, YP 2016, 'Impacts of strategic tillage on soil erosion, nutrient loss in runoff and nitrous oxide emission', in *2016 ASABE Annual International Meeting*: *Proceedings of the 2016 ASABE Annual International Meeting* ASABE, St. Joseph, Mich., p. 1.

Mileusnic´, ZI, Petrovic´, DV & Đevic´, MS 2010, 'Comparison of tillage systems according to fuel consumption', *Energy*, vol. 35, no. 1, pp. 221-8.

Misiewicz, PA 2010, 'The evaluation of the soil pressure distribution and carcass stiffness resulting from pneumatic agricultural tyres', PhD thesis, Cranfield University, UK.

Misiewicz, PA, Richards, TE, Blackburn, K & Godwin, RJ 2016, 'Comparison of methods for estimating the carcass stiffness of agricultural tyres on hard surfaces', *Biosystems Engineering*, vol. 147, pp. 183-92.

Moraes, MTd, Silva, VRd, Zwirtes, AL & Carlesso, R 2014, 'Use of penetrometers in agriculture: a review', *Engenharia Agrícola*, vol. 34, pp. 179-93.

Mouazen, AM & Ramon, H 2002, 'A numerical-statistical hybrid modelling scheme for evaluation of draught requirements of a subsoiler cutting a sandy loam soil, as affected by moisture content, bulk density and depth', *Soil and Tillage Research*, vol. 63, no. 3-4, pp. 155-65.

REFERENCES

Muro, T & O'Brien, J 2004, *Terramechanics: land locomotion mechanics*, A.A. Brakeman Publishers, Tokyo.

Nawaz, MF, Bourrié, G & Trolard, F 2013, 'Soil compaction impact and modelling. A review', *Agronomy for Sustainable Development*, vol. 33, no. 2, pp. 291-309.

Negi, SC, McKyes, E, Raghavan, GSV & Taylor, F 1981, 'Relationships of field traffic and tillage to corn yields and soil properties', *Journal of Terramechanics*, vol. 18, no. 2, pp. 81-90.

Nkakini, S 2015, 'Draught force requirements of a disc plough at various tractor forward speeds in loamy sand soil, during ploughing', *Int. J. Adv. Res. Eng. Tech*, vol. 6, no. 7, pp. 52-68.

Novák, P, Chyba, J, Kumhála, F & Procházka, P 2014, 'Measurement of stubble cultivator draught force under different soil conditions', *Agronomy research*, vol. 12, no. 1, pp. 135-42.

O'Callaghan, J & Farrelly, K 1964, 'Cleavage of soil by tined implements', *Journal of agricultural engineering research*, vol. 9, no. 3, pp. 259-70.

OESD 2018, *Online database for all tractor summary test reports*, http://www.oecd.org/agriculture/tractors/ >.

Oskoui, KE & Voorhees, WB 1991, 'Economic consequences of soil compaction', *Transactions of the ASAE*, vol. 34 no. 6, pp. 2317 - 23.

Pagliai, M, Marsili, A, Servadio, P, Vignozzi, N & Pellegrini, S 2003, 'Changes in some physical properties of a clay soil in Central Italy following the passage of rubber tracked and wheeled tractors of medium power', *Soil and Tillage Research*, vol. 73, no. 1, pp. 119-29.

Panayiotopoulos, KP, Papadopoulou, CP & Hatjiioannidou, A 1994, 'Compaction and penetration resistance of an Alfisol and Entisol and their influence on root growth of maize seedlings', *Soil & Tillage Research*, vol. 31, no. 4, pp. 323-37.

Patterson, DE, Chamen, WCT & Richardson, CD 1980, 'Long-term experiments with tillage systems to improve the economy of cultivations for cereals', *Journal of agricultural engineering research*, vol. 25, no. 1, pp. 1-35.

Payne, P 1956, 'The relationship between the mechanical properties of soil and the performance of simple cultivation implements', *Journal of agricultural engineering research*, vol. 1, no. 1, pp. 23-50.

Payne, P & Tanner, D 1959, 'The relationship between rake angle and the performance of simple cultivation implements', *Journal of agricultural engineering research*, vol. 4, no. 4, pp. 312-25.

Peng, XH, Horn, R, Zhang, B & Zhao, QG 2004, 'Mechanisms of soil vulnerability to compaction of homogenized and recompacted Ultisols', *Soil and Tillage Research*, vol. 76, no. 2, pp. 125-37.

Perumpral, JV 1987, 'Cone penetrometer applications — a review', *Transactions of the ASAE*, vol. 30, no. 4, pp. 939-44.

Perumpral, JV, Grisso, RD & Desai, CS 1983, 'A Soil-Tool Model Based on Limit Equilibrium Analysis', *Transactions of the ASAE*, vol. 26, no. 4, pp. 991-0995.

Plackett, CW 1984, 'The ground pressure of some agricultural tyres at low load and with zero sinkage', *Journal of agricultural engineering research*, vol. 29, no. 2, pp. 159-66.

Qingjie, W, Hao, C, Hongwen, L, Wenying, L, Xiaoyan, W, McHugh, AD, Jin, H & Huanwen, G 2009, 'Controlled traffic farming with no tillage for improved fallow water storage and crop yield on the Chinese Loess Plateau', *Soil and Tillage Research*, vol. 104, no. 1, pp. 192-7.

Rab, A, Bradshaw, J, Campbell, R & Murphy, S 2005, *Review of factors affecting disturbance, compaction and trafficability of soils with particular reference to timber harvesting in the forests of South-West Western Australia*, Department of conservation and land management, Kensington, Western Australia.

Radford, R & Yule, D 2003, 'Compaction persists for five years after cessation of wheel traffic on a Vertisol in Central Queensland', in *Proceedings of the International Soil Tillage Research Organisation* Brisbane, Australia pp. 13-8.

Raper, R, Reeves, D, Burmester, C & Schwab, E 2000, 'Tillage depth, tillage timing, and cover crop effects on cotton yield, soil strength, and tillage energy requirements', *Applied Engineering in Agriculture*, vol. 16, no. 4, pp. 379-86.

Raper, RL 2005, 'Agricultural traffic impacts on soil', *Journal of Terramechanics*, vol. 42, no. 3, pp. 259-80.

Raper, RL & Sharma, AK 2004, 'Soil moisture effects on energy requirements and soil disruption of subsoiling a coastal plain soil', *Transactions of the ASAE*, vol. 47, no. 6, p. 1899.

Raper, RL, Bailey, AC, Burt, EC, Way, TR & Liberati, P 1995, 'Inflation Pressure and Dynamic Load Effects on Soil Deformation and Soil-tire Interface Stresses', *Transactions of the ASAE*, vol. 38, no. 3, pp. 685-9.

Reece, A 1965, 'The Fundamental Equation Of Earth Moving Machinery', in *Proc. Symp. Earth Moving Machinery, Inst. of Mech. Eng. London*.

Reeder, RC 2006, 'Controlled traffic', in R Lal (ed.), *Encyclopedia of soil science*, Second edn, Taylor and Francis Group, London.

Reeder, RC, Wood, RK & Finck, CL 1993, 'Five subsoiler designs and their effects on soil properties and crop yields', *Transactions of the ASAE*, vol. 36, no. 6, pp. 1525-31.

Romkens, MJ & Wang, JY 1986, 'Effect of tillage on surface roughness', *Transactions of the ASAE*, vol. 29, no. 2, pp. 429-0433.

Rowe, RJ & Barnes, KK 1961, 'Influence of speed on elements of draft of a tillage tool', *Transactions of the ASAE*, vol. 4, no. 1, pp. 55-7.

Rowland, D 1972, 'Tracked vehicle ground pressure and its effect on soft ground performance', in *Proc. 4th Int. Conf. of Int. Soc. Terrain Vehicle Systems*.

Rowland, D & Peel, J 1975, 'Soft ground performance prediction and assessment for wheeled and tracked vehicles', *Institute of mechanical engineering*, vol. 205, p. 81.

Saarilahti, M 2002, *Soil interaction model. Manual 1. Seltra. Documentation of the computer programme for calculating of the trafficability of terrain and the mobility of forest tractors.*, 10, University of Helsinki, Department of forest resource management, http://hdl.handle.net/1975/8024>.

REFERENCES

Saffih-Hdadi, K, Défossez, P, Richard, G, Cui, YJ, Tang, AM & Chaplain, V 2009, 'A method for predicting soil susceptibility to the compaction of surface layers as a function of water content and bulk density', *Soil and Tillage Research*, vol. 105, no. 1, pp. 96-103.

Sahu, RK & Raheman, H 2006, 'Draught Prediction of Agricultural Implements using Reference Tillage Tools in Sandy Clay Loam Soil', *Biosystems Engineering*, vol. 94, no. 2, pp. 275-84.

Sánchez-Girón, V, Serrano, A, Suárez, M, Hernanz, JL & Navarrete, L 2007, 'Economics of reduced tillage for cereal and legume production on rainfed farm enterprises of different sizes in semiarid conditions', *Soil and Tillage Research*, vol. 95, no. 1, pp. 149-60.

Sands, R, Greacen, E & Gerard, C 1979, 'Compaction of sandy soils in Radiata pine forests. I. A penetrometer study', *Soil Research*, vol. 17, no. 1, pp. 101-13.

Sarauskis, E, Buragieneė, S, Masilionytė, L, Romaneckas, K, Avizienytė, D & Sakalauskas, A 2014, 'Energy balance, costs and CO_2 analysis of tillage technologies in maize cultivation', *Energy*, vol. 69, pp. 227-35.

Schäfer-Landefeld, L, Brandhuber, R, Fenner, S, Koch, H-J & Stockfisch, N 2004, 'Effects of agricultural machinery with high axle load on soil properties of normally managed fields', *Soil and Tillage Research*, vol. 75, no. 1, pp. 75-86.

Schafer, RL, Johnson, CE, Koolen, AJ, Gupta, SC & Horn, R 1992, 'Future research needs in soil compaction', *Transactions of the ASAE*, vol. 35, no. 6, pp. 1761-70.

Schjønning, P, Lamandé, M, Berisso, FE, Simojoki, A, Alakukku, L & Andreasen, RR 2013, 'Gas Diffusion, Non-Darcy Air Permeability, and Computed Tomography Images of a Clay Subsoil Affected by Compaction', *Soil Science Society of America Journal*, vol. 77, no. 6, pp. 1977-90.

Schlesinger, S 1979, 'Terminology for model credibility', *Simulation*, vol. 32, no. 3, pp. 103-4.

Schwab, EB, Reeves, DW, Burmester, CH & Raper, RL 2002, 'Conservation tillage systems for Cotton in the Tennessee Valley Joint contribution of the USDA-ARS and Auburn University Alabama Agric. Exp. Stn. research supported in part by the Alabama Cotton Commission', *Soil Science Society of America Journal*, vol. 66, no. 2, pp. 569-77.

Seker, C & İşıldar, A 2000, 'Effects of wheel traffic porosity and compaction of soil profile', *Turkish Journal of Agriculture & Forestry*, vol. 24, no. 1, pp. 71-7.

Senatore, C & Sandu, C 2011, 'Torque distribution influence on tractive efficiency and mobility of off-road wheeled vehicles', *Journal of Terramechanics*, vol. 48, no. 5, pp. 372-83.

Shen, J & Kushwaha, RL 1998, *Soil-machine interactions: a finite element perspective*, Marcel Dekker Inc.

Shoop, SA 2009, 'Traction Mechanics. Part VI. Terrain Characterization for Trafficability Studies', in SK Upadhyaya, et al. (eds), *Advances in Soil Dynamics*, American Society of Agricultural and Biological Engineers, 2950 Niles Rd., St. Joseph, MI 49085-9659 USA., ch 2, pp. 186-208.

Sidhu, D & Duiker, SW 2006, 'Soil compaction in conservation tillage', *Agronomy Journal*, vol. 98, no. 5, pp. 1257-64.

REFERENCES

Silva, SRd, Barros, NFd, Costa, LMd & Leite, FP 2008, 'Soil compaction and eucalyptus growth in response to forwarder traffic intensity and load', *Revista Brasileira de Ciência do Solo*, vol. 32, pp. 921-32.

Smith, C, Johnston, M & Lorentz, S 1997, 'The effect of soil compaction and soil physical properties on the mechanical resistance of South African forestry soils', *Geoderma*, vol. 78, no. 1, pp. 93-111.

Smith, DLO, Godwin, RJ & Spoor, G 1989, 'Modeling Soil Disturbance Due to Tillage and Traffic', in WE Larson, et al. (eds), *Mechanics and Related Processes in Structured Agricultural Soils*, Springer Netherlands, Dordrecht, pp. 121-36.

Smith, E, Misiewicz, P, Girardello, V, Arslan, S, Chaney, K, White, D & Godwin, R 2014, 'Effects of traffic and tillage on crop yield (winter wheat Triticum aestivum) and the physical properties of a sandy loam soil', in *2014 Montreal, Quebec Canada July 13 – July 16, 2014*: *Proceedings of the 2014 Montreal, Quebec Canada July 13 – July 16, 2014* ASABE, St. Joseph, Mich., p. 1.

Soane, B, Dickson, J & Blackwell, P 1979, 'Some options for reducing compaction under wheels on loose soil', in *Proceedings 8th Triennial Conference of the International Soil and Tillage Research Organisation*, pp. 347-52.

Soane, BD 1983, *Compaction by agricultural vehicles*, Scottish Institute of Agricultural Engineering (SIAE).

Soane, BD 1990, 'The role of organic matter in soil compactibility: A review of some practical aspects', *Soil and Tillage Research*, vol. 16, no. 1, pp. 179-201.

Soane, BD & van Ouwerkerk, C 1980, 'The role of field traffic studies in soil management research', *Soil and Tillage Research*, vol. 1, pp. 205-6.

Soane, BD, Dickson, JW & Campbell, DJ 1982, 'Compaction by agricultural vehicles: A review III. Incidence and control of compaction in crop production', *Soil and Tillage Research*, vol. 2, no. 1, pp. 3-36.

Soane, BD, Blackwell, PS, Dickson, JW & Painter, DJ 1980a, 'Compaction by agricultural vehicles: A review I. Soil and wheel characteristics', *Soil and Tillage Research*, vol. 1, pp. 207-37.

Soane, BD, Blackwell, PS, Dickson, JW & Painter, DJ 1980b, 'Compaction by agricultural vehicles: A review II. Compaction under tyres and other running gear', *Soil and Tillage Research*, vol. 1, pp. 373-400.

Sohne, W 1958, 'Fundamentals of pressure distribution and soil compaction under tractor tires', *Agricultural Engineering*, vol. 39, p. 290.

Solhjou, A, Desbiolles, JMA & Fielke, JM 2013, 'Soil translocation by narrow openers with various blade face geometries', *Biosystems Engineering*, vol. 114, no. 3, pp. 259-66.

Somasundaram, J, Reeves, S, Wang, W, Heenan, M & Dalal, R 2017, 'Impact of 47 Years of No Tillage and Stubble Retention on Soil Aggregation and Carbon Distribution in a Vertisol', *Land Degradation and Development*, vol. 28, no. 5, pp. 1589-602.

Sommer, C, Dambroth, M & Zach, M 1988, 'The mulch-seed concept as part of conservation tillage and integrated crop production', in *Proc. 11 th Conf. Int. Soil Tillage Res. Org., Edinburgh*, pp. 875-9.

REFERENCES

Souza, GS, Souza, ZM, Silva, RB, Barbosa, RS & Araújo, FS 2014, 'Effects of traffic control on the soil physical quality and the cultivation of sugarcane', *R. Bras. Ci. Solo*, vol. 38, pp. 135-46.

Spoor, G 1997, 'Benefits from traffic control', *Landwards*, vol. 52, pp. 2–5.

Spoor, G & Godwin, RJ 1978, 'An experimental investigation into the deep loosening of soil by rigid tines', *Journal of agricultural engineering research*, vol. 23, no. 3, pp. 243-58.

Stafford, JV 1979, 'The performance of a rigid tine in relation to soil properties and speed', *Journal of agricultural engineering research*, vol. 24, no. 1, pp. 41-56.

Stafford, JV & Tanner, DW 1983, 'Effect of rate on soil shear strength and soil-metal friction I. Shear strength', *Soil and Tillage Research*, vol. 3, no. 3, pp. 245-60.

Summers, JD, Khalilian, A & Batchelder, D 1986, 'Draft relationships for primary tillage in Oklahoma soils', *Transactions of the ASAE*, vol. 29, no. 1, pp. 37-0039.

Swan, AR & Sandilands, M 1995, 'Introduction to geological data analysis', p. 446.

Swick, WC & Perumpral, JV 1988, 'A model for predicting soil-tool interaction', *Journal of Terramechanics*, vol. 25, no. 1, pp. 43-56.

Tagar, AA, Ji, C, Ding, Q, Adamowski, J, Chandio, FA & Mari, IA 2014, 'Soil failure patterns and draft as influenced by consistency limits: An evaluation of the remolded soil cutting test', *Soil and Tillage Research*, vol. 137, pp. 58-66.

Taheri, S, Sandu, C, Taheri, S, Pinto, E & Gorsich, D 2015, 'A technical survey on Terramechanics models for tire–terrain interaction used in modeling and simulation of wheeled vehicles', *Journal of Terramechanics*, vol. 57, no. 0, pp. 1-22.

Taylor, JH 1983, 'Benefits of permanent traffic lanes in a controlled traffic crop production system', *Soil and Tillage Research*, vol. 3, no. 4, pp. 385-95.

Taylor, JH 1994, 'Development and Benefits of Vehicle Gantries and Controlled-Traffic Systems', in BD Soane & C van Ouwerkerk (eds), *Soil Compaction in Crop Production*, vol. 11, pp. 521-37.

Thomsen, LM, Baartman, JEM, Barneveld, RJ, Starkloff, T & Stolte, J 2015, 'Soil surface roughness: comparing old and new measuring methods and application in a soil erosion model', *SOIL*, vol. 1, no. 1, pp. 399-410.

Tiwari, VK, Pandey, KP & Pranav, PK 2010, 'A review on traction prediction equations', *Journal of Terramechanics*, vol. 47, no. 3, pp. 191-9.

TMR 2013, *Guideline for excess dimension - vehicles carrying indivisible articles, special purpose vehicles, vehicles that require a pilot or escort, in Queensland*, 8, 5, Department of Transport and Main Roads, Queensland government, <https://www.nhvr.gov.au/files/t045-qld-guideline-for-excess-dimension.pdf >.

Tullberg, JN 1986, *Controlled traffic tillage and planting*, Australian Department of Primary Industries and Energy, Canberra, Australia

Tullberg, JN 1990, 'Why control field traffic', in *Proceedings of Queensland, Department of Primary Industries Soil Compaction Workshop, Toowoomba, Australia*, , pp. 13-25.

Tullberg, JN 2000, 'Wheel traffic effects on tillage draught', *Journal of agricultural engineering research*, vol. 75, no. 4, pp. 375-82.

REFERENCES

Tullberg, JN 2007, 'Why Controlled Traffic Farming?', in *5th Australian Controlled Traffic and Precision Agriculture Conference*: *Proceedings of the 5th Australian Controlled Traffic and Precision Agriculture Conference* University of Western Australia, pp. 209-13.

Tullberg, JN 2008, 'CTF and Climate Change', in *6th Australian Controlled Traffic Farming Conference*: *Proceedings of the 6th Australian Controlled Traffic Farming Conference* Parkes, NSW, pp. 86-90.

Tullberg, JN 2010, 'Tillage, traffic and sustainability—A challenge for ISTRO', *Soil and Tillage Research*, vol. 111, no. 1, pp. 26-32.

Tullberg, JN 2014, 'Energy in crop production systems ', in J Bundschuh & G Chen (eds), *Sustainable energy solutions in agriculture* Taylor and Francis group, London, UK, ch 3, pp. 53-76.

Tullberg, JN & Murray, S 1987, *Controlled traffic tillage and planting.*, Farm Mechanization Centre, . Agriculture College, Lawes, Old, Australia, National Energy Research Development and Demonstration Council, Canberra, Australia.

Tullberg, JN, Ziebarth, PJ & Li, Y 2001, 'Tillage and traffic effects on runoff', *Soil Research*, vol. 39, no. 2, pp. 249-57.

Tullberg, JN, Yule, DF & McGarry, D 2007, 'Controlled traffic farming—From research to adoption in Australia', *Soil and Tillage Research*, vol. 97, no. 2, pp. 272-81.

Tullberg, JN, McHugh, A, Ghareel Khabbaz, B, Scheer, C & Grace, P 2011, 'Controlled traffic/permanent bed farming reduces GHG emissions.', in *5th World Congress of Conservation Agriculture incorporating 3rd Farming Systems Design Conference*: *Proceedings of the 5th World Congress of Conservation Agriculture incorporating 3rd Farming Systems Design Conference* Brisbane, Australia, pp. 1-3.

Tullberg, JN, Antille, DL, Bluett, C, Eberhard, J & Scheer, C 2018, 'Controlled traffic farming effects on soil emissions of nitrous oxide and methane', *Soil and Tillage Research*, vol. 176, pp. 18-25.

Turnage, G 1972, 'Tire selection and performance prediction for off-road wheeled vehicle operations', in *Proc. 4th Internat. Conf. Internat. Soc. Terrain-Vehicle Systems*.

Unger, PW 1996, 'Soil bulk density, penetration resistance, and hydraulic conductivity under controlled traffic conditions', *Soil and Tillage Research*, vol. 37, no. 1, pp. 67-75.

Upadhyaya, SK, Andrade-Sanchez, P, Sakai, K, Chancellor, WJ & Godwin, RJ 2009, 'Tillage', in SK Upadhyaya, et al. (eds), *In advances in soil dynamics*, ASABE, St. Joseph, MI, vol. 3, ch 3, pp. 273-322.

Van Bergeijk, J, Goense, D & Speelman, L 2001, 'PA—Precision agriculture: Soil tillage resistance as a tool to map soil type differences', *Journal of agricultural engineering research*, vol. 79, no. 4, pp. 371-87.

Varsa, EC, Chong, SK, Abolaji, JO, Farquhar, DA & Olsen, FJ 1997, 'Effect of deep tillage on soil physical characteristics and corn (Zea mays L.) root growth and production', *Soil and Tillage Research*, vol. 43, no. 3, pp. 219-28.

Vepraskas, MJ & Wagger, MG 1990, 'Corn Root Distribution and Yield Response to Subsoiling for Paleudults Having Different Aggregate Sizes', *Soil Science Society of America Journal*, vol. 54, no. 3, pp. 849-54.

REFERENCES

Vermeulen, GD & Mosquera, J 2009, 'Soil, crop and emission responses to seasonal-controlled traffic in organic vegetable farming on loam soil', *Soil and Tillage Research*, vol. 102, no. 1, pp. 126-34.

Vermeulen, GD, Tullberg, JN & Chamen, WCT 2010, 'Controlled Traffic Farming', in AP Dedousis & T Bartzanas (eds), *Soil Engineering*, Springer Berlin Heidelberg, vol. 20, ch 8, pp. 101-20.

Vero, SE, Antille, DL, Lalor, STJ & Holden, NM 2014, 'Field evaluation of soil moisture deficit thresholds for limits to trafficability with slurry spreading equipment on grassland', *Soil use and management*, vol. 30, no. 1, pp. 69-77.

Voorhees, WB 1979, 'Energy aspects of controlled wheel traffic in the northern Corn Belt of the United States', in *Proc. 8th Conference of the International Soil Tillage Research Organization*, ISTRO, University of Hohenheim, FRG, Stuttgart-Hohenheim, pp. 333-8.

Voorhees, WB 1986, 'The effect of soil compaction on crop yield', *Proceedings of the* SAE International.

Voorhees, WB, Senst, CG & Nelson, WW 1978, 'Compaction and soil structure sodification by wheel traffic in the northern corn belt 1', *Soil Science Society of America Journal*, vol. 42, no. 2, pp. 344-9.

Walker, SE, Mitchell, JK, Hirschi, MC & Johnsen, KE 2000, 'Sensitivity analysis of the root zone water quality model', *Transactions of the ASAE*, vol. 43, no. 4, pp. 841-6.

Walsh, P 2002, 'New method yields a worm's-eye view', *Farming Ahead*, no. 132, pp. 16-8.

Wang, X, Gao, H, Tullberg, JN, Li, H, Kuhn, N, McHugh, AD & Li, Y 2008, 'Traffic and tillage effects on runoff and soil loss on the Loess Plateau of northern China', *Soil Research*, vol. 46, no. 8, pp. 667-75.

Wheeler, P & Godwin, R 1996, 'Soil dynamics of single and multiple tines at speeds up to 20 km/h', *Journal of agricultural engineering research*, vol. 63, no. 3, pp. 243-9.

White, J 2007, '*Counting the cost of soil compaction*', Department of Primary Industries Victoria, Ballarat, Australia.

Whitlow, R 2001, *Basic soil mechanics*, Fourth edition. edn, Prentice Hall, an imprint of Pearson Education, Harlow, England.

Williford, J 1980, 'A controlled-traffic system for cotton production', *Transactions of the ASAE*, vol. 23, no. 1, pp. 65-0070.

Willis, TM, Hall, DJM, McKenzie, DC & Barchia, I 1997, 'Soybean yield as affected by crop rotations, deep tillage and irrigation layout on a hardsetting Alfisol', *Soil and Tillage Research*, vol. 44, no. 3, pp. 151-64.

Wismer, RD & Luth, HJ 1973, 'Off-road traction prediction for wheeled vehicles', *Journal of Terramechanics*, vol. 10, no. 2, pp. 49-61.

Wong, JY 2010, *Terramechanics and off-road vehicle engineering: terrain behaviour, off-road vehicle performance and design*, 2nd edn, Elsevier, Amsterdam.

Wood, R & Burt, E 1987, 'Thrust and motion resistance from soil-tire interface stress measurements', *Transactions of the ASAE*, vol. 30, no. 5, pp. 1288-92.

REFERENCES

Yavuzcan, HG 2000, 'Wheel traffic impact on soil conditions as influenced by tillage system in Central Anatolia', *Soil and Tillage Research*, vol. 54, no. 3–4, pp. 129-38.

Yavuzcan, HG, Vatandas, M & Gürhan, R 2002, 'Soil strength as affected by tillage system and wheel traffic in wheat -corn rotation in central Anatolia', *Journal of Terramechanics*, vol. 39, no. 1, pp. 23-34.

Yong, RN, Fattah, EA & Skiadas, N 1984, *Vehicle traction mechanics*, Elsevier, Amsterdam, the Netherlands.

Yule, D, Cannon, R & Chapman, W 2000, 'Controlled traffic farming–technology for sustainability', in *Proceedings of the 15th Conference of the International Soil Tillage Research Organization*, pp. 2-7.

Zeng, D & Yao, Y 1992, 'A dynamic model for soil cutting by blade and tine', *Journal of Terramechanics*, vol. 29, no. 3, pp. 317-27.

Zoz, FM 1970, 'Predicting tractor field performance', *ASAE Paper*, pp. 70-118.

Zoz, FM & Grisso, RD 2003, 'Traction and Tractor Performance', in *Agricultural Equipment Technology Conference, 9-11 February 2003*,, ASAE, Louisville, Kentucky USA., pp. 1-47, <http://elibrary.asabe.org/abstract.asp?adid=16586&t=6>.

APPENDICES

APPENDIX TO CHAPTER 3

APPENDICES

APPENDIX TO CHAPTER 3

Appendix A3.1: Plot layout for soil measurements

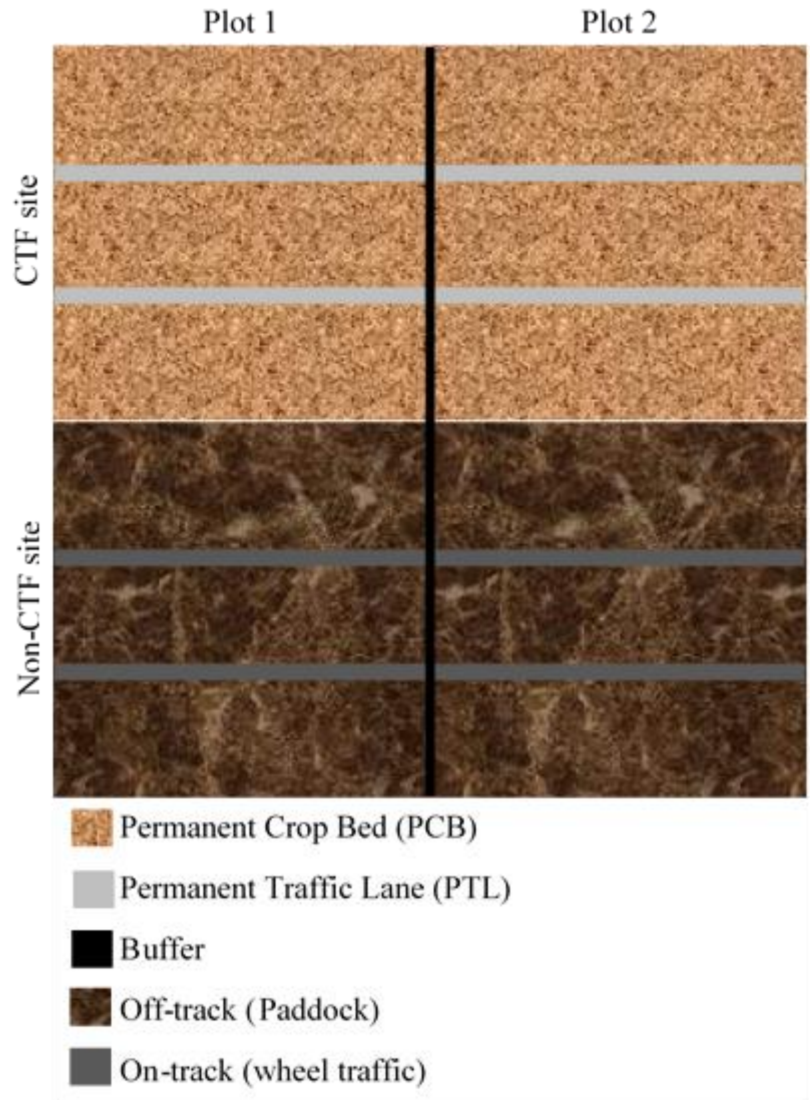


Figure A3.1: plots of experiment layout for soil measurements

Appendix A3.2: Penetrometer

Figure A3.2: Rimik Penetrometer used to measure the penetration resistance of studied soils

Appendix A3.3: Shear vane

Figure A3.3: Shear vane used to measure shear force of studied soils.

Appendix A3.4: Profile meter

Figure A3.4: Profile meter used to measure soil surface roughness and rut depth.

Appendix A3.5: Rimik DataNode Load Cell Analogue Reading Process

A3.5.1: Load Cell Interface Board

Load Cells are generally manufactured to output 2 or 3mV per (supply) Volt. In the instance of Force Meters recently manufactured for USQ all load cells supplied for the project operate at 3mV/V.

Rimik DataNodes are designed to operate from the 5V rail in voltage input mode. This means that with 5V supplied to the load cell it will output in the range of 0 to 15mV. The load cell may exceed 15mV if a load in excess of it maximum capacity is applied. The maximum capacity is generally accepted as the limit of the linear range of the device however a load cell should be able to tolerate approximately 150% of maximum capacity before mechanical failure render the load cell inoperable. Readings in excess of the maximum capacity may not be accurate.

In order that the DataNode can accurately determine the value of the input signal across its full 0 to 5V range, the signal from the load cell must be amplified.

The amplification circuit is depicted in the attached document

Load_Cell_Interface_Board – Schematic (**Figure A3.5**)

This circuit can accept two load cell inputs and provide two amplified outputs to the DataNode I/O ports. The output from this circuit will operate between the calibrated zero output (50mV) and the maximum output of the circuit (5.000V).

The gain of the amplification circuit is set by the resistor configuration and is designed so that 15mV input is equal to 4.750V output. This enables the system to read past the maximum capacity of the load cell but only to approximately 105%. Firmware within the DataNode limits the maximum recorded reading to the maximum capacity of the load cell. The user should be aware that maximum capacity readings may exceed the recorded result. If that is a regular occurence it is recommended to move to a higher capacity load cel

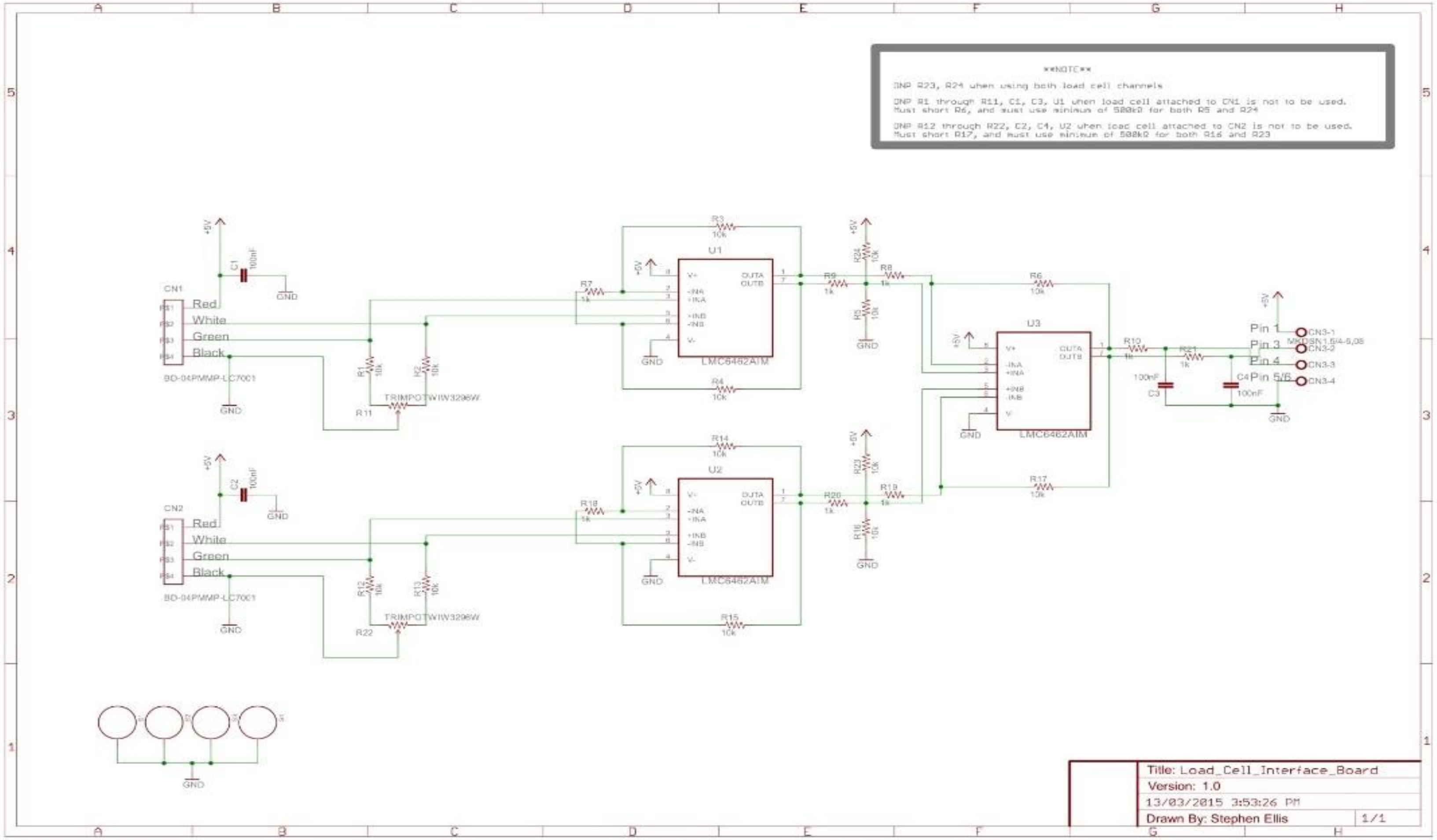


Figure A3.5: Rimik Load Cell Interface Board (http://www.rimik.com)

A3.5.2: Electrical Zero Calibration of the Load Cell Circuit

Rimik recommends calibrating the minimum or electric zero output of the load cell circuit to 50mV. In order to do this the technician measures the output voltage of one circuit (connected to a specified load cell) and adjusts the respective trimpot (R11 or R22) until the output voltage is 50mV

A3.5.3: DataNode Sensor Sampling System

The input voltage to the DataNode I/O port (max 5V) is passed through a voltage divider to split the voltage in half (i.e. a maximum of 2.5V). The input voltage is compared against a fixed regulated reference voltage of 2.500V within the DataNode's Microprocessor ADC (Analogue to Digital Converter). The raw result is then used within the code to generate a reading.

The DataNode uses Oversampling and Decimation in conjunction with a median filter to produce the result recorded and/or displayed to a user.

The DataNode has a 10 bit Analogue to Digital Converter [ADC] – for any given analogue input, the ADC can resolve that input to one of 1024 digital steps. Using the method of oversampling and decimation, an approximation of a 12-bit ADC is generated, allowing the DataNode to resolve analogue inputs into any of 4096 digital values.

The process is as follows: the DataNode initiates a reading for a given input channel. The ADC is put into free running mode and a series of 16 readings are taken. The sum of all 16 readings is then divided by 16 to generate the average reading over the time taken to complete the readings – this is oversampling and decimation.

10 of these oversampled and decimated results are calculated and sorted into numerical order. The highest and lowest value are ignored (in order to reduce noise in the reading) and the remaining 8 values are averaged and scaled against the ADC's maximum reading to get a raw reading in the appropriate unit.

For channels set up for use with load cells, this raw reading then has the load cell 'no load' calibration reading subtracted before being multiplied by the slope calculated during calibration, to give the load.

The total time to read each channel (i.e. a total of 160 readings) is less than 15 ms.

A3.5.4: Calibration of the Input Channel

A specified load cell is attached to a DataNode I/O channel via the load cell amplification circuit. It is necessary that load cells and amplification input circuits are correctly labelled as they need to be matched in all future use for calibration to remain effective. The output of load cell amplification circuits are internally and permanently wired to DataNode I/O ports and provide the DataNode remains correctly configured, there is no need for future alteration of channel setup (except if re-calibrating the system).

Load Cell calibration is carried out in the DataNode Interface software in Technician mode so that it is protected from accidental change when in standard User mode. The calibration process is accessed in the Node Channel Setup tab depicted below.

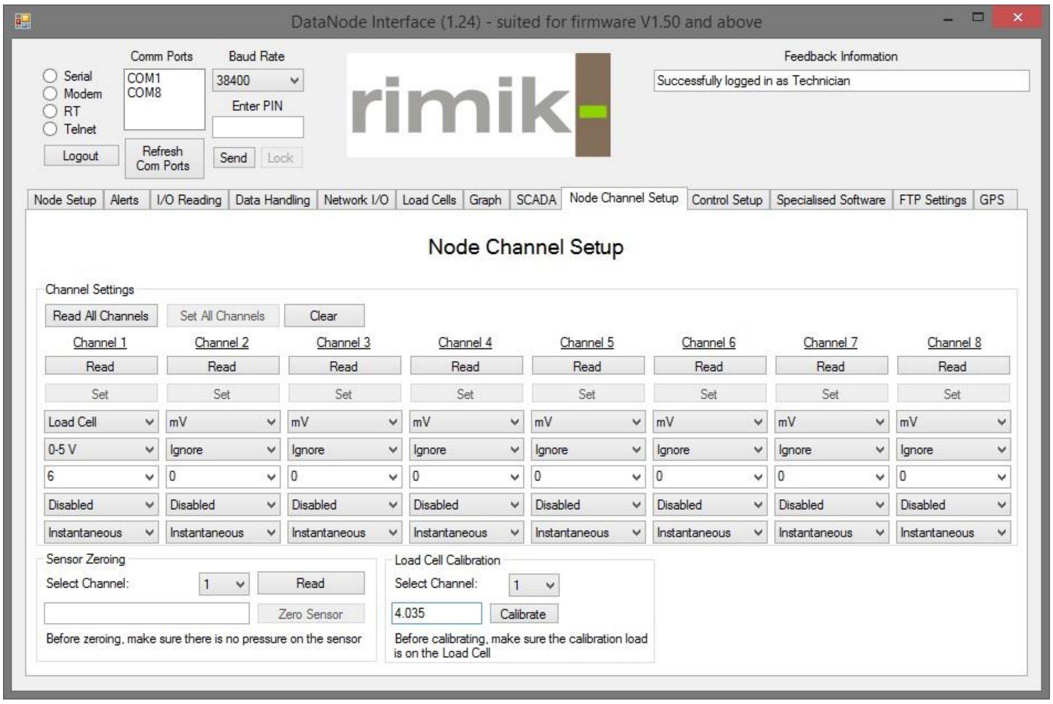
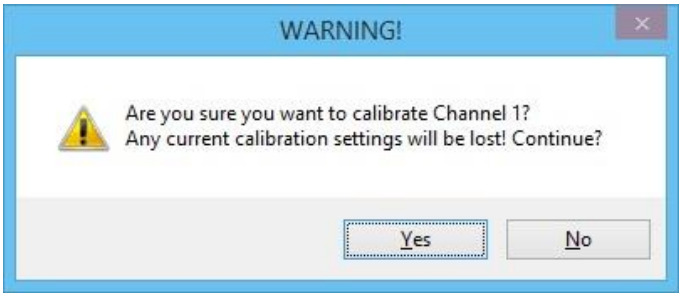


Figure A3.6: Rimik DataNode Interface software (http://www.rimik.com)

Channel one has been set up as a Load Cell input. Its input type is 0-5V and the maximum capacity in this case is 8kN. The readings are taken on an instantaneous basis. Note that this system is designed to be calibrated and read in kN.

In order to now carry out calibration of the sensor the first step is to select the channel and set the zero intercept via "Zero Sensor". This value is stored against the channel setup and used in determining the calibrated result from raw reading values returned from the reading cycle. It will remain in permanent memory until the Technician reset the zero. This value will be the raw electrical zero i.e. 50mV or similar.

The next step is to apply a known load to the load cell. This is generally at least half of the maximum capacity. In our case we have used 4.035kN. Upon selecting "Calibrate", the Technician receives the following warning and a Yes response is required to complete the calibration process.



The DataNode will take the current raw reading of the sensor in mV then calculate and permanently store the slope for this channel. The calculation is shown below:

$$\boldsymbol{Slope} = \frac{\boldsymbol{Calibration\ Input}}{\boldsymbol{Current\ Raw\ Reading\ (mV) - Zero\ Raw\ Reading\ (mV)}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textbf{Equation A3.1}$$

As an example:

$$\boldsymbol{Slope} = \frac{\mathbf{4.035}}{\mathbf{2390-50}} = \mathbf{0.001724} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textbf{Equation A3.2}$$

A3.5.5: Converted (Calibrated) Reading Calculation:

When in normal reading mode the DaaNode will return converted and calibrated result each second.

To calculate the actual load applied to the Load Cell the DataNode uses the final raw result from the ADC (see the reading process above) to convert it directly to a calibrated kN value

$$\boldsymbol{Converted\ Reading} = (\boldsymbol{Current\ Reading} - \boldsymbol{Zero\ Reading}) * \boldsymbol{Slope} \ldots\ldots \textbf{Equation A3.3}$$

As an example:

$$\boldsymbol{Sensor\ Reading} = (\mathbf{1234} - \mathbf{50}) * \mathbf{0.001724} = \mathbf{2.042}\ \boldsymbol{kN} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textbf{Equation A3.4}$$

Appendix A3.6: Calibration curves-Transducers and pull meter

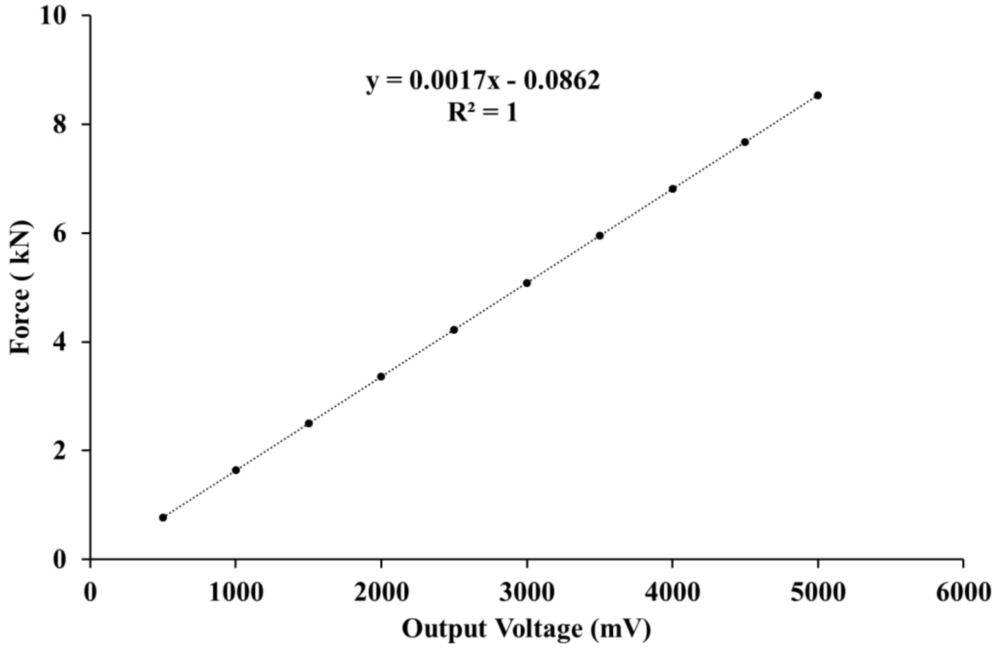


Figure A3.7: Transducers calibration

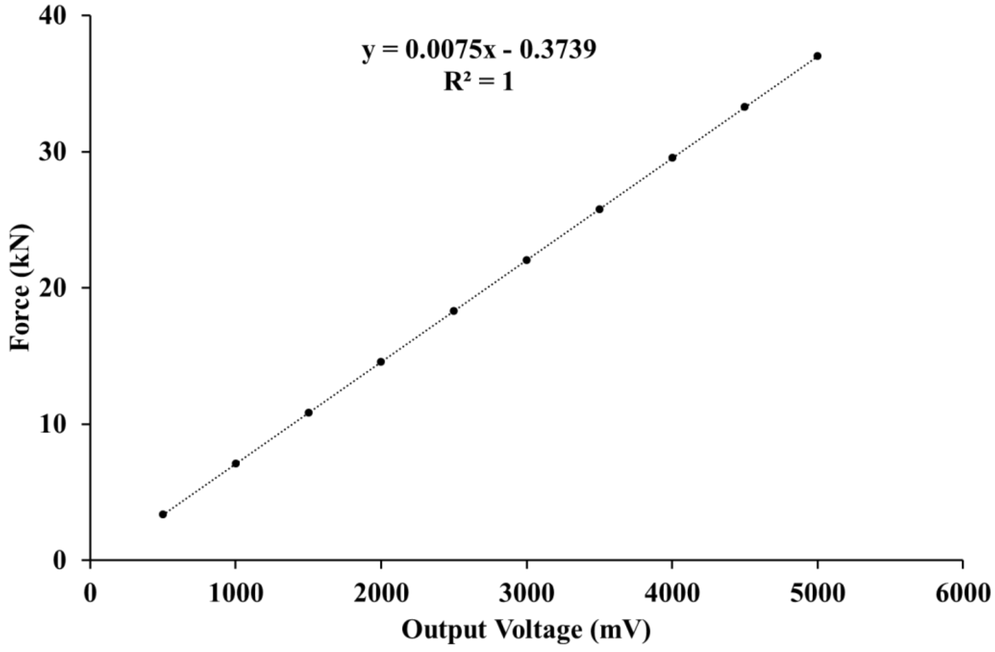


Figure A3.8: Pull meter calibration

Appendix A3.7: Experimental tines

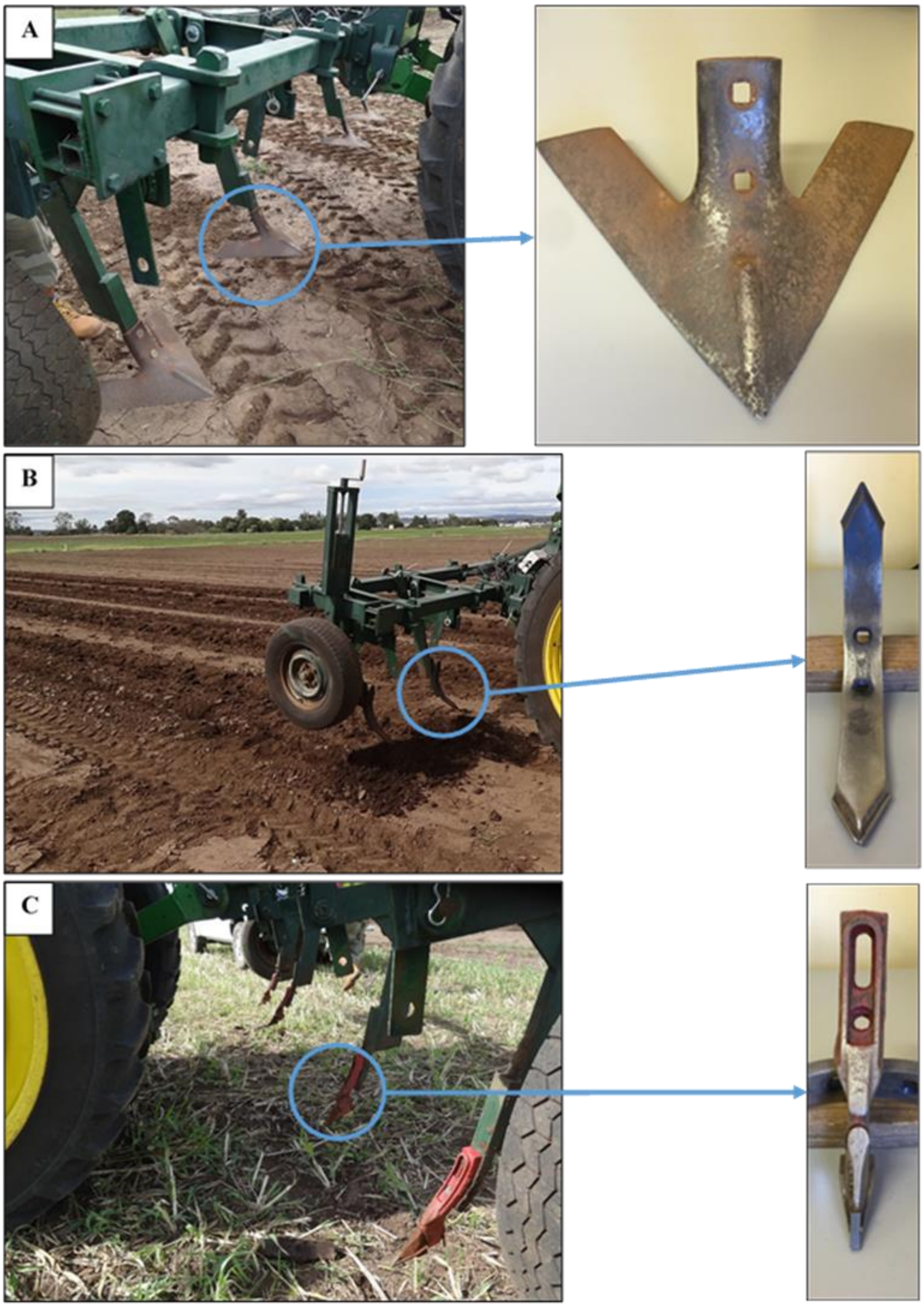


Figure A3.9: Experimental tines A: Sweep tines; B: Chisel tines; and C: seeding opener tines

Appendix A3.8: Hitch of implements

A3.8.1: Three-Point Hitch

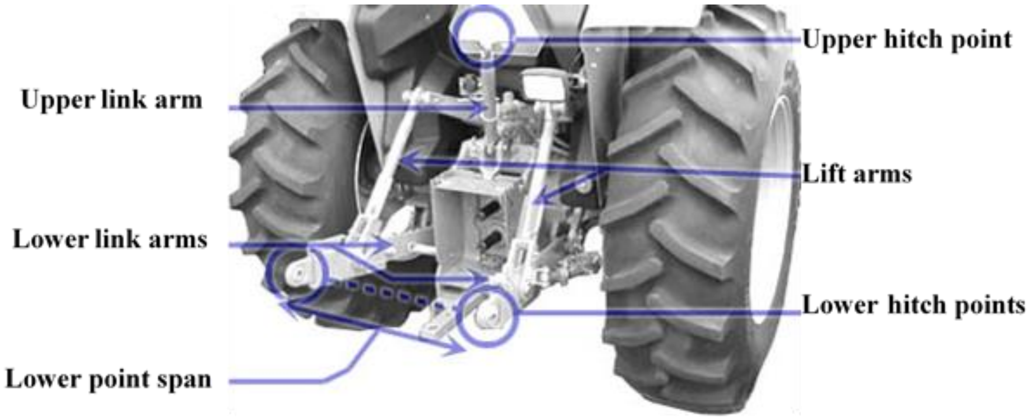


Figure A3.10: Three-point linkage

Table A3.1: Three-point hitch specifications

Category	Hitch pin size		Lower hitch spacing	Tractor drawbar power
	upper link	lower links		
0	17 mm	17 mm	500 mm	<15 kW
1	19 mm	22.4 mm	718 mm	15-35 kW
2	25.5 mm	28.7 mm	870 mm	30-75 kW
3	31.75 mm	37.4 mm	1010 mm	60-168 kW
4	45 mm	51 mm	1220 mm	135-300 kW

A3.8.2: Quick hitch

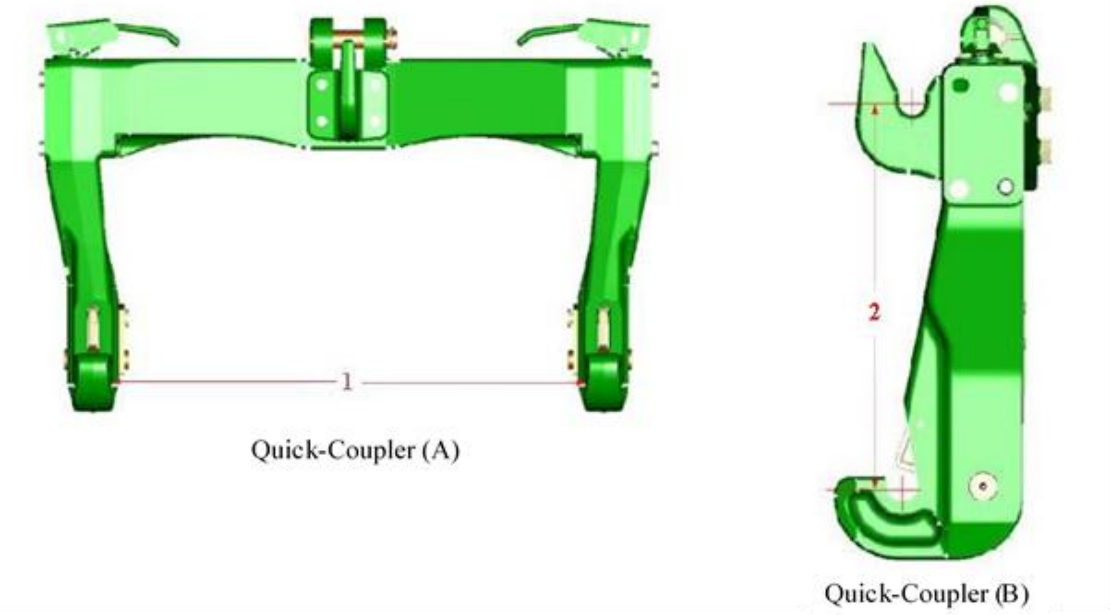


Figure A3.11: Quick hitch to fit tractor 3-point hitches A: Front view, B: Side view

Table A3.2: Specifications of quick hitches

Category	Lower hitch point span (A)	Pin centerline – lower to upper (B)
2	828.55 mm min. 834.14 mm max.	375.41 mm min. 377.95 mm max.
3	967.74 mm min. 975.36 mm max.	477 mm min. 479.55 mm max.
4	1170.94 mm min. 1174 mm max.	679.96 mm min. 683 mm max.

Appendix A3.9: Specifications of Experimental tractors

A3.9.1: Tractors' specification (Felton, Queensland)

Table A3.3: Tractors' specification in trial of Felton (Queensland)

Description	Main tractor	Main tractor	Second Tractor
Usage	Tillage trial	Motion resistance trial	
Manufacturer	John Deere	John Deere	John Deere
Dimensions of axles	Standard	3 m CTF	3 m CTF
Model	6520	8130	8130
Year of manufacture	2006	2006	2009
Rated Power (hp)	103	174	174
Drawbar	Cat 2-3	Cat 3-4	Cat 3-4
Variants	Wheel	Wheel	Wheel
Total Static Weight (kN)	35.58	105.65	108.60
Static weight on front axle (kN)	14.23	52.06	53.24
Static weight on rear axle (kN)	21.35	53.59	55.36
Front wheels size	16.9 R 28	18.4 R 34	18.4 R 34
Rear wheels size	18.4 R 38	18.4 R 50	18.4 R 50
Air pressure of front wheels (kPa)	140	190	190
Air pressure of rear wheels(kPa)	110	190	190

A3.9.2: Tractor's specification (Pittsworth, Queensland)

Table A3.4: Tractors' specification in trial of Pittsworth (Queensland)

Description	Main tractor	Second Tractor
Usage	Tillage and motion resistance trial	Tow the main tractor
Manufacturer	John Deere	CaseIH
Dimensions of axles	3 m CTF	Standard
Model	8330	MX120
Year of manufacture	2006-2009	1997-2002
Rated Power (hp)	174	120
Drawbar	Cat 3-4	Cat 3-4
Variants	Wheel	Wheel
Total Static Weight (kN)	106.95	55.42
Static weight on front axle (kN)	49.64	23.16
Static weight on rear axle (kN)	57.31	32.26
Front wheels size	16.9 R 34	14.9 R 28
Rear wheels size	18.4 R 50	18.4 R 38
Air pressure of front wheels (kPa)	170	160
Air pressure of rear wheels(kPa)	115	110

A3.9.3: Tractors' specification (Gatton, Queensland)

Table A3.5 Tractors' specification in trial of Gatton (Queensland)

Description	Main tractor	Second Tractor
Usage	Tillage and motion resistance trial	Tow the main tractor
Manufacturer	John Deere	John Deere
Dimensions of axles	Standard	Standard
Model	6105R	1750
Year of manufacture	2014	1994
Rated Power (hp)	105	50
Drawbar	Cat 2-3	Cat 2
Variants	Wheel	Wheel
Total Static Weight (kN)	52	27
Static weight on front axle (kN)	23	11
Static weight on rear axle (kN)	28	16
Front wheels size	11.2 R 36	6.5 R 16
Rear wheels size	11.2 R 48	12.4 R 32
Air pressure of front wheels (kPa)	185	230
Air pressure of rear wheels(kPa)	210	120

A3.9.4: Tractor's specification (Kingaroy, Queensland)

Table A3.6: Tractor's specification in trial of Kingaroy (Queensland)

Description	Main tractor
Usage	Tillage trial
Manufacturer	John Deere
Dimensions of axles	Standard
Model	6320
Year of manufacture	2005
Rated Power (hp)	93
Drawbar	Cat 2-3
Variants	Wheel
Total Static Weight (kN)	53
Static weight on front axle (kN)	24
Static weight on rear axle (kN)	29
Front wheels size	16.9 R 24
Rear wheels size	18.4 R 38
Air pressure of front wheels (kPa)	185
Air pressure of rear wheels(kPa)	125

A3.9.5: Tractors' specification (Hopetoun, Victoria)

Table A3.7: Tractors' specification in trial of Hopetoun trial (Victoria)

Description	Main tractor	Second Tractor
Usage	Tillage and motion resistance trial	Tow the main tractor
Manufacturer	New Holland	CaseIH
Dimensions of axles	3 m CTF	3 m CTF
Model	8670	9330
Year of manufacture	2002	1999
Rated Power (hp)	175	240
Drawbar	Cat 3-4	Cat 4
Variants	Wheel	Wheel
Total Static Weight (kN)	85	105
Static weight on front axle (kN)	39	54
Static weight on rear axle (kN)	46	51
Front wheels size	16.9 R 28	18.4 R 38
Rear wheels size	18.4 R 38	18.4 R 38
Air pressure of front wheels (kPa)	105	165
Air pressure of rear wheels(kPa)	100	165

A3.9.6: Tractors' specification (Swan Hill, Victoria)

Table A4.8: Tractors' specification in trial of Swan Hill (Victoria)

Description	Main tractor	Second Tractor
Usage	Tillage trial and tow the tractor	motion resistance trial
Manufacturer	John Deere	John Deere
Dimensions of axles	3 m CTF	3 m CTF
Model	8360 RT	9200
Year of manufacture	2013	1996-2001
Rated Power (hp)	268	268
Drawbar	Cat 4	Cat 4
Variants	Crawler	Wheel
Total Static Weight (kN)	174	152
Static weight on front axle (kN)	-	84
Static weight on rear axle (kN)	-	68
Front wheels size	-	20.8 R 42
Rear wheels size	-	20.8 R 42
Air pressure of front wheels (kPa)	-	170
Air pressure of rear wheels(kPa)	-	170

A3.9.7: Tractors' specification (Loxton, South Australia)

Table A4.9: Tractors' specification in trial of Loxton (South Australia)

Description	Main tractor	Second Tractor
Manufacturer	John Deere	John Deere
Model	8360 RT	8220
Year of manufacture	2011-2013	2001-
Rated Power	268 hp	-
Drawbar	Cat 4	Cat 3
Variants	crawler	Wheel
Total Weight (kN)	174	-
Weight on front wheels	-	-
Weight on rear wheels	-	-
Front wheels size	-	-
Rear wheels size	-	-
Air pressure of front wheels	-	-
Air pressure of front wheels	-	-

A3.9.8: Tractors' specification (Waikerie, South Australia)

Table A4.10: Tractors' specification in trial of Waikerie (South Australia)

Description	Main tractor	Second Tractor
Manufacturer	CASE IH	Case IH
Model	cvx1195	Jx 1100
Year of manufacture	2006	2005
Rated Power	195 hp	100 hp
Drawbar	Cat 3	Cat 2
Variants	Wheel	Wheel
Total Weight (kN)	65	40
Weight on front wheels (kN)	26	16
Weight on rear wheels(kN)	39	24
Front wheels size	540/65 R30	380/70 R 24
Rear wheels size	650/65 R42	480/70 R 34
Air pressure of front wheels	196.5 kPa	-
Air pressure of front wheels	113.8 kPa	-

Appendix A3.10: Direct shear box device

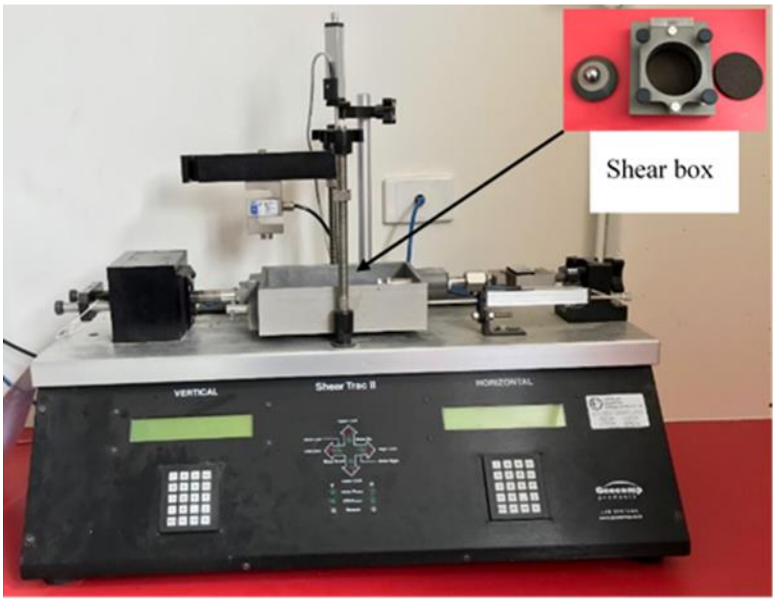


Figure A3.12: ShearTrac-II

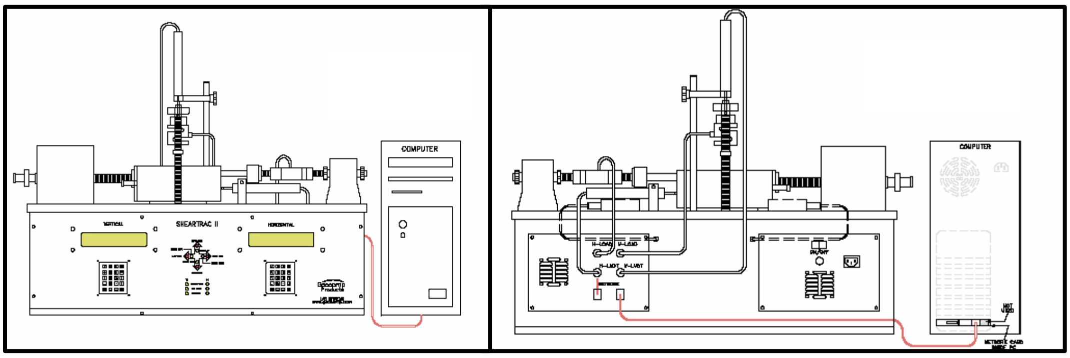


Figure A3.13: Front diagram (left) and back diagram (right) of ShearTrac-II (Geocomp, 2007)

APPENDIX TO CHAPTER 4

APPENDICES

APPENDIX TO CHAPTER 4

Appendix A4.1: Statistical analyses corresponding to draught force in Chapter 4

A4.1.1: Statistical analysis - draught force measurements in **Felton** site

Factors structure:

Tine: Sweep, chisel, opener

Traffic system: Wheeled track, non-wheeled track

Operating depth: 75 mm, 100 mm, 125 mm

Table A4.1: Analysis of variance – draught force measurements of sweep tines (Felton site)

Variate: **Draught force (kN)**

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	123.499	123.499	335.120	**<0.001**	**0.69**
Depth	2	71.789	35.894	97.401	**<0.001**	
Traffic . Depth	2	0.360	0.180	0.489	**0.614**	
Residual	234	86.234	0.369			
Total	239	281.882	1.179			

Table A4.2: Analysis of variance – draught force measurements of chisel tines (Felton site)

Variate: **Draught force (kN)**

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	48.160	48.160	218.766	**<0.001**	**0.67**
Depth	2	53.943	26.972	122.518	**<0.001**	
Traffic . Depth	2	1.482	0.741	3.367	**<0.036**	
Residual	234	51.514	0.220			
Total	239	155.099	0.649			

Table A4.3: Analysis of variance – draught force measurements of opener tines (Felton site)

Variate: **Draught force (kN)**

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	97.397	97.397	496.576	**<0.001**	**0.89**
Depth	2	38.029	19.015	96.945	**<0.001**	
Traffic . Depth	2	0.320	0.160	0.816	**0.444**	
Residual	234	45.896	0.196			
Total	239	181.643	0.760			

Table A4.4: Analysis of variance – draught force measurements of all tines (Felton site)

Variate: **Draught force (kN)**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	363.719	363.719	1203.616	**<0.001**	**0.77**
Tine	2	244.476	122.238	404.509	**<0.001**	
Depth	2	162.836	81.418	269.428	**<0.001**	
Traffic.Tine	2	2.396	1.198	3.964	**0.019**	
Traffic.Depth	2	1.721	0.861	2.848	**0.059**	
Tine Depth	4	3.491	0.873	2.888	**0.022**	
Traffic.Tine.Depth	4	1.166	0.291	.965	**0.426**	
Residual	702	212.137	0.302			
Total	719	71.4627	0.099			

A4.1.2: Regression analysis – relationship between operating depth and draught force, **Felton** site**.**

1. **Sweep tine**

1.1 Non-wheeled soil

1.1.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.5: Summary of analysis for sweep tine Felton (Non-wheeled soil)

Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**Adjusted R^2**	**SE**
Regression	1	3.854	3.854	162.720	**<0.001**	**0.58**	**0.154**
Residual	118	2.795	0.024				
Total	119	6.648	0.056				

Table A4.6: Estimates of parameters for sweep tine, Felton (Non-wheeled soil)

Parameter	**estimate**	**s.e.**	**t(96)**	**t pr.**
Constant	1.140	0.08	14.24	**<0.001**
Depth	0.009	0.001	12.76	**<0.001**

1.1.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.7: Summary of analysis for sweep tine , Felton (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	30.707	30.707	183.372	**<0.001**	**0.61**	**0.409**
Residual	118	19.760	0.167				
Total	119	50.468	0.424				

Table A4.8: Estimates of parameters for Sweep tine, Felton (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.34	0.187	1.819	**0.072**
Depth	0.025	0.002	13.541	**<0.001**

1.1.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.9: Summary of analysis for sweep tine, Felton (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	31.114	15.557	94.051	**<0.001**	**0.61**	**0.407**
Residual	117	19.353	0.165				
Total	119	50.468	0.424				

Table A4.10: Estimates of parameters for sweep tine, Felton (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	2.234	1.222	1.829	**0.070**
Depth	-0.015	.025	1.569	**0.119**
Depth Sq	0.00	0.000	1.829	**0.070**

1.2 Wheeled soil

1.2.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.11: Summary of analysis for sweep tine, Felton (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	2.134	2.134	68.069	<**0.001**	**0.36**	**0.177**
Residual	118	3.700	0.031				
Total	119	5.834	0.049				

Table A4.12: Estimates of parameters for sweep tine, Felton (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	2.159	0.175	12.373	<**0.001**
Depth	0.007	0.001	8.250	<**0.001**

1.2.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.13: Summary of analysis for sweep tine, Felton (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	40.144	40.144	69.832	<**0.001**	**0.37**	**0.758**
Residual	118	67.833	0.575				
Total	119	107.977	0.907				

Table A4.14: Estimates of parameters for sweep tine, Felton (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	1.419	0.346	4.101	<**0.001**
Depth	0.028	0.003	8.357	<**0.001**

1.2.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.15: Summary of analysis for sweep tine, Felton (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	41.023	20.512	35.844	**<0.001**	**0.83**	**0.638**
Residual	117	66.953	0.572				
Total	119	107.977	0.907				

Table A4.16: Estimates of parameters for sweep tine, Felton (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	4.204	2.273	1.850	**0.067**
Depth	-0.030	0.047	-0.634	**0.527**
Depth Sq	0.00	0.000	1.240	**0.218**

2. Chisel tine

2.1 Non-wheeled soil

2.1.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.17: Summary of analysis for chisel tine, Felton (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	11.256	11.256	236.054	**<0.001**	**0.66**	**0.218**
Residual	118	5.627	0.048				
Total	119	16.882	0.142				

Table A4.18: Estimates of parameters for chisel tine, Felton (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.281	0.028	10.033	**<0.001**
Depth	0.015	0.001	15.364	**<0.001**

2.1.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.19: Summary of analysis for chisel tine, Felton (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	20.150	20.150	224.384	**<0.001**	**0.65**	**0.300**
Residual	118	10.597	0.090				
Total	119	30.747	0.258				

Table A4.20: Estimates of parameters for chisel tine, Felton (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.656	0.137	-4.795	**<0.001**
Depth	0.020	0.001	14.979	**<0.001**

2.1.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.21: Summary of analysis for chisel tine, Felton (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	20.511	10.256	117.230	**<0.001**	**0.66**	**0.296**
Residual	117	10.236	0.087				
Total	119	30.747	0.258				

Table A4.22: Estimates of parameters for chisel tine, Felton (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	1.129	0.889	1.270	**0.207**
Depth	-0.017	0.018	-0.934	**0.352**
Depth Sq	0.000	0.000	2.032	**0.044**

2.2 Wheeled soil

2.2.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.23: Summary of analysis for chisel tine, Felton (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	7.076	7.076	114.631	**<0.001**	**0.49**	**0.248**
Residual	118	7.284	0.062				
Total	119	14.360	0.121				

Table A4.24: Estimates of parameters for Chisel tine, Felton (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.640	0.073	8.818	**<0.001**
Depth	0.012	0.001	10.707	**<0.001**

2.2.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.25: Summary of analysis for chisel tine, Felton (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	36.383	36.383	107.846	**<0.001**	**0.47**	**0.581**
Residual	118	39.808	0.337				
Total	119	76.191	0.64				

Table A4.26: Estimates of parameters for chisel tine, Felton (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.463	0.265	-1.748	**0.083**
Depth	0.027	0.003	10.385	**<0.001**

2.2.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.27: Summary of analysis for chisel tine, Felton (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	36.485	18.243	53.756	<0.001	**0.47**	**0.583**
Residual	117	39.705	0.339				
Total	119	76.191	0.64				

Table A4.28: Estimates of parameters for chisel tine, Felton (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.489	1.750	0.280	**0.780**
Depth	0.007	0.036	0.196	**0.845**
Depth Sq	0.00	0.00	0.551	**0.583**

3. Opener tine

3.1 Non-wheeled soil

3.1.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.29: Summary of analysis for opener tine, Felton (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	3.176	3.176	132.974	**<0.001**	**0.53**	**0.155**
Residual	118	2.818	0.024				
Total	119	5.994	0.05				

Table A4.30: Estimates of parameters for opener tine, Felton (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.654	0.030	21.536	**<0.001**
Depth	0.011	0.00	24.063	**<0.001**

3.1.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.31: Summary of analysis for opener tine, Felton (Non-wheeled soil)

Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**Adjusted R^2**	**SE**
Regression	1	16.426	16.426	160.154	**<0.001**	**0.57**	**0.320**
Residual	118	12.102	0.103				
Total	119	28.528	0.24				

Table A4.32: Estimates of parameters for opener tine, Felton (Non-wheeled soil)

Parameter	**estimate**	**s.e.**	**t(96)**	**t pr.**
Constant	-0.126	0.089	-1.416	**0.159**
Depth	0.021	0.001	24.491	**<0.001**

3.1.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.33: Summary of analysis for opener tine, Felton (Non-wheeled soil)

Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**Adjusted R^2**	**SE**
Regression	2	16.751	8.375	83.202	**<0.001**	**0.58**	**0.317**
Residual	117	11.778	0.101				
Total	119	28.528	0.24				

Table A4.34: Estimates of parameters opener tine, Felton (Non-wheeled soil)

Parameter	**estimate**	**s.e.**	**t(96)**	**t pr.**
Constant	-0.289	0.589	-0.491	**0.625**
Depth	0.025	0.012	2.035	**0.044**
Depth Sq	-1.700E-5	0.00	-0.280	**0.780**

3.2 Wheeled soil

3.2.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.35: Summary of analysis for opener tine, Felton (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	1.713	1.713	83.799	**<0.001**	**0.41**	**0.143**
Residual	118	2.412	0.020				
Total	119	4.125	0.035				

Table A4.36: Estimates of parameters for opener tine, Felton (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	1.210	0.046	26.432	**<0.001**
Depth	0.008	0.00	21.872	**<0.001**

3.2.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.37: Summary of analysis for opener tine, Felton (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	22.197	22.197	88.129	**<0.001**	**0.42**	**0.502**
Residual	118	29.721	0.252				
Total	119	51.918	0.436				

Table A4.38: Estimates of parameters for opener tine, Felton (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.580	0.098	5.908	**<0.001**
Depth	0.022	0.001	22.756	**<0.001**

3.2.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.39: Summary of analysis for opener tine, Felton (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	23.248	11.624	47.436	**<0.001**	**0.44**	**0.495**
Residual	117	28.670	0.245				
Total	119	51.918	0.436				

Table A4.40: Estimates of parameters opener tine, Felton (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.239	0.644	-0.371	**0.711**
Depth	0.039	0.013	2.925	**0.004**
Depth Sq	-8.540E-5	0.00	-1.286	**0.201**

A4.1.3: Statistical analysis - draught force measurements in **Pittsworth** site

Factors structure:

Tine: Sweep, chisel, opener

Traffic: wheeled track, non-wheeled track

Work depth: 75 mm, 100 mm, 125 mm

Table A4.41: Analysis of variance – draught force measurements of sweep tines (Pittsworth site)

Variate: **Draught force (kN)**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	580.544	580.544	1945.122	**<0.001**	**0.93**
Depth	2	399.734	199.867	669.659	**<0.001**	
Traffic . Depth	2	8.423	4.212	14.111	**<0.001**	
Residual	234	69.840	0.298			
Total	239	1058.541	4.429			

Table A4.42: Analysis of variance – draught force measurements of chisel tines (Pittsworth site)

Variate: **Draught force (kN)**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	76.118	76.118	1026.379	**<0.001**	**0.93**
Depth	2	134.364	67.182	905.893	**<0.001**	
Traffic . Depth	2	12.783	6.392	86.187	**<0.001**	
Residual	234	17.354	0.074			
Total	239	240.619	1.007			

Table A4.43: Analysis of variance – draught force measurements of opener tines (Pittsworth site)

Variate: **Draught force (kN)**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	34.015	34.015	807.671	**<0.001**	**0.89**
Depth	2	46.885	23.443	556.643	**<0.001**	
Traffic . Depth	2	0.028	0.014	0.336	**0.715**	
Residual	234	9.855	0.042			
Total	239	90.783	0.380			

Table A4.44: Analysis of variance – draught force measurements of all tines (Pittsworth site)

Variate: **Draught force (kN**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	497.985	497.985	3601.252	**<0.001**	**0.96**
Tine	2	979.277	489.638	3540.889	**<0.001**	
Depth	2	489.432	244.716	1769.697	**<0.001**	
Traffic.Tine	2	192.697	96.348	696.756	**<0.001**	
Traffic.Depth	2	11.538	5.769	41.721	**<0.001**	
Tine Depth	4	91.551	22.888	165.516	**<0.001**	
Traffic.Tine.Depth	4	9.698	2.425	17.533	**<0.001**	
Residual	702	97.073	0.138			
Total	719	2369.251	3.295			

A4.1.4: Regression analysis – relationship between operating depth and draught force, Pittsworth site**.**

1. Sweep tine

1.1 Non-wheeled soil

1.1.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.45: Summary of analysis for sweep tine, Pittsworth (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	20.707	20.707	886.739	**<0.001**	**0.88**	**0.153**
Residual	118	2.756	0.023				
Total	119	23.463	0.197				

Table A4.46: Estimates of parameters for sweep tine, Pittsworth (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.375	0.001	29.78	**<0.001**
Depth	0.02	0.026	14.34	**<0.001**

1.1.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.47: Summary of analysis for sweep tine, Pittsworth (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	169.042	169.042	876.924	**<0.001**	**0.88**	**0.439**
Residual	118	22.747	0.193				
Total	119	191.789	1.612				

Table A4.48: Estimates of parameters for sweep tine, Pittsworth (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-2.67	0.200	-13.33	**<0.001**
Depth	0.058	0.002	29.61	**<0.001**

1.1.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.49: Summary of analysis for sweep tine, Pittsworth (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	169.583	84.791	446.753	**<0.001**	**0.88**	**0.436**
Residual	117	22.206	0.190				
Total	119	191.789	1.612				

Table A4.50: Estimates of parameters for sweep tine, Pittsworth (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-4.854	1.309	-3.709	**<0.001**
Depth	0.104	0.027	3.831	**<0.001**
Depth Sq	0.00	0.00	-1.688	**0.094**

1.2 Wheeled soil

1.2.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.51: Summary of analysis for sweep tine, Pittsworth (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	6.554	6.554	341.650	**<0.001**	**0.74**	**0.139**
Residual	118	2.264	0.019				
Total	119	8.818	0.074				

Table A4.52: Estimates of parameters for sweep tine, Pittsworth (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	1.923	0.122	15.82	**<0.001**
Depth	0.011	0.001	18.48	**<0.001**

1.2.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.53: Summary of analysis for sweep tine, Pittsworth (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	218.990	218.99	384.425	**<0.001**	**0.76**	**0.755**
Residual	118	67.219	0.570				
Total	119	286.209	2.405				

Table A4.54: Estimates of parameters for sweep tine, Pittsworth (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.364	0.344	-1.06	**0.293**
Depth	0.066	0.003	19.61	**<0.001**

1.2.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.55: Summary of analysis for sweep tine, Pittsworth (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	238.575	119.287	292.997	**<0.001**	**0.83**	**0.638**
Residual	117	47.634	0.407				
Total	119	286.209	2.405				

Table A4.56: Estimates of parameters for sweep tine, Pittsworth (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-13.505	1.917	-7.045	**<0.001**
Depth	0.340	0.04	8.587	**<0.001**
Depth Sq	-0.001	0.00	-6.936	**<0.001**

2. Chisel tine

2.1 Non-wheeled soil

2.1.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.57: Summary of analysis for chisel tine, Pittsworth (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	15.816	15.816	737.269	**<0.001**	**0.86**	**0.146**
Residual	118	2.531	.021				
Total	119	18.347	0.154				

Table A4.58: Estimates of parameters for chisel tine, Pittsworth (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.239	0.016	14.958	**<0.001**
Depth	0.018	0.001	27.153	**<0.001**

2.1.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.59: Summary of analysis for chisel tine, Pittsworth (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	32.398	32.398	750.181	**<0.001**	**0.86**	**0.208**
Residual	118	5.096	0.043				
Total	119	37.494	0.315				

Table A4.60: Estimates of parameters for chisel tine, Pittsworth (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-1.022	0.095	-10.769	**<0.001**
Depth	0.025	0.001	27.389	**<0.001**

2.1.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.61: Summary of analysis for chisel tine, Pittsworth (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	32.419	16.209	373.701	**<0.001**	**0.86**	**0.208**
Residual	117	5.075	0.043				
Total	119	37.494	0.315				

Table A4.62: Estimates of parameters for chisel tine, Pittsworth (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.590	0.626	-0.943	**0.347**
Depth	0.016	0.013	1.272	**0.206**
Depth Sq	4.500E-5	0.000	0.697	**0.487**

2.2 Wheeled soil

2.2.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.63: Summary of analysis for chisel tine, Pittsworth (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	20.661	20.661	631.824	**<0.001**	**0.84**	**0.181**
Residual	118	3.859	0.033				
Total	119	24.520	0.206				

Table A4.64: Estimates of parameters for chisel tine, Pittsworth (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.317	0.026	12.115	**<0.001**
Depth	0.020	0.001	25.136	**<0.001**

2.2.2 Regression analysis – linear model
Response variate: Draught force

Fitted terms: Constant, depth

Table A4.65: Summary of analysis for chisel tine, Pittsworth (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	114.385	114.385	1069.333	**<0.001**	**0.90**	**0.327**
Residual	118	12.622	0.107				
Total	119	127.008	1.067				

Table A4.66: Estimates of parameters for chisel tine, Pittsworth (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-2.133	0.149	-14.286	**<0.001**
Depth	0.048	0.001	32.701	**<0.001**

2.2.3 Regression analysis – quadratic model
Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.67: Summary of analysis for chisel tine, Pittsworth (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	114.729	57.364	546.604	**<0.001**	**0.90**	**0.324**
Residual	117	12.279	0.105				
Total	119	127.008	1.067				

Table A4.68: Estimates of parameters for chisel tine, Pittsworth (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-3.873	0.973	-3.980	**<0.001**
Depth	0.084	0.020	4.181	**<0.001**
Depth Sq	0.000	0.000	-1.809	**0.073**

3. Opener tine

3.1 Non-wheeled soil

3.1.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.69: Summary of analysis for opener tine, Pittsworth (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	5.993	5.993	579.052	**<0.001**	**0.83**	**0.102**
Residual	118	1.221	0.010				
Total	119	7.214	0.061				

Table A4.70: Estimates of parameters for opener tine, Pittsworth (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	1.021	0.072	14.177	**<0.001**
Depth	0.008	0.001	11.531	**<0.001**

3.1.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.71: Summary of analysis for opener tine, Pittsworth (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	22.909	22.909	599.809	**<0.001**	**0.83**	**0.195**
Residual	118	4.507	0.038				
Total	119	27.416	0.23				

Table A4.72: Estimates of parameters for opener tine, Pittsworth (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.509	0.146	3.479	**<0.001**
Depth	0.018	9.001	12.655	**<0.001**

3.1.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.73: Summary of analysis for opener tine, Pittsworth (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	22.912	11.456	297.601	**<0.001**	**0.83**	**0.196**
Residual	117	4.504	0.038				
Total	119	27.416	0.23				

Table A4.74: Estimates of parameters for opener tine, Pittsworth (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	2.201	0.953	2.309	**0.023**
Depth	-0.017	0.020	-0.872	**0.385**
Depth Sq	0.00	0.00	1.796	**0.075**

3.2 Wheeled soil

3.2.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.75: Summary of analysis for Opener tine, Pittsworth (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	3.287	3.287	478.376	**<0.001**	**0.80**	**0.083**
Residual	118	0.811	0.007				
Total	119	4.097	0.034				

Table A4.76: Estimates of parameters for opener tine, Pittsworth (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	1.962	0.128	15.323	**<0.001**
Depth	0.006	0.001	9.154	**<0.001**

3.2.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.77: Summary of analysis for opener tine, Pittsworth (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	23.926	23.926	517.850	**<0.001**	**0.81**	**0.215**
Residual	118	5.452	0.046				
Total	119	29.378	0.247				

Table A4.78: Estimates of parameters for opener tine, Pittsworth (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	1.476	0.229	6.445	**<0.001**
Depth	0.021	0.002	9.388	**<0.001**

3.2.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.79: Summary of analysis for opener tine, Pittsworth (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	24.002	12.001	261.185	**<0.001**	**0.81**	**0.214**
Residual	117	5.376	0.046				
Total	119	29.378	0.247				

Table A4.80: Estimates of parameters for opener tine, Pittsworth (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	4.520	1.487	3.039	**0.003**
Depth	-0.042	0.031	-1.380	**0.170**
Depth Sq	0.00	0.00	2.071	**0.041**

A4.1.5: Statistical analysis - draught force measurements in **Gatton** site

Factors structure:

Tine: Sweep, chisel, opener

Traffic system: Wheeled track, non-wheeled track

Operating depth: 75 mm, 100 mm, 125 mm

Table A4.81: Analysis of variance – draught force measurements of sweep tines (Gatton site)

Variate: **Draught force (kN)**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	45.049	45.049	249.374	**<0.001**	**0.71**
Depth	2	56.686	28.343	156.895	**<0.001**	
Traffic . Depth	2	0.514	0.257	1.422	**0.243**	
Residual	234	42.272	0.181			
Total	239	144.521	0.605			

Table A4.82: Analysis of variance – draught force measurements of chisel tines (Gatton site)

Variate: **Draught force (kN)**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	50.389	50.389	888.190	**<0.001**	**0.88**
Depth	2	37.237	18.619	328.181	**<0.001**	
Traffic . Depth	2	10.192	5.096	89.826	**<0.001**	
Residual	234	13.275	0.057			
Total	239	111.094	0.465			

Table A4.83: Analysis of variance – draught force measurements of opener tines (Gatton site)

Variate: **Draught force (kN)**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	79.834	79.834	2097.608	**<0.001**	**0.93**
Depth	2	25.868	12.934	339.843	**<0.001**	
Traffic . Depth	2	3.421	1.711	44.945	**<0.001**	
Residual	234	8.906	0.038			
Total	239	118.029	0.494			

Table A4.84: Analysis of variance – draught force measurements of all tines (Gatton site)

Variate: **Draught force (kN)**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	172.451	172.451	1878.269	**<0.001**	**0.90**
Tine	2	290.287	145.143	1580.846	**<0.001**	
Depth	2	116.736	58.368	635.723	**<0.001**	
Traffic.Tine	2	2.821	1.411	15.365	**<0.001**	
Traffic.Depth	2	9.514	4.757	51.814	**<0.001**	
Tine.Depth	4	3.055	0.764	8.320	**<0.001**	
Traffic.Tine.Depth	4	4.612	1.153	12.559	**<0.001**	
Residual	702	64.453	0.092			
Total	719	663.931	0.923			

A4.1.6: Regression analysis – relationship between operating depth and draught force, **Gatton** site**.**

1. **Sweep tine**

1.1 Non-wheeled soil

1.1.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.85: Summary of analysis for sweep tine Gatton (Non-wheeled soil)

Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**Adjusted R^2**	**SE**
Regression	1	5.805	5.805	99.089	**<0.001**	**0.45**	**0.242**
Residual	118	6.912	0.059				
Total	119	12.717	0.107				

Table A4.86: Estimates of parameters for sweep tine, Gatton (Non-wheeled soil)

Parameter	**estimate**	**s.e.**	**t(96)**	**t pr.**
Constant	0.788	0.087	9.052	**<0.001**
Depth	0.011	0.001	9.954	**<0.001**

1.1.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.87: Summary of analysis for sweep tine , Gatton (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	25.901	25.901	110.174	**<0.001**	**0.48**	**0.485**
Residual	118	27.741	0.235				
Total	119	53.642	0.451				

Table A4.88: Estimates of parameters for Sweep tine, Gatton (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.150	0.221	0.680	**0.498**
Depth	0.023	0.002	10.496	**<0.001**

1.1.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.89: Summary of analysis for sweep tine, Gatton (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	26.237	13.118	56.007	**<0.001**	**0.48**	**0.484**
Residual	117	27.405	0.234				
Total	119	53.642	0.451				

Table A4.90: Estimates of parameters for sweep tine, Gatton (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-1.571	1.454	-1.080	**0.282**
Depth	0.059	0.030	1.952	**0.053**
Depth Sq	0.00	0.00	-1.198	**0.233**

1.2 Wheeled soil

1.2.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.91: Summary of analysis for sweep tine, Gatton (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	2.859	2.859	208.243	<**0.001**	**0.64**	**0.117**
Residual	118	1.620	0.014				
Total	119	4.478	0.038				

Table A4.92: Estimates of parameters for sweep tine, Gatton (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	2.215	0.063	35.339	<**0.001**
Depth	0.189	0.013	14.431	<**0.001**

1.2.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.93: Summary of analysis for sweep tine, Gatton (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	28.525	28.525	194.500	<**0.001**	**0.62**	**0.383**
Residual	118	17.305	0.147				
Total	119	45.830	0.385				

Table A4.94: Estimates of parameters for sweep tine, Gatton (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	2.099	0.092	22.690	<**0.001**
Depth	0.597	0.043	13.946	<**0.001**

1.2.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.95: Summary of analysis for sweep tine, Gatton (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	30.963	15.481	121.833	**<0.001**	**0.67**	**0.356**
Residual	117	14.867	0.127				
Total	119	45.830	0.385				

Table A4.96: Estimates of parameters for sweep tine, Gatton (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	1.091	0.246	4.440	**<0.001**
Depth	1.807	0.279	6.476	**<0.001**
Depth Sq	-0.302	0.069	-4.380	**<0.001**

2. Chisel tine

2.1 Non-wheeled soil

2.1.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.97: Summary of analysis for chisel tine, Gatton (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	5.187	5.187	68.974	**<0.001**	**0.36**	**0.274**
Residual	118	8.874	0.075				
Total	119	14.061	0.118				

Table A4.98: Estimates of parameters for chisel tine, Gatton (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.329	0.041	7.989	**<0.001**
Depth	0.010	0.001	8.305	**<0.001**

2.1.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.99: Summary of analysis for chisel tine, Gatton (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	3.741	3.741	49.856	**<0.001**	**0.29**	**0.274**
Residual	118	8.855	0.075				
Total	119	12.596	0.106				

Table A4.100: Estimates of parameters for chisel tine, Gatton (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.098	0.125	0.787	**0.433**
Depth	0.009	0.001	7.061	**<0.001**

2.1.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.101: Summary of analysis for chisel tine, Gatton (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	4.485	2.242	32.347	**<0.001**	**0.35**	**0.263**
Residual	117	8.111	0.069				
Total	119	12.596	0.106				

Table A4.102: Estimates of parameters for chisel tine, Gatton (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-2.462	0.791	-3.113	**0.002**
Depth	0.062	0.016	3.796	**<0.001**
Depth Sq	0.000	0.000	-3.275	**0.001**

2.2 Wheeled soil

2.2.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.103: Summary of analysis for chisel tine, Gatton (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	14.208	14.208	689.758	**<0.001**	**0.85**	**0.144**
Residual	118	2.431	0.021				
Total	119	16.638	0.140				

Table A4.104: Estimates of parameters for Chisel tine, Gatton (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.759	0.026	28.849	**<0.001**
Depth	0.421	0.016	26.263	**<0.001**

2.2.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.105: Summary of analysis for chisel tine, Gatton (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	41.371	41.371	724.569	**<0.001**	**0.86**	**0.239**
Residual	118	6.738	0.057				
Total	119	48.109	0.404				

Table A4.106: Estimates of parameters for chisel tine, Gatton (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.442	0.058	7.651	**<0.001**
Depth	0.719	0.027	26.918	**<0.001**

2.2.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.107: Summary of analysis for chisel tine, Gatton (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	42.944	21.472	486.443	**<0.001**	**0.89**	**0.210**
Residual	117	5.165	0.044				
Total	119	48.109	0.404				

Table A4.108: Estimates of parameters for chisel tine, Gatton (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.368	0.145	-2.541	**0.012**
Depth	1.691	0.164	10.282	**<0.001**
Depth Sq	-0.243	0.041	-5.970	**<0.001**

3. Opener tine

3.1 Non-wheeled soil

3.1.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.109: Summary of analysis for opener tine, Gatton (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	5.049	5.049	415.908	**<0.001**	**0.78**	**0.110**
Residual	118	1.432	0.012				
Total	119	6.481	0.055				

Table A4.110: Estimates of parameters for opener tine, Gatton (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.375	0.019	19.885	**<0.001**
Depth	0.010	0.000	20.394	**<0.001**

3.1.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.111: Summary of analysis for opener tine, Gatton (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	5.187	5.187	364.887	**<0.001**	**0.75**	**0.119**
Residual	118	1.677	0.014				
Total	119	6.864	0.058				

Table A4.112: Estimates of parameters for opener tine, Gatton (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.032	0.054	0.593	**0.555**
Depth	0.010	0.001	19.102	**<0.001**

3.1.2 Regression analysis – quadratic model

Response variate: Draught Force

Fitted terms: Constant, Depth, depth Sq.

Table A4.113: Summary of analysis for opener tine, Gatton (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	5.312	2.656	200.272	**<0.001**	**0.77**	**0.115**
Residual	117	1.552	0.013				
Total	119	6.864	0.058				

Table A4.114: Estimates of parameters opener tine, Gatton (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-1.020	0.346	-2.948	**0.004**
Depth	0.032	0.007	4.493	**<0.001**
Depth Sq	0.000	0.000	-3.077	**0.003**

3.2 Wheeled soil

3.2.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.115: Summary of analysis for opener tine, Gatton (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	5.152	5.152	334.425	**<0.001**	**0.74**	**0.124**
Residual	118	1.818	0.015				
Total	119	6.970	0.059				

Table A4.116: Estimates of parameters for opener tine, Gatton (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	1.290	0.039	33.358	**<0.001**
Depth	0.254	0.014	18.287	**<0.001**

3.2.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.117: Summary of analysis for opener tine, Gatton (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	22.398	22.398	295.841	**<0.001**	**0.71**	**0.275**
Residual	118	8.934	0.076				
Total	119	31.332	0.263				

Table A4.118: Estimates of parameters for opener tine, Gatton (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	1.146	0.066	17.245	**<0.001**
Depth	0.529	0.031	17.200	**<0.001**

3.2.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.119: Summary of analysis for opener tine, Gatton (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	23.977	11.989	190.732	**<0.001**	**0.76**	**0.251**
Residual	117	7.354	0.063				
Total	119	31.332	0.263				

Table A4.120: Estimates of parameters opener tine, Gatton (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.335	0.173	1.937	**0.055**
Depth	1.503	0.196	7.658	**<0.001**
Depth Sq	-0.243	0.049	-5.013	**<0.001**

A4.1.7: Statistical analysis - draught force measurements in **Kingaroy** site

Factors structure:

Traffic: wheeled track, non-wheeled track

Table A4.121: Analysis of variance – draught force measurements of chisel tines (Kingaroy site)

Variate: **Draught force (kN)**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	R^2
Traffic	1	4.719	4.719	2.947	0.09	**0.03**
Residual	78	124.913	1.601			
Total	79	129.632	1.641			

A4.1.8: Statistical analysis - draught force measurements in **Hopetoun** site

Factors structure:

Tine: Sweep, chisel, opener

Traffic system: Wheeled track, non-wheeled track

Operating depth: 75 mm, 100 mm, 125 mm with sweep tine and 75 mm, 100 mm with chisel and opener tines

Table A4.122: Analysis of variance – draught force measurements of sweep tines (Hopetoun site)

Variate: **Draught force (kN)**

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	3.800	3.800	1.063	**0.304**	**0.53**
Depth	2	948.039	474.019	132.627	<**0.001**	
Traffic . Depth	2	0.955	0.478	0.134	**0.875**	
Residual	234	836.335	3.574			
Total	239	1789.129	7.486			

Table A4.123: Analysis of variance – draught force measurements of chisel tines (Hopetoun site)

Variate: **Draught force (kN)**

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	0.339	0.339	1.168	**0.282**	**0.58**
Depth	1	62.463	62.463	214.842	<**0.001**	
Traffic . Depth	1	0.051	0.051	0.175	**0.677**	
Residual	156	45.355	0.291			
Total	159	108.208	0.681			

Table A4.124: Analysis of variance – draught force measurements of opener tines (Hopetoun site)

Variate: **Draught force (kN)**

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	0.882	0.882	15.563	<**0.001**	**0.80**
Depth	1	35.194	35.194	620.942	<**0.001**	
Traffic . Depth	1	0.068	0.068	1.201	**0.275**	
Residual	156	8.842	0.057			
Total	159	44.986	0.283			

Table A4.125: Analysis of variance – draught force measurements of all tines (Hopetoun site)

Variate: **Draught force (kN)**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	R^2
Traffic	1	2.660	2.660	4.814	**0.029**	**0.51**
Tine	2	123.945	61.972	112.180	**<0.001**	
Depth	1	140.953	140.953	255.147	**<0.001**	
Traffic.Tine	2	0.259	0.130	0.235	**0.791**	
Traffic.Depth	1	0.586	0.586	1.061	**0.304**	
Tine.Depth	2	1.966	0.983	1.780	**0.170**	
Traffic.Tine.Depth	2	0.238	0.119	0.215	**0.806**	
Residual	468	258.540	0.552			
Total	479	529.147	1.105			

A4.1.9: Regression analysis – relationship between operating depth and draught force, **Hopetoun** site**.**

1. Sweep tine

1.1 Non-wheeled soil

1.1.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.126: Summary of analysis for sweep tine Hopetoun (Non-wheeled soil)

Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**Adjusted** R^2	**SE**
Regression	1	22.169	22.169	109.263	**<0.001**	**0.48**	**0.450**
Residual	118	23.941	0.203				
Total	119	46.110	0.388				

Table A4.127: Estimates of parameters for sweep tine, Hopetoun (Non-wheeled soil)

Parameter	**estimate**	**s.e.**	**t(96)**	**t pr.**
Constant	1.153	0.125	9.192	**<0.001**
Depth	0.526	0.050	10.453	**<0.001**

1.1.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.128: Summary of analysis for sweep tine , Hopetoun (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	407.028	407.028	107.340	**<0.001**	**0.47**	**1.947**
Residual	118	447.449	3.792				
Total	119	854.477	7.181				

Table A4.129: Estimates of parameters for Sweep tine, Hopetoun (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.484	0.470	-1.028	**0.306**
Depth	2.256	0.218	10.361	**<0.001**

1.1.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.130: Summary of analysis for sweep tine, Hopetoun (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	453.818	226.909	66.262	**<0.001**	**0.52**	**1.851**
Residual	117	400.659	3.424				
Total	119	854.477	7.181				

Table A4.131: Estimates of parameters for sweep tine, Hopetoun (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	3.932	1.275	3.083	**0.003**
Depth	-3.043	1.448	-2.101	**0.038**
Depth Sq	1.325	0.358	3.696	**<0.001**

1.2 Wheeled soil

1.2.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.132: Summary of analysis for sweep tine, Hopetoun (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	21.535	21.535	127.248	**<0.001**	**0.52**	**0.411**
Residual	118	19.970	0.169				
Total	119	41.506	0.349				

Table A4.133: Estimates of parameters for sweep tine, Hopetoun (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.446	0.084	5.326	**<0.001**
Depth	0.021	0.002	11.280	**<0.001**

1.2.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.134: Summary of analysis for sweep tine, Hopetoun (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	457.159	457.159	113.881	**<0.001**	**0.49**	**2.004**
Residual	118	473.693	4.014				
Total	119	930.852	7.822				

Table A4.135: Estimates of parameters for sweep tine, Hopetoun (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-5.283	0.915	-5.777	**<0.001**
Depth	0.096	0.009	10.672	**<0.001**

1.2.3 **Regression analysis – quadratic model**
Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.136: Summary of analysis for sweep tine, Hopetoun (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	495.176	247.588	66.489	**<0.001**	**0.52**	**1.930**
Residual	117	435.676	3.724				
Total	119	930.852	7.822				

Table A4.137: Estimates of parameters for sweep tine, Hopetoun (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	13.025	5.797	2.247	**0.027**
Depth	-0.286	0.120	-2.389	**0.018**
Depth Sq	0.002	0.001	3.195	**0.002**

2. Chisel tine

2.1 Non-wheeled soil

2.1.1 **Regression analysis – exponential model**
Response variate: Draught force

Fitted terms: Constant, depth

Table A4.138: Summary of analysis for chisel tine, Hopetoun (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	13.106	13.106	88.729	**<0.001**	**0.53**	**0.384**
Residual	78	11.521	0.148				
Total	79	24.628	0.312				

Table A4.139: Estimates of parameters for chisel tine, Hopetoun (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.078	0.024	3.291	**0.001**
Depth	0.032	0.003	9.420	**<0.001**

2.1.1 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.140: Summary of analysis for chisel tine, Hopetoun (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	29.476	29.476	83.435	**<0.001**	**0.51**	**0.594**
Residual	78	27.556	0.353				
Total	79	57.032	0.722				

Table A4.141: Estimates of parameters for chisel tine, Hopetoun (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-2.708	0.470	-5.762	**<0.001**
Depth	0.049	0.005	9.134	**<0.001**

2.1.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

The depth sq. term was excluded, so the model is similar to a linear model.

2.2 Wheeled soil

2.2.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.142: Summary of analysis for chisel tine, Hopetoun (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	12.797	12.797	194.018	**<0.001**	**0.71**	**0.257**
Residual	78	5.145	0.066				
Total	79	17.941	0.227				

Table A4.143: Estimates of parameters for Chisel tine, Hopetoun (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.089	0.018	4.925	**<0.001**
Depth	0.032	0.002	13.929	**<0.001**

2.2.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.144: Summary of analysis for chisel tine, Hopetoun (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	33.037	33.037	144.777	**<0.001**	**0.65**	**0.478**
Residual	78	17.799	0.228				
Total	79	50.837	0.644				

Table A4-145: Estimates of parameters for chisel tine, Hopetoun (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-2.865	0.378	-7.586	**<0.001**
Depth	0.051	0.004	12.032	**<0.001**

2.2.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, Depth, depth Sq.

Table A4.146: Summary of analysis for chisel tine, Hopetoun (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	33.037	33.037	144.777	**<0.001**	**0.65**	**0.478**
Residual	78	17.799	0.228				
Total	79	50.837	0.644				

Table A4.147: Estimates of parameters for chisel tine, Hopetoun (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.662	0.198	-3.341	**0.001**
Depth	Excluded terms			
Depth Sq	0.00	0.00	12.032	**<0.001**

3. Opener tine

3.1 Non-wheeled soil

3.1.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.148: Summary of analysis for opener tine, Hopetoun (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	5.095	5.095	355.117	**<0.001**	**0.82**	**0.120**
Residual	78	1.119	0.014				
Total	79	6.214	0.079				

Table A4.149: Estimates of parameters for opener tine, Hopetoun (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.297	0.028	10.561	**<0.001**
Depth	0.020	0.001	18.845	**<0.001**

3.1.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.150: Summary of analysis for opener tine, Hopetoun (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	16.043	16.043	329.124	**<0.001**	**0.81**	**0.221**
Residual	78	3.802	0.049				
Total	79	19.845	0.251				

Table A4.151: Estimates of parameters for opener tine, Hopetoun (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-1.327	0.175	-7.605	**<0.001**
Depth	0.036	0.002	18.142	**<0.001**

3.1.3 Regression analysis – quadratic model

Response variate: Draught Force

Fitted terms: Constant, Depth, depth Sq.

The depth sq. term was excluded, so the model is similar to a linear model.

3.2 Wheeled soil

3.2.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.152: Summary of analysis for opener tine, Hopetoun (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	5.170	5.170	331.576	**<0.001**	**0.81**	**0.125**
Residual	78	1.216	0.016				
Total	79	6.386	0.081				

Table A4.153: Estimates of parameters for opener tine, Hopetoun (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.317	0.031	10.130	**<0.001**
Depth	0.020	0.001	18.209	**<0.001**

3.2.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.154: Summary of analysis for opener tine, Hopetoun (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	19.179	19.179	296.904	**<0.001**	**0.79**	**0.254**
Residual	78	5.038	0.065				
Total	79	24.217	0.307				

Table A4.155: Estimates of parameters for opener tine, Hopetoun (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-1.471	0.201	-7.321	**<0.001**
Depth	0.039	0.002	17.231	**<0.001**

3.2.3 Regression analysis – quadratic model

Response variate: Draught Force

Fitted terms: Constant, Depth, depth Sq.

The depth sq. term was excluded, the model is exactly as a linear model.

A4.1.10: Statistical analysis - draught force measurements in **Swan Hill** site

Factors structure:

Tine: Sweep, chisel, opener

Traffic system: Wheeled track, non-wheeled track

Operating depth: 75 mm, 100 mm, 125 mm

Table A4.156: Analysis of variance – draught force measurements of sweep tines (Swan Hill site)

Variate: **Draught force (kN)**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	8.855	8.855	259.880	**<0.001**	**0.74**
Depth	2	13.245	6.623	194.366	**<0.001**	
Traffic . Depth	2	0.017	0.009	0.250	**0.779**	
Residual	234	7.973	0.034			
Total	239	30.091	0.126			

Table A4.157: Analysis of variance – draught force measurements of chisel tines (Swan Hill site)

Variate: **Draught force (kN)**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	1.152	1.152	220.194	**<0.001**	**0.90**
Depth	2	10.362	5.181	990.016	**<0.001**	
Traffic . Depth	2	0.019	0.009	1.782	**0.171**	
Residual	234	1.225	0.005			
Total	239	12.757	0.053			

Table A4.158: Analysis of variance – draught force measurements of opener tines (Swan Hill site)

Variate: **Draught force (kN)**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	4.417	4.417	64.703	**<0.001**	**0.75**
Depth	2	41.274	20.637	302.281	**<0.001**	
Traffic . Depth	2	1.938	0.969	14.194	**<0.001**	
Residual	234	15.975	0.068			
Total	239	63.604	0.266			

Table A4.159: Analysis of variance – draught force measurements of all tines (Swan Hill site)

Variate: **Draught force (kN)**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	12.611	12.611	351.693	**<0.001**	**0.83**
Tine	2	44.203	22.102	616.350	**<0.001**	
Depth	2	57.528	28.764	802.147	**<0.001**	
Traffic.Tine	2	1.813	0.907	25.284	**<0.001**	
Traffic.Depth	2	0.879	0.440	12.261	**<0.001**	
Tine.Depth	4	7.353	1.838	51.260	**<0.001**	
Traffic.Tine.Depth	4	1.094	0.274	7.630	**<0.001**	
Residual	702	25.173	0.036			
Total	719	150.656	0.210			

A4.1.11: Regression analysis – relationship between operating depth and draught force, **Swan Hill** site**.**

1. **Sweep tine**

1.1 Non-wheeled soil

1.1.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.160: Summary of analysis for sweep tine Swan Hill (Non-wheeled soil)

Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**Adjusted R^2**	**SE**
Regression	1	4.314	4.314	222.902	**<0.001**	**0.65**	**0.139**
Residual	118	2.284	0.019				
Total	119	6.598	0.055				

Table A4.161: Estimates of parameters for sweep tine, Swan Hill (Non-wheeled soil)

Parameter	**estimate**	**s.e.**	**t(96)**	**t pr.**
Constant	0.455	0.029	15.749	**<0.001**
Depth	0.009	0.001	14.930	**<0.001**

1.1.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.162: Summary of analysis for sweep tine , Swan Hill (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	6.012	6.012	233.720	**<0.001**	**0.66**	**0.160**
Residual	118	3.035	0.026				
Total	119	9.047	0.076				

Table A4.163: Estimates of parameters for Sweep tine, Swan Hill (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.087	0.073	1.186	**0.238**
Depth	0.011	0.001	15.288	**<0.001**

1.1.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.164: Summary of analysis for sweep tine, Swan Hill (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	6.235	3.118	129.755	**<0.001**	**0.68**	**0.155**
Residual	117	2.811	0.024				
Total	119	9.047	0.076				

Table A4.165: Estimates of parameters for sweep tine, Swan Hill (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	1.492	0.466	3.203	**0.002**
Depth	-0.018	0.010	-1.906	**0.059**
Depth Sq	0.000	0.000	3.052	**0.003**

1.2 Wheeled soil

1.2.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.166: Summary of analysis for sweep tine, Swan Hill (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	2.703	2.703	141.076	**<0.001**	**0.54**	**0.138**
Residual	118	2.261	0.019				
Total	119	4.964	0.042				

Table A4.167: Estimates of parameters for sweep tine, Swan Hill (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.736	0.047	15.828	**<0.001**
Depth	0.007	0.001	11.878	**<0.001**

1.2.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.168: Summary of analysis for sweep tine, Swan Hill (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	6.868	6.868	152.301	**<0.001**	**0.56**	**0.212**
Residual	118	5.321	0.045				
Total	119	12.189	0.102				

Table A4.169: Estimates of parameters for sweep tine, Swan Hill (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.395	0.097	4.080	**<0.001**
Depth	0.012	0.001	12.341	**<0.001**

1.2.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.170: Summary of analysis for sweep tine, Swan Hill (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	7.027	3.514	79.636	**<0.001**	**0.57**	**0.210**
Residual	117	5.162	0.044				
Total	119	12.189	0.102				

Table A4.171: Estimates of parameters for sweep tine, Swan Hill (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	1.580	0.631	2.504	**0.014**
Depth	-0.013	0.013	-0.996	**0.321**
Depth Sq	0.000	0.000	1.899	**0.060**

2. Chisel tine

2.1 Non-wheeled soil

2.1.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.172: Summary of analysis for chisel tine, Swan Hill (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	10.376	10.376	880.660	**<0.001**	**0.88**	**0.109**
Residual	118	1.390	0.012				
Total	119	11.766	0.099				

Table A4.173: Estimates of parameters for chisel tine, Swan Hill (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.163	0.008	20.185	**<0.001**
Depth	0.014	0.000	29.676	**<0.001**

2.1.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.174: Summary of analysis for chisel tine, Swan Hill (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	4.724	4.724	833.019	**<0.001**	**0.88**	**0.075**
Residual	118	0.669	0.006				
Total	119	5.393	0.045				

Table A4.175: Estimates of parameters for chisel tine, Swan Hill (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.252	0.034	-7.319	**<0.001**
Depth	0.010	0.000	28.862	**<0.001**

2.1.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.176: Summary of analysis for chisel tine, Swan Hill (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	4.829	2.414	500.732	**<0.001**	**0.89**	**0.069**
Residual	117	0.564	0.005				
Total	119	5.393	0.045				

Table A4.177: Estimates of parameters for chisel tine, Swan Hill (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-1.214	0.209	-5.818	**<0.001**
Depth	0.030	0.004	6.907	**<0.001**
Depth Sq	0.000	0.000	-4.666	**<0.001**

2.2 Wheeled soil

2.2.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.178: Summary of analysis for chisel tine, Swan Hill (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	8.269	8.269	831.814	**<0.001**	**0.88**	**0.100**
Residual	118	1.173	0.010				
Total	119	9.442	0.079				

Table A4.179: Estimates of parameters for Chisel tine, Swan Hill (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.229	0.010	21.974	**<0.001**
Depth	0.013	0.000	28.841	**<0.001**

2.2.2 Regression analysis – linear model

Response variate: Draught Force

Fitted terms: Constant, depth

Table A4.180: Summary of analysis for chisel tine, Swan Hill (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	5.497	5.497	906.754	**<0.001**	**0.88**	**0.078**
Residual	118	0.715	0.006				
Total	119	6.212	0.052				

Table A4.181: Estimates of parameters for chisel tine, Swan Hill (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.189	0.036	-5.332	**<0.001**
Depth	0.010	0.000	30.112	**<0.001**

2.2.3 Regression analysis – quadratic model

Response variate: Draught Force

Fitted terms: Constant, Depth, depth Sq.

Table A4.182: Summary of analysis for chisel tine, Swan Hill (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	5.552	2.776	491.770	**<0.001**	**0.89**	**0.075**
Residual	117	0.660	0.006				
Total	119	6.212	0.052				

Table A4.183: Estimates of parameters for chisel tine, Swan Hill (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.885	0.226	-3.922	**<0.001**
Depth	0.025	0.005	5.357	**<0.001**
Depth Sq	-7.260E-5	0.000	-3.119	**0.002**

3. Opener tine

3.1 Non-wheeled soil

3.1.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.184: Summary of analysis for opener tine, Swan Hill (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	9.652	9.652	386.140	**<0.001**	**0.76**	**0.158**
Residual	118	2.949	0.025				
Total	119	12.601	0.106				

Table A4.185: Estimates of parameters for opener tine, Swan Hill (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.256	0.018	13.858	**<0.001**
Depth	0.014	0.001	19.650	**<0.001**

3.1.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.186: Summary of analysis for opener tine, Swan Hill (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	12.113	12.113	255.288	**<0.001**	**0.68**	**0.218**
Residual	118	5.599	0.047				
Total	119	17.713	0.149				

Table A4.187: Estimates of parameters for opener tine, Swan Hill (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.472	0.099	-4.746	**<0.001**
Depth	0.016	0.001	15.978	**<0.001**

3.1.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.188: Summary of analysis for opener tine, Swan Hill (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	12.701	6.350	148.239	**<0.001**	**0.71**	**0.207**
Residual	117	5.012	0.043				
Total	119	17.713	0.149				

Table A4.189: Estimates of parameters opener tine, Swan Hill (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	1.803	0.622	2.900	**0.004**
Depth	-0.032	0.013	-2.482	**0.014**
Depth Sq	0.000	0.000	3.702	**<0.001**

3.2 Wheeled soil

3.2.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.190: Summary of analysis for opener tine, Swan Hill (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	14.475	14.475	380.830	<**0.001**	**0.76**	**0.195**
Residual	118	4.485	0.038				
Total	119	18.960	0.159				

Table A4.191: Estimates of parameters for opener tine, Swan Hill (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.228	0.020	11.238	**<0.001**
Depth	0.017	0.001	19.515	**<0.001**

3.2.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.192: Summary of analysis for opener tine, Swan Hill (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	28.513	28.513	259.575	<**0.001**	**0.69**	**0.331**
Residual	118	12.962	0.110				
Total	119	41.474	0.349				

Table A4.193: Estimates of parameters for opener tine, Swan Hill (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-1.032	0.151	-6.822	**<0.001**
Depth	0.024	0.001	16.111	**<0.001**

3.2.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.194: Summary of analysis for opener tine, Swan Hill (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	30.511	15.256	162.808	**<0.001**	**0.73**	**0.306**
Residual	117	10.963	0.094				
Total	119	41.474	0.349				

Table A4.195: Estimates of parameters opener tine, Swan Hill (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	3.166	0.920	3.442	**0.001**
Depth	-0.064	0.019	-3.350	**0.001**
Depth Sq	0.000	0.000	4.618	**<0.001**

A4.1.12: Statistical analysis - draught force measurements in **Loxton** site

Factors structure:

Tine: Sweep, chisel, opener

Traffic system: Wheeled track, non-wheeled track

Operating depth: 75 mm, 100 mm, 125 mm

Table A4.196: Analysis of variance – draught force measurements of sweep tines (Loxton site)

Variate: **Draught force (kN)**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	8.782	8.782	222.110	**<0.001**	**0.61**
Depth	2	5.540	2.770	70.059	**<0.001**	
Traffic . Depth	2	0.301	0.151	3.811	**0.024**	
Residual	234	9.252	0.040			
Total	239	23.876	0.100			

Table A4.197: Analysis of variance – draught force measurements of chisel tines (Loxton site)

Variate: **Draught force (kN)**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	0.399	0.399	111.683	**<0.001**	**0.55**
Depth	2	0.580	0.290	81.289	**<0.001**	
Traffic . Depth	2	0.047	0.024	6.627	**0.002**	
Residual	234	0.835	0.004			
Total	239	1.861	0.008			

Table A4.198: Analysis of variance – draught force measurements of opener tines (Loxton site)

Variate: **Draught force (kN)**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	0.495	0.495	64.382	**<0.001**	**0.79**
Depth	2	6.224	3.112	404.739	**<0.001**	
Traffic . Depth	2	0.035	0.018	2.279	**0.105**	
Residual	234	1.799	0.008			
Total	239	8.554	0.036			

Table A4.199: Analysis of variance – draught force measurements of all tines (Loxton site)

Variate: **Draught force (kN)**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	6.159	6.159	363.718	**<0.001**	**0.90**
Tine	2	86.411	43.206	2551.638	**<0.001**	
Depth	2	10.374	5.187	306.343	**<0.001**	
Traffic.Tine	2	3.517	1.759	103.857	**<0.001**	
Traffic.Depth	2	0.186	0.093	5.498	**0.004**	
Tine.Depth	4	1.970	0.493	29.090	**<0.001**	
Traffic.Tine.Depth	4	0.198	0.049	2.917	**0.021**	
Residual	702	11.887	0.017			
Total	719	120.702	0.168			

A4.1.13: Regression analysis – relationship between operating depth and draught force, **Loxton** site**.**

1. Sweep tine

1.1 Non-wheeled soil

1.1.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.200: Summary of analysis for sweep tine Loxton (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	1.879	1.879	155.912	<**0.001**	**0.57**	**0.110**
Residual	118	1.422	0.012				
Total	119	3.300	0.028				

Table A4.201: Estimates of parameters for sweep tine, Loxton (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.689	9.035	19.959	**<0.001**
Depth	0.006	9.000	12.486	**<0.001**

1.1.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.202: Summary of analysis for sweep tine , Loxton (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	3.109	3.109	152.713	<**0.001**	**0.56**	**0.143**
Residual	118	2.402	0.020				
Total	119	5.511	0.046				

Table A4.203: Estimates of parameters for Sweep tine, Loxton (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.501	0.065	7.700	**<0.001**
Depth	0.008	0.001	12.358	**<0.001**

1.1.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.204: Summary of analysis for sweep tine, Loxton (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	3.117	1.559	76.187	**<0.001**	**0.56**	**0.143**
Residual	117	2.394	0.020				
Total	119	5.511	0.046				

Table A4.205: Estimates of parameters for sweep tine, Loxton (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.775	0.430	1.805	.074
Depth	0.002	0.009	0.244	.808
Depth Sq	2.860E-5	0.000	0.645	.520

1.2 Wheeled soil

1.2.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.206: Summary of analysis for sweep tine, Loxton (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	0.836	0.836	39.317	**<0.001**	**0.24**	**0.146**
Residual	118	2.509	0.021				
Total	119	3.345	0.028				

Table A4.207: Estimates of parameters for sweep tine, Loxton (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	1.096	0.073	15.025	**<0.001**
Depth	0.004	0.001	6.270	**<0.001**

1.2.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.208: Summary of analysis for sweep tine, Loxton (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	2.309	2.309	37.447	**<0.001**	**0.23**	**0.248**
Residual	118	7.275	0.062				
Total	119	9.583	0.081				

Table A4.209: Estimates of parameters for sweep tine, Loxton (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.993	0.113	8.762	**<0.001**
Depth	0.007	0.001	6.119	**<0.001**

1.2.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.210: Summary of analysis for sweep tine, Loxton (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	2.724	1.362	23.237	**<0.001**	**0.27**	**0.242**
Residual	117	6.859	0.059				
Total	119	9.583	0.081				

Table A4.211: Estimates of parameters for sweep tine, Loxton (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.922	0.727	-1.267	**0.208**
Depth	0.047	0.015	3.108	**0.002**
Depth Sq	0.000	0.000	-2.663	**0.009**

2. **Chisel tine**

2.1 Non-wheeled soil

2.1.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.212: Summary of analysis for chisel tine, Loxton (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	1.369	1.369	132.996	**<0.001**	**0.53**	**0.101**
Residual	118	1.215	0.010				
Total	119	2.584	0.022				

Table A4.213: Estimates of parameters for chisel tine, Loxton (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.348	0.016	21.592	**<0.001**
Depth	0.005	0.000	11.532	**<0.001**

2.1.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.214: Summary of analysis for chisel tine, Loxton (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	0.459	0.459	139.887	**<0.001**	**0.54**	**0.057**
Residual	118	0.387	0.003				
Total	119	0.846	0.007				

Table A4.215: Estimates of parameters for chisel tine, Loxton (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.290	0.026	11.104	**<0.001**
Depth	0.003	0.00	11.827	**<0.001**

2.1.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.216: Summary of analysis for chisel tine, Loxton (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	0.460	0.230	69.550	**<0.001**	**0.54**	**0.057**
Residual	117	0.387	0.003				
Total	119	0.846	0.007				

Table A4.217: Estimates of parameters for chisel tine, Loxton (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.217	0.173	1.259	**0.210**
Depth	0.005	0.004	1.274	**0.205**
Depth Sq	-7.600E-6	0.000	-0.427	**0.670**

2.2 Wheeled soil

2.2.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.218: Summary of analysis for chisel tine, Loxton (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	0.341	0.341	39.463	**<0.001**	**0.24**	**0.093**
Residual	118	1.020	0.009				
Total	119	1.361	0.011				

Table A4.219: Estimates of parameters for Chisel tine, Loxton (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.517	0.022	23.570	**<0.001**
Depth	0.003	0.000	6.282	**<0.001**

2.2.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.220: Summary of analysis for chisel tine, Loxton (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	0.158	0.158	40.528	**<0.001**	**0.25**	**0.062**
Residual	118	0.459	0.004				
Total	119	0.616	0.005				

Table A4.221: Estimates of parameters for chisel tine, Loxton (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.497	0.028	17.477	**<0.001**
Depth	0.002	0.000	6.366	**<0.001**

2.2.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.222: Summary of analysis for chisel tine, Loxton (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	0.168	0.084	21.892	**<0.001**	**0.26**	**0.062**
Residual	117	0.448	0.004				
Total	119	0.616	0.005				

Table A4.223: Estimates of parameters for chisel tine, Loxton (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.798	0.186	4.292	**<0.001**
Depth	-0.005	0.004	-1.171	**0.244**
Depth Sq	3.140E-5	0.000	1.637	**0.104**

3. Opener tine

3.1 Non-wheeled soil

3.1.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.224: Summary of analysis for opener tine, Loxton (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	3.475	3.475	379.781	**<0.001**	**0.76**	**0.096**
Residual	118	1.080	0.009				
Total	119	4.555	0.038				

Table A4.225: Estimates of parameters for opener tine, Loxton (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.413	0.018	22.904	**<0.001**
Depth	0.008	0.000	19.488	**<0.001**

3.1.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.226: Summary of analysis for opener tine, Loxton (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	3.065	3.065	373.575	**<0.001**	**0.76**	**0.091**
Residual	118	0.968	0.008				
Total	119	4.034	0.034				

Table A4.227: Estimates of parameters for opener tine, Loxton (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.008	0.000	19.328	**<0.001**
Depth	0.186	0.041	4.503	**<0.001**

3.1.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.228: Summary of analysis for opener tine, Loxton (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	3.170	1.585	214.847	**<0.001**	**0.78**	**0.086**
Residual	117	0.863	0.007				
Total	119	4.034	0.034				

Table A4.229: Estimates of parameters opener tine, Loxton (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.776	0.258	-3.007	**0.003**
Depth	0.028	0.005	5.230	**<0.001**
Depth Sq	0.000	0.000	-3.772	**<0.001**

3.2 Wheeled soil

3.2.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.230: Summary of analysis for opener tine, Loxton (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	2.678	2.678	255.577	**<0.001**	**0.68**	**0.102**
Residual	118	1.237	0.010				
Total	119	3.915	0.033				

Table A4.231: Estimates of parameters for opener tine, Loxton (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.502	0.023	21.401	**<0.001**
Depth	0.007	0.000	15.987	**<0.001**

3.2.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.232: Summary of analysis for opener tine, Loxton (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	2.760	2.760	257.568	**<0.001**	**0.68**	**0.104**
Residual	118	1.265	0.011				
Total	119	4.025	0.034				

Table A4.233: Estimates of parameters for opener tine, Loxton (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.317	0.047	6.709	**<0.001**
Depth	0.007	0.000	16.049	**<0.001**

3.2.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.234: Summary of analysis for opener tine, Loxton (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	3.089	1.544	193.051	**<0.001**	**0.76**	**0.089**
Residual	117	0.936	0.008				
Total	119	4.025	0.034				

Table A4.235: Estimates of parameters opener tine, Loxton (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-1.385	0.269	-5.154	**<0.001**
Depth	0.043	0.006	7.729	**<0.001**
Depth Sq	0.000	0.000	-6.409	**<0.001**

A4.1.14: Statistical analysis - draught force measurements in **Waikerie** site

Factors structure:

Tine: Sweep, chisel, opener

Traffic system: Wheeled track, non-wheeled track

Operating depth: 75 mm, 100 mm, 125 mm

Table A4.236: Analysis of variance – draught force measurements of sweep tines (Waikerie site)

Variate: **Draught force (kN)**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	0.142	0.142	6.181	**0.014**	**0.82**
Depth	2	24.020	12.010	522.343	**<0.001**	
Traffic . Depth	2	0.226	0.113	4.917	**0.008**	
Residual	234	5.380	0.023			
Total	239	29.768	0.125			

Table A4.237: Analysis of variance – draught force measurements of chisel tines (Waikerie site)

Variate: **Draught force (kN)**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	0.038	0.038	7.717	**0.006**	**0.49**
Depth	2	1.048	0.524	106.411	**<0.001**	
Traffic . Depth	2	0.021	0.010	2.095	**0.125**	
Residual	234	1.152	0.005			
Total	239	2.259	0.009			

Table A4.238: Analysis of variance – draught force measurements of opener tines (Waikerie site)

Variate: **Draught force (kN)**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	0.001	0.001	0.043	**0.835**	**0.37**
Depth	2	4.022	2.011	66.902	**<0.001**	
Traffic . Depth	2	0.042	0.021	0.693	**0.501**	
Residual	234	7.033	0.030			
Total	239	11.098	0.046			

Table A4.239: Analysis of variance – draught force measurements of all tines (Waikerie site)

Variate: **Draught force (kN)**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	0.016	0.016	0.821	**0.365**	**0.87**
Tine	2	60.674	30.337	1569.881	**<0.001**	
Depth	2	18.793	9.396	486.250	**<0.001**	
Traffic.Tine	2	0.166	0.083	4.283	**0.014**	
Traffic.Depth	2	0.022	0.011	0.581	**0.559**	
Tine.Depth	4	10.296	2.574	133.205	**<0.001**	
Traffic.Tine.Depth	4	0.266	0.066	3.440	**0.009**	
Residual	702	13.566	0.019			
Total	719	120.702	0.168			

A4.1.15: Regression analysis – relationship between operating depth and draught force, **Waikerie** site**.**

1. **Sweep tine**

1.1 Non-wheeled soil

1.1.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.240: Summary of analysis for sweep tine Waikerie (Non-wheeled soil)

Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**Adjusted R^2**	**SE**
Regression	1	5.802	5.802	283.138	**<0.001**	**0.70**	**0.143**
Residual	118	2.418	0.020				
Total	119	8.220	0.069				

Table A4.241: Estimates of parameters for sweep tine, Waikerie (Non-wheeled soil)

Parameter	**estimate**	**s.e.**	**t(96)**	**t pr.**
Constant	0.379	0.025	15.305	**<0.001**
Depth	0.011	0.001	16.827	**<0.001**

1.1.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.242: Summary of analysis for sweep tine , Waikerie (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	8.528	8.528	251.196	<**0.001**	**0.68**	**0.184**
Residual	118	4.006	0.034				
Total	119	12.534	0.105				

Table A4.243: Estimates of parameters for Sweep tine, Waikerie (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.152	0.084	-1.805	**0.074**
Depth	0.013	0.001	15.849	<**0.001**

1.1.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.244: Summary of analysis for sweep tine, Waikerie (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	9.793	4.896	208.943	<**0.001**	**0.78**	**0.153**
Residual	117	2.742	0.023				
Total	119	12.534	0.105				

Table A4.245: Estimates of parameters for sweep tine, Waikerie (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	3.187	0.460	6.930	<**0.001**
Depth	-0.057	0.010	-5.953	<**0.001**
Depth Sq	0.000	0.000	7.346	<**0.001**

1.2 Wheeled soil

1.2.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.246: Summary of analysis for sweep tine, Waikerie (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	7.859	7.859	401.365	<**0.001**	**0.77**	**0.140**
Residual	118	2.310	0.020				
Total	119	10.169	0.086				

Table A4.247: Estimates of parameters for sweep tine, Waikerie (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.328	0.021	15.657	<**0.001**
Depth	0.013	0.001	20.034	<**0.001**

1.2.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.248: Summary of analysis for sweep tine, Waikerie (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	12.577	12.577	328.726	<**0.001**	**0.73**	**0.196**
Residual	118	4.515	0.038				
Total	119	17.092	0.144				

Table A4.249: Estimates of parameters for sweep tine, Waikerie (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.383	0.089	-4.292	<**0.001**
Depth	0.016	0.001	18.131	<**0.001**

1.2.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.250: Summary of analysis for sweep tine, Waikerie (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	14.453	7.227	320.457	**<0.001**	**0.84**	**0.150**
Residual	117	2.638	0.023				
Total	119	17.092	0.144				

Table A4.251: Estimates of parameters for sweep tine, Waikerie (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	3.684	0.451	8.166	**<0.001**
Depth	-0.069	0.009	-7.398	**<0.001**
Depth Sq	0.000	0.000	9.121	**<0.001**

2. Chisel tine

2.1 Non-wheeled soil

2.1.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.252: Summary of analysis for chisel tine, Waikerie (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	2.994	2.994	73.639	**<0.001**	**0.38**	**0.202**
Residual	118	4.798	0.041				
Total	119	7.793	0.066				

Table A4.253: Estimates of parameters for chisel tine, Waikerie (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.215	0.020	10.865	**<0.001**
Depth	0.008	0.001	8.581	**<0.001**

2.1.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.254: Summary of analysis for chisel tine, Waikerie (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	0.621	0.621	78.399	**<0.001**	**0.39**	**0.089**
Residual	118	0.935	0.008				
Total	119	1.556	0.013				

Table A4.255: Estimates of parameters for chisel tine, Waikerie (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.128	0.041	3.146	**0.002**
Depth	0.004	0.000	8.854	<**0.001**

2.1.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.256: Summary of analysis for chisel tine, Waikerie (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	0.631	.316	39.921	**<0.001**	**0.40**	**0.089**
Residual	117	0.925	0.008				
Total	119	1.556	0.013				

Table A4.257: Estimates of parameters for chisel tine, Waikerie (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.169	0.267	-0.634	**0.528**
Depth	0.010	0.006	1.760	**0.081**
Depth Sq	-3.100E-5	0.000	-1.125	**0.263**

2.2 Wheeled soil

2.2.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.258: Summary of analysis for chisel tine, Waikerie (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	2.168	2.168	144.495	<**0.001**	**0.55**	**0.122**
Residual	118	1.770	0.015				
Total	119	3.938	0.033				

Table A4.259: Estimates of parameters for Chisel tine, Waikerie (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.232	0.013	17.888	<**0.001**
Depth	0.007	0.001	12.021	<**0.001**

2.2.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.260: Summary of analysis for chisel tine, Waikerie (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	0.389	0.389	166.767	<**0.001**	**0.58**	**0.048**
Residual	118	0.275	0.002				
Total	119	0.665	0.006				

Table A4.261: Estimates of parameters for chisel tine, Waikerie (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.176	0.022	7.989	<**0.001**
Depth	0.003	0.000	12.914	<**0.001**

2.2.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.262: Summary of analysis for chisel tine, Waikerie (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	0.437	0.219	112.603	**<0.001**	**0.65**	**0.044**
Residual	117	0.227	0.002				
Total	119	0.665	0.006				

Table A4.263: Estimates of parameters for chisel tine, Waikerie (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.476	0.132	-3.592	**<0.001**
Depth	0.016	0.003	5.986	**<0.001**
Depth Sq	-6.800E-5	0.000	-4.980	**<0.001**

3. Opener tine

3.1 Non-wheeled soil

3.1.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.264: Summary of analysis for opener tine, Waikerie (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	2.997	2.997	59.787	**<0.001**	**0.33**	**0.224**
Residual	118	5.915	0.050				
Total	119	8.912	0.075				

Table A4.265: Estimates of parameters for opener tine, Waikerie (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.357	0.036	9.785	**<0.001**
Depth	0.008	0.001	7.732	**<0.001**

3.1.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.266: Summary of analysis for opener tine, Waikerie (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	1.947	1.947	73.380	**<0.001**	**0.38**	**0.163**
Residual	118	3.131	0.027				
Total	119	5.078	0.043				

Table A4.267: Estimates of parameters for opener tine, Waikerie (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.178	0.074	2.400	**0.018**
Depth	0.006	0.001	8.566	**<0.001**

3.1.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.268: Summary of analysis for opener tine, Waikerie (Non-wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	2.067	1.034	40.180	**<0.001**	**0.40**	**0.160**
Residual	117	3.010	0.026				
Total	119	5.078	0.043				

Table A4.269: Estimates of parameters opener tine, Waikerie (Non-wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.853	0.482	-1.770	**0.079**
Depth	0.028	0.010	2.786	**0.006**
Depth Sq	0.000	0.000	-2.165	**0.032**

3.2 Wheeled soil

3.2.1 Regression analysis – exponential model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.270: Summary of analysis for opener tine, Waikerie (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	2.130	2.130	30.675	**<0.001**	**0.20**	**0.263**
Residual	118	8.193	0.069				
Total	119	10.322	0.087				

Table A4.271: Estimates of parameters for opener tine, Waikerie (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.403	0.048	8.315	**<0.001**
Depth	0.007	0.001	5.538	**<0.001**

3.2.2 Regression analysis – linear model

Response variate: Draught force

Fitted terms: Constant, depth

Table A4.272: Summary of analysis for opener tine, Waikerie (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	1.624	1.624	43.622	**<0.001**	**0.26**	**0.193**
Residual	118	4.394	0.037				
Total	119	6.019	0.051				

Table A4.273: Estimates of parameters for opener tine, Waikerie (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.237	0.088	2.692	**0.008**
Depth	0.006	0.001	6.605	**<0.001**

3.2.3 Regression analysis – quadratic model

Response variate: Draught force

Fitted terms: Constant, depth, depth Sq.

Table A4.274: Summary of analysis for opener tine, Waikerie (Wheeled soil)

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	2	1.996	0.998	29.021	**<0.001**	**0.32**	**0.185**
Residual	117	4.023	0.034				
Total	119	6.019	0.051				

Table A4.275: Estimates of parameters opener tine, Waikerie (Wheeled soil)

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-1.572	0.557	-2.822	**0.006**
Depth	0.043	0.012	3.772	**<0.001**
Depth Sq	0.000	0.000	-3.286	**0.001**

A4.1.16: Statistical analysis of dataset- draught force measurements in most sites

Factors structure:

Site: Felton, Pittsworth, Gatton, Swan Hill, Loxton, Waikerie

Tine: Sweep, chisel, opener

Traffic system: Wheeled track, non-wheeled track

Operating depth: 75 mm, 100 mm, 125 mm

Table A4.276: Analysis of variance – draught force measurements of all tines in most of sites

Variate: **Draught force (kN)**

Source of varaiation	**d.f.**	**s.s**	**m. s.**	**v.r.**	**Fpr.**	**R^2**
Site	5	3417.628	683.526	6785.499	**<0.001**	**0.95**
Traffic	1	613.635	613.635	6091.685	**<0.001**	
Depth	2	604.702	302.351	3001.499	**<0.001**	
Tine	2	1204.525	602.262	5978.783	**<0.001**	
Site.Traffic	5	439.306	87.861	872.216	**<0.001**	
Site.Depth	10	250.998	25.100	249.171	**<0.001**	
Site.Tine	10	500.803	50.080	497.158	**<0.001**	
Traffic.Depth	2	11.628	5.814	57.716	**<0.001**	
Traffic.Tine	2	43.882	21.941	217.815	**<0.001**	
Depth.Tine	4	31.919	7.980	79.217	**<0.001**	
Site.Traffic.Depth	10	12.234	1.223	12.145	**<0.001**	
Site.Traffic.Tine	10	159.527	15.953	158.366	**<0.001**	
Site.Depth.Tine	20	85.797	4.290	42.586	**<0.001**	
Traffic.Depth.Tine	4	3.881	0.970	9.631	**<0.001**	
Site.Traffic.Depth.Tine	20	13.154	0.658	6.529	**<0.001**	
Residual	4212	424.289	0.101			
Total	4319	7817.907	1.810			

Appendix A4.2: Summary results of draught force for Northern region and Southern region sites in Chapter 4

A4.2.1: Felton (QLD) site

Table A4.2.0.1: The mean values of draught force and draught increasing for each tine in Felton (QLD) site. P values for the interaction between traffic and depth factors are P=0.614, P< 0.05 and P= 0.444 for sweep, chisel and opener tines, respectively. Different letters indicate that mean values are significantly different at a 95% confidence interval

Site: Felton	Draught force (kN)				
Tine	Depth (mm)				
	Traffic	75	100	125	Mean
Sweep	Non-wheeled	2.24	2.74	3.48	**2.82 b**
	SD	**± 0.33**	**± 0.35**	**± 0.51**	**± 0.65**
	Wheeled	3.6	4.13	5.02	**4.25 a**
	SD	**± 0.60**	**± 0.67**	**± 0.95**	**± 0.95**
	n	**40**	**40**	**40**	**120**
	Draught increase				
	Differences (ratio)	1.61	1.51	1.44	**1.51**
	SD	**± 0.07**	**± 0.07**	**± 0.11**	**± 0.11**
	Percentage (%)	60.94	51.08	44.36	**50.71**
	SD	**± 6.84**	**± 7.35**	**± 11.18**	**± 11.07**
Chisel	Draught force (kN)				
	Depth (mm)				
	Traffic	75	100	125	Mean
	Non-wheeled	0.89 f	1.27 e	1.86 c	**1.34 b**
	SD	**± 0.185**	**± 0.224**	**± 0.467**	**± 0.508**
	Wheeled	1.58 d	2.19 b	2.93 a	**2.23 a**
	SD	**± 0.632**	**± 0.783**	**± 0.857**	**± 0.80**
	n	**40**	**40**	**40**	**120**
	Draught increase				
	Differences (ratio)	1.78	1.71	1.57	**1.66**
	SD	**± 0.25**	**± 0.21**	**± 0.11**	**± 0.22**
	Percentage (%)	78	71	57	**66**
	SD	**± 24.75**	**± 20.59**	**± 10.80**	**± 21.67**
Opener	Draught force (kN)				
	Depth (mm)				
	Traffic	75	100	125	Mean
	Non-wheeled	1.47	2.02	2.55	**2.01 b**
	SD	**± 0.159**	**± 0.197**	**± 0.225**	**± 0.48**
	Wheeled	2.2	2.8	3.3	**2.77 a**
	SD	**± 0.223**	**± 0. 173**	**± 0.242**	**± 0.497**
	n	**40**	**40**	**40**	**120**
	Draught increase				
	Differences (ratio)	1.49	1.39	1.29	**1.38**
	SD	**± 0.04**	**± 0.06**	**± 0.03**	**± 0.09**
	Percentage (%)	49	39	30	**37.81**
	SD	**± 3.55**	**± 5.64**	**± 3.02**	**± 9.15**

A4.2.2: Pittsworth (QLD) site

Table 4.2.2: The mean values of draught force and draught increasing for each tine in Pittsworth (QLD) site. P values for the interaction between traffic and depth factors are P < 0.001, P< 0.001 and P= 0.715 for sweep, chisel and opener tines, respectively. Different letters indicate that mean values are significantly different at a 95% confidence interval

Site: Pittsworth	Draught force (kN)				
Tine	**Depth (mm)**				
	Traffic	**75**	**100**	**125**	**Mean**
Sweep	**Non-wheeled**	1.64 f	3.24 e	4.55 c	**3.14 b**
	SD	**± 0.222**	**± 0.347**	**± 0.632**	**± 1.269**
	Wheeled	4.31 d	6.83 b	7.62 a	**6.25 a**
	SD	**± 0.585**	**± 0.468**	**± 0.811**	**± 1.55**
	n	**40**	**40**	**40**	**120**
	Draught increase				
	Differences (ratio)	2.63	2.11	1.68	**1.99**
	SD	**± 0.06**	**± 0.09**	**± 0.21**	**± 0.40**
	Percentage (%)	163	111	68	**99**
	SD	**± 6.16**	**± 8.71**	**± 20.82**	**± 40**
Chisel	**Draught force (kN)**				
	Depth (mm)				
	Traffic	**75**	**100**	**125**	**Mean**
	Non-wheeled	0.90 e	1.50 d	2.17 c	**1.52 b**
	SD	**± 0.144**	**± 0.217**	**± 0.249**	**± 0.561**
	Wheeled	1.42 d	2.73 b	3.81 a	**2.65 a**
	SD	**± 0.362**	**± 0.362**	**± 0.228**	**± 1.003**
	n	**40**	**40**	**40**	**120**
	Draught increase				
	Differences (ratio)	1.58	1.81	1.76	**1.74**
	SD	**± 0.15**	**± 0.04**	**± 0.10**	**± 0.16**
	Percentage (%)	58	81	76	**74**
	SD	**± 15.27**	**± 4.46**	**± 10.04**	**± 15.47**
Opener	**Draught force (kN)**				
	Depth (mm)				
	Traffic	**75**	**100**	**125**	**Mean**
	Non-wheeled	1.9	2.25	2.81	**2.32 b**
	SD	**± 0.329**	**± 0.311**	**± 0.311**	**± 0.49**
	Wheeled	3.18	3.43	4.18	**3.6 a**
	SD	**± 0.573**	**± 0.464**	**± 0.576**	**± 0.684**
	n	**40**	**40**	**40**	**120**
	Draught increase				
	Differences (ratio)	1.71	1.53	1.49	**1.55**
	SD	**± 0.11**	**± 0.33**	**± 0.06**	**± 0.23**
	Percentage (%)	71	53	49	**55**
	SD	**± 11.06**	**± 33.71**	**± 6.39**	**± 23.10**

A4.2.3: Gatton (QLD) site

Table A4.2.3: The mean values of draught force and draught increasing for each tine in Gatton (QLD) site. P values for the interaction between traffic and depth factors are P= 0.243, P< 0.001 and P< 0.001 for sweep, chisel and opener tines, respectively. Different letters indicate that mean values are significantly different at a 95% confidence interval

Site: Gatton	Draught force (kN)				
Tine	**Depth (mm)**				
	Traffic	**75**	**100**	**125**	**Mean**
Sweep	**Non-wheeled**	1.82	2.5	2.96	**2.43 b**
	SD	**± 0.634**	**± 0.427**	**± 0.345**	**± 0.671**
	Wheeled	2.59	3.49	3.79	**3.29 a**
	SD	**± 0.236**	**± 0.435**	**± 0.369**	**± 0.621**
	n	**40**	**40**	**40**	**120**
	Draught increase				
	Differences (ratio)	1.43	1.40	1.28	**1.35**
	SD	**± 0.41**	**± 0.12**	**± 0.05**	**± 0.27**
	Percentage (%)	43	40	28	**35**
	SD	**± 41**	**± 12**	**± 5**	**± 27**
Chisel	**Draught force (kN)**				
	Depth (mm)				
	Traffic	**75**	**100**	**125**	**Mean**
	Non-wheeled	0.69 e	1.07 d	1.12 c	**0.96 b**
	SD	**± 0.20**	**± 0.36**	**± 0.21**	**± 0.32**
	Wheeled	1.08 d	2.04 b	2.52 a	**1.88 a**
	SD	**± 0.096**	**± 0.16**	**± 0.314**	**± 0.64**
	n	**40**	**40**	**40**	**120**
	Draught increase				
	Differences (ratio)	1.56	1.90	2.24	**1.95**
	SD	**± 0.33**	**± 0.41**	**± 0.35**	**± 0.45**
	Percentage (%)	56	90	124	**95**
	SD	**± 33.38**	**± 40.97**	**± 35.16**	**± 44.92**
Opener	**Draught force (kN)**				
	Depth (mm)				
	Traffic	**75**	**100**	**125**	**Mean**
	Non-wheeled	0.77 f	1.10 e	1.28 d	**1.05 b**
	SD	**± 0.061**	**± 0.113**	**± 0.153**	**± 0.240**
	Wheeled	1.59 c	2.37 b	2.65 a	**2.20 a**
	SD	**0.094**	**0.361**	**0.223**	**0.513**
	n	**40**	**40**	**40**	**120**
	Draught increase				
	Differences (ratio)	2.06	2.16	2.07	**2.09**
	SD	**± 0.05**	**± 0.13**	**± 0.08**	**± 0.099**
	Percentage (%)	**106**	**116**	**107**	**109**
	SD	**± 5.41**	**± 12.55**	**± 8.14**	**± 9.95**

A4.2.4: Kingaroy (QLD) site

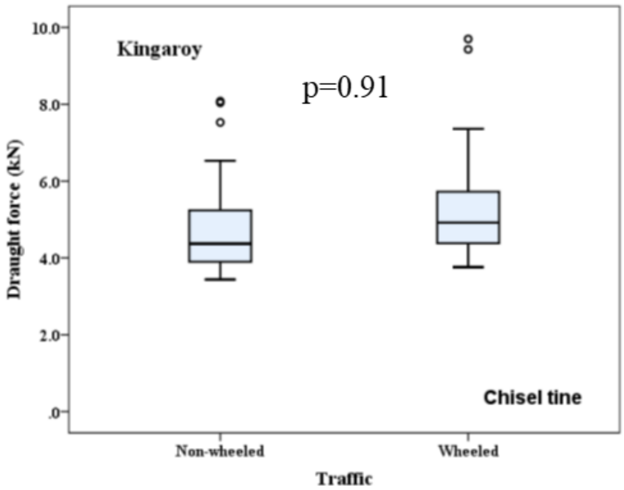


Figure A4.2.4: Tractor wheel traffic effects on draught forces for chisel tine in Kingaroy site. Box plots show: Min, Q1, Med, Q3 and Max (n=40). P =0.09. The symbols (○) denote mild outliers, respectively

Table A4.2.4: The mean values of draught force and draught increasing for chisel tines in Kingaroy (QLD) site

Site: Kingaroy	Draught force (kN)	
Tine	**Depth (200 mm)**	
	Traffic	
	Non-wheeled	4.76
	SD	**± 1.22**
	Wheeled	5.24
	SD	**± 1.31**
Chisel	**N**	**40**
	Draught increase	
	Differences (ratio)	1.10
	SD	**± 0.05**
	Percentage (%)	**10**
	SD	**± 5.29**

A4.2.5: Hopetoun (VIC) site

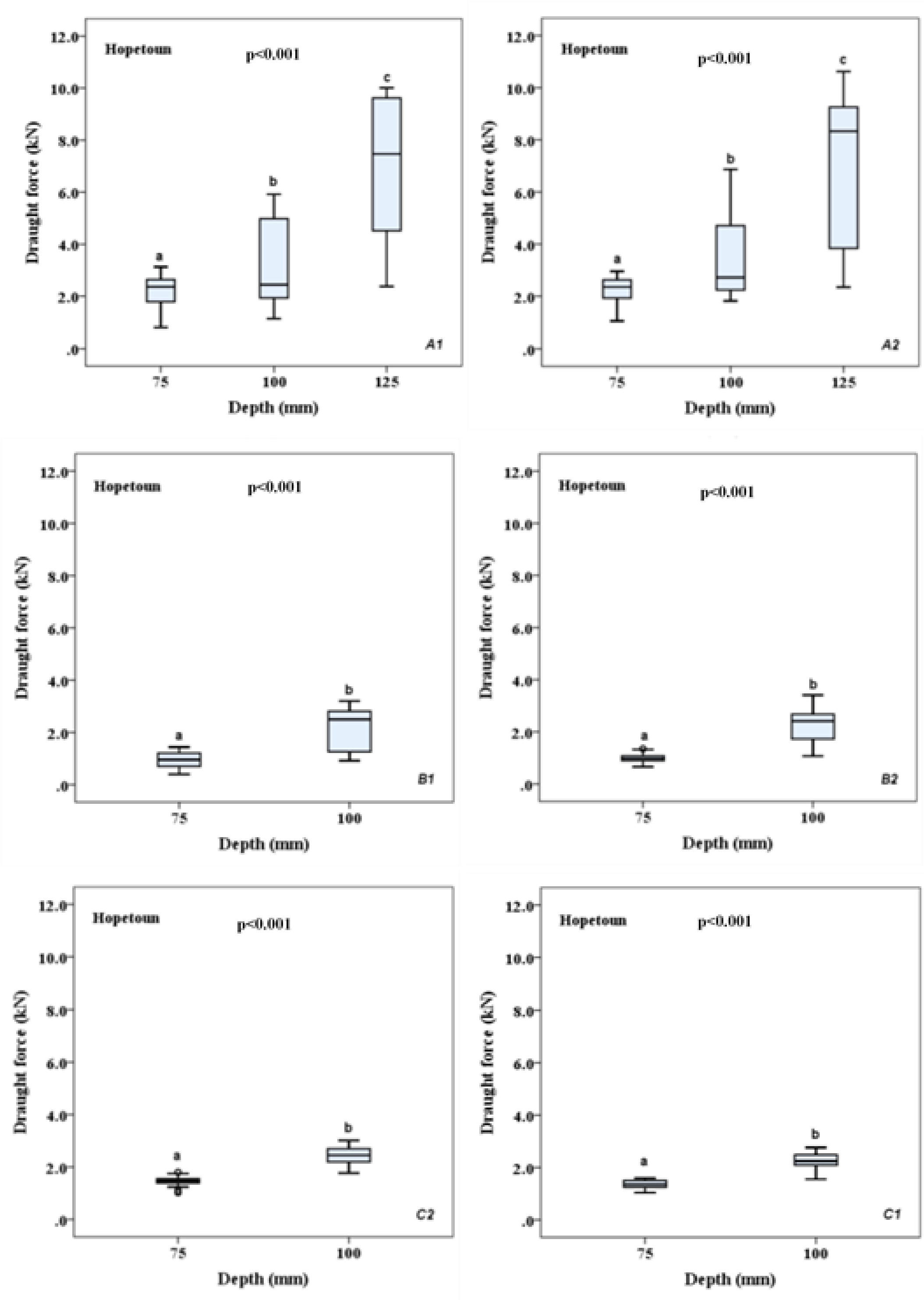


Figure A4.2.5: The effect of tractor wheel traffic and operating depth on draught force of different tines. Box plots show: Min, Q1, Med, Q3 and Max (n=40). P < 0.001. The symbols (○) and (*) denote mild and extreme outliers, respectively. Different letters indicate that mean values are significantly different at a 95% confidence interval. Figures show: (A) Sweep (B) Chisel and (C) Opener; (1) non-wheeled soil (2) wheeled soil for Hopetoun (VIC) site, respectively

Table A4.2.5: The mean values of draught force and draught increasing for each tine in Hopetoun (VIC) site. P values for the interaction between traffic and depth factors are P = 0.875, P= 0.677 and P= 0.275 for sweep, chisel and opener tines, respectively

Site: Hopetoun	Draught force (kN)				
Tine	**Depth (mm)**				
Sweep	**Traffic**	**75**	**100**	**125**	**Mean**
	Non-wheeled	2.21	3.15	6.72	**4.03**
	SD	**± 0.608**	**± 1.49**	**± 2.77**	**± 2.68**
	Wheeled	2.29	3.48	7.07	**4.28**
	SD	**± 0.45**	**± 1.57**	**± 2.92**	**± 2.80**
	n	**40**	**40**	**40**	**120**
	Draught increase				
	Differences (ratio)	1.03	1.10	1.04	**1.06**
	SD	**± 0.17**	**± 0.11**	**± 0.10**	**± 0.13**
	Percentage (%)	3	10	4	**6**
	SD	**± 16.87**	**± 10.61**	**± 9.76**	**± 13.37**
Chisel	**Draught force (kN)**				
	Depth (mm)				
	Traffic	**75**	**100**	**125**	**Mean**
	Non-wheeled	0.93	2.15	-	**1.54**
	SD	**± 0.30**	**± 0.79**	-	**± 0.85**
	Wheeled	0.99	2.17	-	**1.63**
	SD	**± 0.17**	**± 0.65**	-	**± 0.80**
	n	**40**	**40**	-	**80**
	Draught increase				
	Differences (ratio)	1.06	1.06	-	**1.05**
	SD	**± 0.22**	**± 0.16**	-	**± 0.19**
	Percentage (%)	6	6	-	**6**
	SD	**± 22.05**	**± 16.33**	-	**± 19.43**
Opener	**Draught force (kN)**				
	Depth (mm)				
	Traffic	**75**	**100**	**125**	**Mean**
	Non-wheeled	1.36	2.26	-	**1.81**
	SD	**± 0.151**	**± 0.273**	-	**± 0.501**
	Wheeled	1.47	2.45	-	**1.96**
	SD	**± 0.16**	**± 0.323**	-	**± 0.554**
	n	**40**	**40**	-	**80**
	Draught increase				
	Differences (ratio)	1.08	1.03	-	**1.08**
	SD	**± 0.04**	**± 0.03**	-	**± 0.03**
	Percentage (%)	8	8	-	**8**
	SD	**± 4.05**	**± 3.32**	-	**± 3.70**

A4.2.6: Swan Hill (VIC) site

Table 4.2.6: The mean values of draught force and draught increasing for each tine in Sawn Hill (VIC) site. P values for the interaction between traffic and depth factors are P= 0.779, P= 0.171 and P< 0.001 for sweep, chisel and opener tines, respectively. Different letters indicate that mean values are significantly different at a 95% confidence interval

Site: Swan Hill	Draught force (kN)				
Tine	**Depth (mm)**				
	Traffic	**75**	**100**	**125**	**Mean**
Sweep	**Non-wheeled**	0.94	1.22	1.49	**1.18 b**
	SD	**± 0.150**	**± 0.140**	**± 0.180**	**± 0.276**
	Wheeled	1.30	1.52	1.89	**1.57 a**
	SD	**± 0.144**	**± 0.223**	**± 0.250**	**± 0.320**
	n	**40**	**40**	**40**	**120**
	Draught increasing				
	Differences (ratio)	1.38	1.35	1.27	**1.33**
	SD	**± 0.09**	**± 0.05**	**± 0.07**	**± 0.09**
	Percentage (%)	38.23	35.17	26.84	**32.71**
	SD	**± 8.66**	**± 4.75**	**± 7.10**	**± 8.76**
	Draught force (kN)				
	Depth (mm)				
	Traffic	**75**	**100**	**125**	**Mean**
Chisel	**Non-wheeled**	0.46	0.76	0.94	**0.72 b**
	SD	**± 0.026**	**± 0.043**	**± 0.11**	**± 0.213**
	Wheeled	0.58	0.89	1.11	**0.86 a**
	SD	**± 0.056**	**± 0.060**	**± 0.10**	**± 0.23**
	n	**40**	**40**	**40**	**120**
	Draught increasing				
	Differences (ratio)	1.27	1.17	1.17	**1.19**
	SD	**± 0.06**	**± 0.04**	**± 0.04**	**± 0.07**
	Percentage (%)	27.21	16.73	17.40	**19.44**
	SD	**± 6**	**± 4.02**	**± 4.04**	**± 6.64**
	Draught force (kN)				
	Depth (mm)				
	Traffic	**75**	**100**	**125**	**Mean**
Opener	**Non-wheeled**	0.75 f	0.99 d	1.52 b	**1.09 b**
	SD	**± 0.075**	**± 0.084**	**± 0.34**	**± 0.39**
	Wheeled	0.85 e	1.17 c	2.04 a	**1.36 a**
	SD	**± 0.09**	**± 0.18**	**± 0.49**	**± 0.59**
	n	**40**	**40**	**40**	**120**
	Draught increasing				
	Differences (ratio)	1.14	1.19	1.34	**1.24**
	SD	**± 0.04**	**± 0.08**	**± 0.10**	**± 0.12**
	Percentage (%)	14.15	19.10	34.25	**24.77**
	SD	**± 3.74**	**± 8.27**	**± 10.32**	**± 11.57**

A4.2.7: Loxton (SA) site

Table 4.2.7: The mean values of draught force and draught increasing for each tine in Loxton (SA) site. P values for the interaction between traffic and depth factors are P= 0.024, P= 0.002 and P= 0.105 for sweep, chisel and opener tines, respectively. Different letters indicate that mean values are significantly different at a 95% confidence interval

Site: Loxton	Draught force (kN)				
Tine	Depth (mm)				
Sweep	Traffic	75	100	125	Mean
	Non-wheeled	1.10 f	1.28 e	1.49 cd	**1.29 b**
	SD	± 0.131	± 0.081	± 0.195	± 0.215
	Wheeled	1.46 c	1.76 ab	1.80 a	**1.67 a**
	SD	± 0.165	± 0.269	± 0.277	± 0.284
	n	40	40	40	120
	Draught increasing				
	Differences (ratio)	1.33	1.38	1.21	**1.29**
	SD	± 0.21	± 0.17	± 0.22	± 0.21
	Percentage (%)	33.17	37.51	20.63	**29.45**
	SD	± 20.65	± 17.05	± 22.13	± 21.11
Chisel	Draught force (kN)				
	Depth (mm)				
	Traffic	75	100	125	Mean
	Non-wheeled	0.52 e	0.60 d	0.67 c	**0.59 b**
	SD	± 0.063	± 0.058	± 0.052	± 0.084
	Wheeled	0.64 bc	0.66 b	0.73 a	**0.68 a**
	SD	± 0.058	± 0.064	± 0.064	± 0.072
	n	40	40	40	120
	Draught increasing				
	Differences (ratio)	1.23	1.11	1.08	**1.15**
	SD	± 0.17	± 0.15	± 0.12	± 0.16
	Percentage (%)	23.41	10.81	7.67	**15.25**
	SD	± 16.89	± 14.86	± 12.25	± 16.30
Opener	Draught force (kN)				
	Depth (mm)				
	Traffic	75	100	125	Mean
	Non-wheeled	0.75	1.01	1.14	**0.97 b**
	SD	± 0.036	± 0.112	± 0.091	± 0.184
	Wheeled	0.84	1.13	1.21	**1.06 a**
	SD	± 0.046	± 0.118	± 0.90	± 0.184
	n	40	40	40	120
	Draught increasing				
	Differences (ratio)	1.11	1.12	1.06	**1.09**
	SD	± 0.081	± 0.14	± 0.06	± 0.105
	Percentage (%)	11.32	12.10	5.78	**9.28**
	SD	± 8.13	± 14.01	± 6.31	± 10.48

A4.2.8: Waikerie (SA) site

Table A4.2.8: The mean values of draught force and draught increasing for each tine in Waikerie (SA) site. P values for the interaction between traffic and depth factors are P= 0.008, P= 0.125 and P= 0.501 for sweep, chisel and opener tines, respectively. Different letters indicate that mean values are significantly different at a 95% confidence interval

Site: Waikerie	Draught force (kN)				
Tine	**Depth (mm)**				
	Traffic	**75**	**100**	**125**	**Mean**
	Non-wheeled	0.90 d	1.01 c	1.55 ab	**1.15**
	SD	**± 0.081**	**± 0.103**	**± 0.230**	**± 0.325**
	Wheeled	0.90 d	1.03 c	1.69 a	**1.20**
	SD	**± 0.048**	**± 0.124**	**± 0.234**	**± 0.380**
Sweep	**n**	**40**	**40**	**40**	**120**
	Draught increase				
	Differences (ratio)	1	1.02	1.09	**1.04**
	SD	**± 0.12**	**± 0.20**	**± 0.19**	**± 0.18**
	Percentage (%)	0	1.79	8.61	**4.34**
	SD	**± 12.35**	**± 20.22**	**± 18.53**	**± 17.87**
	Draught force (kN)				
	Depth (mm)				
	Traffic	**75**	**100**	**125**	**Mean**
	Non-wheeled	0.39	0.49	0.56	**0.48**
	SD	**± 0.093**	**± 0.050**	**± 0.112**	**± 0.114**
Chisel	**Wheeled**	0.37	0.48	0.51	**0.46**
	SD	**± 0.060**	**± 0.024**	**± 0.041**	**± 0.075**
	n	**40**	**40**	**40**	**120**
	Draught increase				
	Differences (ratio)	0.97	0.98	0.91	**0.96**
	SD	**± 0.34**	**± 0.11**	**± 0.16**	**± 0.231**
	Percentage (%)	-3.44	-2.22	-9.13	**-4.17**
	SD	**± 33.98**	**± 11.31**	**± 16.40**	**± 23.11**
	Draught force (kN)				
	Depth (mm)				
	Traffic	**75**	**100**	**125**	**Mean**
	Non-wheeled	0.62	0.85	0.94	**0.80**
	SD	**± 0.12**	**± 0.083**	**± 0.24**	**± 0.21**
Opener	**Wheeled**	0.63	0.89	0.91	**0.81**
	SD	**± 0.90**	**± 0.133**	**± 0.28**	**± 0.23**
	n	**40**	**40**	**40**	**120**
	Draught increase				
	Differences (ratio)	1	1.05	0.97	**1.01**
	SD	**± 0.25**	**± 0.15**	**± 0.13**	**± 0.19**
	Percentage (%)	0.1	4.56	-2.75	**1.25**
	SD	**± 25.39**	**± 14.72**	**± 13.47**	**± 19.10**

Appendix A4.3: Statistical analyses corresponding to soil surface roughness in Chapter 4

A4.3.1: Statistical analysis – soil surface roughness measurements in **Felton** site

Factors structure:

Tine: Sweep, chisel, opener

Traffic system: Wheeled track, non-wheeled track

Operating depth: 0, 75 mm, 100 mm, 125 mm

Table A4.3.1: Analysis of variance – soil surface roughness measurements of non-wheeled soil and wheeled soil for all tines (Felton site)

Variate: **Soil surface roughness (%)**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	6650.010	6650.010	200.021	**<0.001**	**0.93**
Tine	2	1570.771	785.385	23.623	**<0.001**	
Depth	3	22060.448	7353.483	221.180	**<0.001**	
Traffic.Tine	2	107.771	53.885	1.621	**0.205**	
Traffic.Depth	3	2508.115	836.038	25.147	**<0.001**	
Tine.Depth	6	1194.896	199.149	5.990	**<0.001**	
Traffic.Tine.Depth	6	93.229	15.538	0.467	**0.830**	
Residual	72	2393.750	33.247			
Total	95	36578.990	385.042			

A4.3.2: Statistical analysis – soil surface roughness measurements in **Pittsworth** site

Table A4.3.2: Analysis of variance – soil surface roughness measurements of non-wheeled soil and wheeled soil for all tines (Pittsworth site)

Variate: **Soil surface roughness (%)**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	5781.510	5781.510	637.227	**<0.001**	**0.98**
Tine	2	2150.646	1075.323	118.520	**<0.001**	
Depth	3	23009.781	7669.927	845.365	**<0.001**	
Traffic.Tine	2	312.521	156.260	17.223	**<0.001**	
Traffic.Depth	3	1996.865	665.622	73.364	**<0.001**	
Tine.Depth	6	1072.188	178.698	19.696	**<0.001**	
Traffic.Tine.Depth	6	389.979	64.997	7.164	**<0.001**	
Residual	72	653.250	9.073			
Total	95	35366.740	372.281			

A4.3.3: Statistical analysis – soil surface roughness measurements in **Gatton** site

Table A4.3.3: Analysis of variance – soil surface roughness measurements of non-wheeled soil and wheeled soil for all tines (Gatton site)

Variate: **Soil surface roughness (%)**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	2992.667	2992.667	280.745	**<0.001**	**0.96**
Tine	2	1185.438	592.719	55.604	**<0.001**	
Depth	3	17577.333	5859.111	549.650	**<0.001**	
Traffic.Tine	2	42.021	21.010	1.971	**0.147**	
Traffic.Depth	3	1093.000	364.333	34.179	**<0.001**	
Tine.Depth	6	947.479	157.913	14.814	**<0.001**	
Traffic.Tine.Depth	6	274.562	45.760	4.293	**<0.001**	
Residual	72	767.500	10.660			
Total	95	24880	261.894			

A4.3.4: Statistical analysis – soil surface roughness measurements in **Hopetoun** site

Table A4.3.4: Analysis of variance – soil surface roughness measurements of non-wheeled soil and wheeled soil for all tines (Hopetoun site)

Variate: **Soil surface roughness (%)**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	33.347	33.347	2.523	**0.118**	**0.97**
Tine	2	846.361	423.181	32.016	**<0.001**	
Depth*	2	22825.861	11412.931	863.465	**<0.001**	
Traffic.Tine	2	111.028	55.514	4.200	**0.020**	
Traffic.Depth	2	1093.000	17.097	1.294	**0.283**	
Tine.Depth	4	432.722	108.181	8.185	**<0.001**	
Traffic.Tine.Depth	4	126.056	31.514	2.384	**0.063**	
Residual	54	713.750	13.218			
Total	71	25123.319	353.850			

***** Depth**:** 0, 75 mm, 100 mm

A4.3.5: Statistical analysis – soil surface roughness measurements in **Swan Hill** site

Table A4.3.5: Analysis of variance – soil surface roughness measurements of non-wheeled soil and wheeled soil for all tines (Swan Hill site)

Variate: **Soil surface roughness (%)**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	1700.167	1700.167	152.824	**<0.001**	**0.96**
Tine	2	1048.188	524.094	47.110	**<0.001**	
Depth	3	15777.583	5259.194	472.737	**<0.001**	
Traffic.Tine	2	163.021	81.510	7.327	**<0.001**	
Traffic.Depth	3	615.417	205.139	18.439	**<0.001**	
Tine.Depth	6	631.729	105.288	9.464	**<0.001**	
Traffic.Tine.Depth	6	144.896	24.149	2.171	**0.056**	
Residual	72	801.000	11.125			
Total	95	20882	219.811			

A4.3.6: Statistical analysis – soil surface roughness measurements in **Loxton** site

Table A4.3.6: Analysis of variance – soil surface roughness measurements of non-wheeled soil and wheeled soil for all tines (Loxton site)

Variate: **Soil surface roughness (%)**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	1342.510	1342.510	132.186	**<0.001**	**0.94**
Tine	2	432.813	216.406	21.308	**<0.001**	
Depth	3	9489.115	3163.038	311.438	**<0.001**	
Traffic.Tine	2	14.146	7.073	0.696	**0.502**	
Traffic.Depth	3	456.281	152.094	14.975	**<0.001**	
Tine.Depth	6	261.604	43.601	4.293	**<0.001**	
Traffic.Tine.Depth	6	62.438	10.406	1.025	**0.416**	
Residual	72	731.250	10.156			
Total	95	12790.156	134.633			

A4.3.7: Statistical analysis– soil surface roughness measurements in **Waikerie** site

Table A4.3.7: Analysis of variance – soil surface roughness measurements of non-wheeled soil and wheeled soil for all tines (Waikerie site)

Variate: **Soil surface roughness (%)**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	816.667	816.667	22.866	**<0.001**	**0.89**
Tine	2	304.188	152.094	4.259	**0.018**	
Depth	3	20212.708	6737.569	188.647	**<0.001**	
Traffic.Tine	2	122.271	61.135	1.712	**0.188**	
Traffic.Depth	3	315.583	105.194	2.945	**0.039**	
Tine.Depth	6	364.229	60.705	1.700	**0.133**	
Traffic.Tine.Depth	6	312.479	52.080	1.458	**0.205**	
Residual	72	2571.500	35.715			
Total	95	25019.625	263.364			

A4.3.8: Statistical analysis of dataset- soil surface roughness measurements in most sites

Factors structure:

Site: Felton, Pittsworth, Gatton, Swan Hill, Loxton, Waikerie

Tine: Sweep, chisel, opener

Traffic system: Wheeled track, non-wheeled track

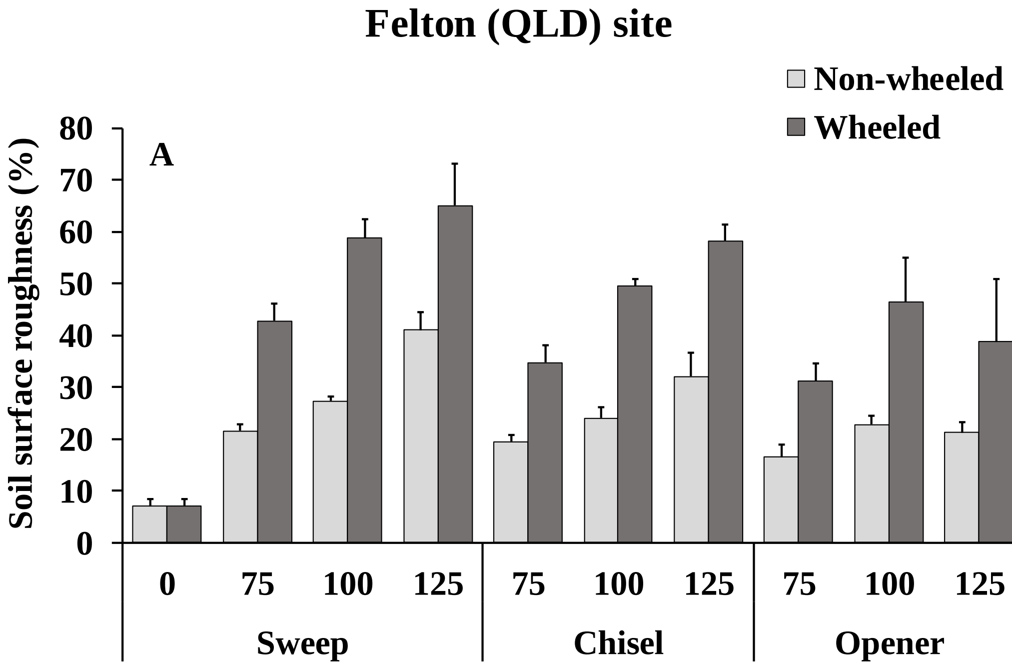
Operating depth: 0**,** 75 mm, 100 mm, 125 mm

Table A4.3.8: Analysis of variance – soil surface roughness measurements of non-wheeled soil and wheeled soil for all tines in most of sites

Variate: **Soil surface roughness (%)**						
Source of varaiation	**d.f.**	**s.s**	**m. s.**	**v.r.**	**Fpr.**	**R^2**
Site	5	6927.655	1385.531	75.591	**<0.001**	**0.95**
Traffic	1	16932.516	16932.516	923.796	**<0.001**	
Depth	3	104883.839	34961.280	1907.400	**<0.001**	
Tine	2	4061.316	2030.658	110.788	**<0.001**	
Site.Traffic	5	2351.016	470.203	25.653	**<0.001**	
Site.Depth	15	3243.130	216.209	11.796	**<0.001**	
Site.Tine	10	2630.726	263.073	14.353	**<0.001**	
Traffic.Depth	3	5808.214	1936.071	105.627	**<0.001**	
Traffic.Tine	2	154.698	77.349	4.220	**0.015**	
Depth.Tine	6	2313.031	385.505	21.032	**<0.001**	
Site.Traffic.Depth	15	1177.047	78.470	4.281	**<0.001**	
Site.Traffic.Tine	10	607.052	60.705	3.312	**<0.001**	
Site.Depth.Tine	30	2159.094	71.970	3.926	**<0.001**	
Traffic.Depth.Tine	6	553.344	92.224	5.032	**<0.001**	
Site.Traffic.Depth.Tine	30	724.240	24.141	1.317	**0.125**	
Residual	432	7918.250	18.329			
Total	575	162445.165	282.513			

Appendix A4.4: Soil surface roughness results for the rest of Northern region and Southern region sites in Chapter 4

Appendix A4.4.1: Queensland sites



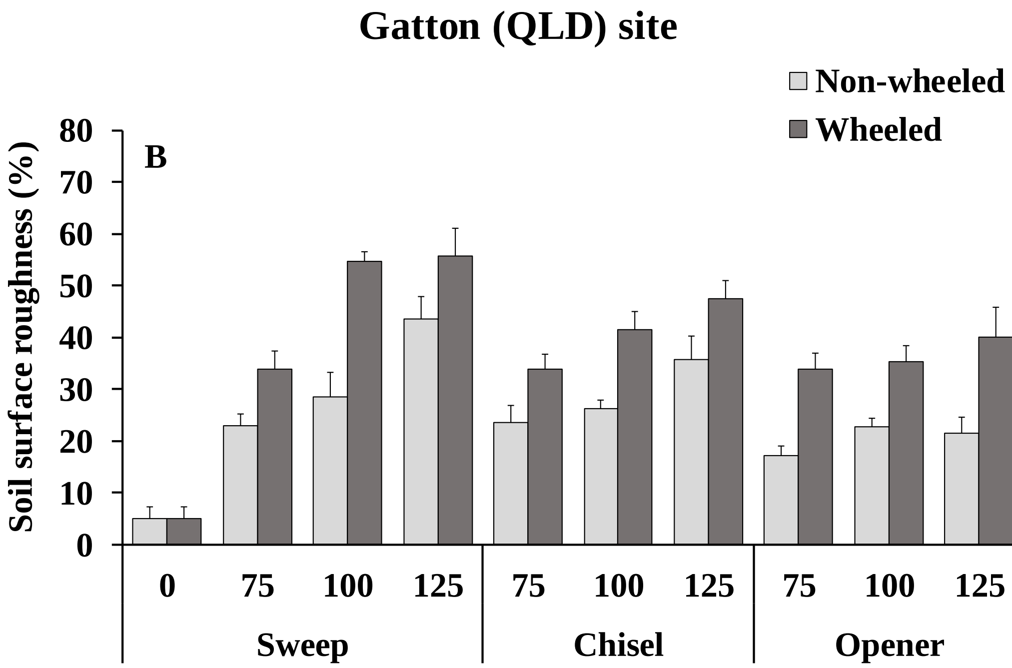
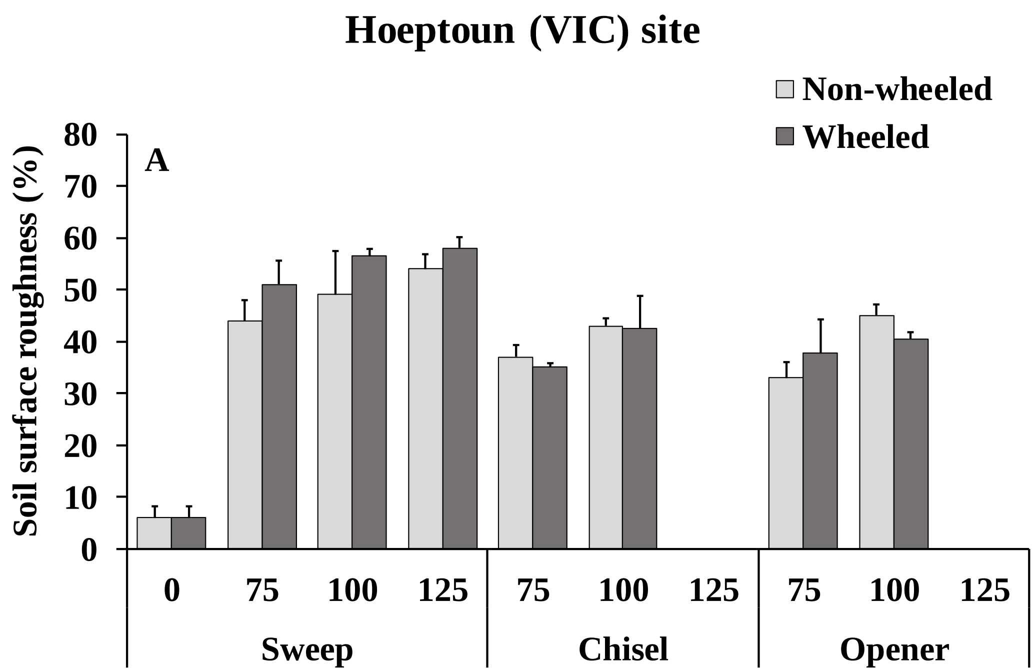


Figure A4.4.1: Tractor wheel traffic and operating depth effects on the soil surface roughness for different tines at Queensland sites: (A) Felton site, and (B) Gatton site, respectively. Bars denote SD; the operating depth in mm; 0 = control (n=4)

Appendix A4.4.2: Southern region sites



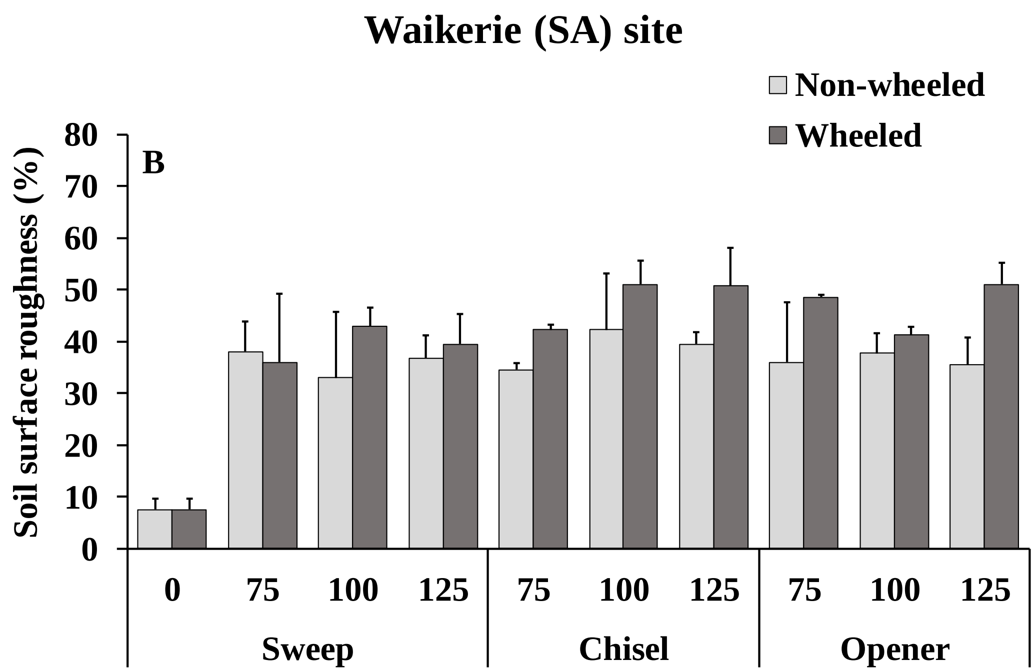


Figure A4.4.2: Tractor wheel traffic and operating depth effects on the soil surface roughness for different tines at Southern region sites: (A) Hopetoun site, and (B) Waikerie site, respectively. Bars denote SD; the operating depth in mm; 0 = control (n=4)

Appendix A4.5: Pictures for clods of soil for some studied sites

Figure A4.5.1: Large soil clods after soil-engaging implement operations denote detrimental effects of tractor wheel traffic on soil structure for different studied sites

APPENDIX TO CHAPTER 5

APPENDICES

APPENDIX TO CHAPTER 5

A5.1: Summary of regression analysis of predicted and measured values for all tines in studied sites.

Site	Tine	Linear model	P-value	R^2	SE	Mean difference
Felton	Sweep	Y=-1.12+1.50 x	<0.001	0.87	0.37	5.20 ± 18.60
	Chisel	Y= -0.21 + 1.21 x	<0.001	0.75	0.35	2 ± 31.90
	Opener	Y= -1.66 + 1.62 x	<0.001	0.87	0.30	-12 ± 21.30
Pittsworth	Sweep	Y= 0.56 + 0.81 x	<0.001	0.95	0.23	2.80 ± 14.20
	Chisel	Y= -0.26 + 1.03 x	<0.001	0.98	0.09	-16.60 ± 9.80
	Opener	Y= -1.4 + 1.74 x	<0.001	0.97	0.15	0.51 ± 20
Gatton	Sweep	Y= -0.21 + 0.93 x	<0.001	0.76	0.35	-16.40 ± 13.40
	Chisel	Y= 0.3 + 0.86 x	<0.001	0.57	0.24	-12.80 ± 21.40
	Opener	Y= -0.9 + 2.17 x	<0.001	0.88	0.20	26.21 ± 27.61
Kingaroy	Chisel	Y= 1.15 + 0.69 x	<0.001	0.67	0.58	-6.25 ± 11.10
Hopetoun	Sweep	Y= 2.12 + 0.28 x	<0.001	0.79	0.39	3.84 ± 45
	Chisel	Y= 0.44 + 0.23 x	<0.001	0.89	0.07	-39.66 ± 18.14
	Opener	Y= 0.17 + 0.51 x	<0.001	0.91	0.08	-38.98 ± 4.92
Swan Hill	Sweep	Y= -0.44 + 1.66 x	<0.001	0.90	0.15	26.93 ± 16.61
	Chisel	Y= -0.13 + 1.08 x	<0.001	0.89	0.08	-12.56 ± 11.95
	Opener	Y= 0.11 + 0.69 x	<0.001	0.85	0.11	-20.68 ± 10.81
Loxton	Sweep	Y= -0.07 + 1.10 x	<0.001	0.65	0.17	4.71 ± 13.62
	Chisel	Y= -0.68 + 2.08 x	<0.001	0.71	0.11	-8.85 ± 24.90
	Opener	Y= -0.64 + 1.54 x	<0.001	0.84	0.12	-14.59 ± 17.97
Waikerie	Sweep	Y= 0.084 + 0.97 x	<0.001	0.79	0.16	4.60 ± 15.57
	Chisel	Y= -0.06 + 1.11 x	<0.001	0.52	0.12	-1.29 ± 27.63
	Opener	Y= -0.07 + 0.88 x	<0.001	0.53	0.17	-20.43 ± 26.72

A5.2: Regression analysis

A5.2.1: Relationship between predicted and measured draught force, **Felton** site

1. **Sweep tine**

Table A5.2: Summary of analysis for sweep tine, Felton

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	113.35	113.35	816.55	**<0.001**	**0.87**	**0.37**
Residual	118	16.38	0.14				
Total	119	129.73	1.09				

Table A5.3: Estimates of parameters for sweep tine, Felton

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-1.20	0.15	-7.89	**<0.001**
Measured	1.50	0.05	28.58	**<0.001**

2. **Chisel tine**

Table A5.4: Summary of analysis for chisel tine, Felton

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	44.82	44.82	346.71	**<0.001**	**0.75**	**0.36**
Residual	118	15.26	0.129				
Total	119	60.08	0.51				

Table A5.5: Estimates of parameters for chisel tine, Felton

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.21	0.09	-2.24	**0.027**
Measured	1.21	0.07	18.62	**<0.001**

3. **Opener tine**

Table A5.6: Summary of analysis for opener tine, Felton

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	75.13	75.13	808.66	**<0.001**	**0.87**	**0.31**
Residual	118	10.96	0.09				
Total	119	86.09	0.72				

Table A5.7: Estimates of parameters for opener tine, Felton

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-1.66	0.14	-12.28	**<0.001**
Measured	1.62	0.06	28.44	**<0.001**

A5.2.2: Relationship between predicted and measured draught force, **Pittsworth** site

1. **Sweep tine**

Table A5.8: Summary of analysis for sweep tine, Pittsworth

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	126.002	126.002	2409.29	**<0.001**	**0.95**	**0.23**
Residual	118	6.17	0.05				
Total	119	132.17	1.11				

Table A5.9: Estimates of parameters for sweep tine, Pittsworth

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.56	0.06	10.01	**<0.001**
Measured	0.81	0.02	49.09	**<0.001**

2. **Chisel tine**

Table A5.10: Summary of analysis for chisel tine, Pittsworth

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	39.77	39.77	4707.64	**<0.001**	**0.98**	**0.09**
Residual	118	0.1	0.008				
Total	119	40.77	0.343				

Table A5.11: Estimates of parameters for chisel tine, Pittsworth

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.26	0.024	-10.62	**<0.001**
Measured	1.03	0.015	68.61	**<0.001**

3. **Opener tine**

Table A5.12: Summary of analysis for opener tine, Pittsworth

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	83.14	83.14	3674.76	**<0.001**	**0.97**	**0.15**
Residual	118	2.67	0.023				
Total	119	85.81	0.714				

Table A5.13: Estimates of parameters for opener tine, Pittsworth

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-1.40	0.06	-23.53	**<0.001**
Measured	1.74	0.03	60.62	**<0.001**

A5.2.3: Relationship between predicted and measured draught force, **Gatton** site

1. **Sweep tine**

Table A5.14: Summary of analysis for sweep tine, Gatton

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	45.96	45.96	375.3	<**0.001**	**0.76**	**0.35**
Residual	118	14.45	0.12				
Total	119	60.41	0.51				

Table A5.15: Estimates of parameters for sweep tine, Gatton

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.21	0.12	-1.74	**0.085**
Measured	0.93	0.05	19.37	<**0.001**

2. **Chisel tine**

Table A5.16: Summary of analysis for chisel tine, Gatton

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	9.27	9.27	158.59	<**0.001**	**0.57**	**0.24**
Residual	118	6.90	0.06				
Total	119	16.17	0.14				

Table A5.17: Estimates of parameters for chisel tine, Gatton

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.03	0.07	0.374	**0.71**
Measured	0.86	0.07	12.59	<**0.001**

3. **Opener tine**

Table A5.18: Summary of analysis for opener tine, Gatton

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	32.25	32.25	836.84	<**0.001**	**0.88**	**0.154**
Residual	118	4.55	0.04				
Total	119	36.80	0.31				

Table A5.19: Estimates of parameters for opener tine, Gatton

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.9	0.08	-11.18	<**0.001**
Measured	2.17	0.08	28.93	<**0.001**

A5.2.4: Relationship between predicted and measured draught force, **Kingaroy** site

Chisel tine

Table A5.20: Summary of analysis for chisel tine, Kingaroy

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	27.40	27.40	80.77	**<0.001**	**0.67**	**0.58**
Residual	38	12.89	0.34				
Total	39	40.29	1.03				

Table A5.21: Estimates of parameters for chisel tine, Kingaroy

Parameter	estimate	s.e.	t(96)	t pr.
Constant	1.15	0.38	3.07	**0.004**
Measured	0.69	0.08	8.99	**<0.001**

A5.2.5: Relationship between predicted and measured draught force, **Hopetoun** site

1. **Sweep tine**

Table A5.22: Summary of analysis for sweep tine, Hopetoun

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	69.71	69.71	459.43	<**0.001**	**0.79**	**0.39**
Residual	118	17.90	0.15				
Total	119	87.61	0.74				

Table A5.23: Estimates of parameters for sweep tine, Hopetoun

Parameter	estimate	s.e.	t(96)	t pr.
Constant	2.12	0.06	21.43	**<0.001**
Measured	0.28	0.01	32.98	**<0.001**

2. **Chisel tine**

Table A5.24: Summary of analysis for chisel tine, Hopetoun

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	3.03	3.03	650.13	<**0.001**	**0.89**	**0.07**
Residual	78	0.36	0.005				
Total	79	3.39	0.043				

Table A5.25: Estimates of parameters for chisel tine, Hopetoun

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.44	0.02	27.42	**<0.001**
Measured	0.23	0.01	25.50	**<0.001**

3. **Opener tine**

Table A5.26: Summary of analysis for opener tine, Hopetoun

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	5.16	5.16	845.29	<**0.001**	**0.91**	**0.08**
Residual	78	0.48	0.006				
Total	79	5.64	0.071				

Table A5.27: Estimates of parameters for opener tine, Hopetoun

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.17	0.03	5.12	**<0.001**
Measured	0.51	0.02	29.07	**<0.001**

A5.2.6: Relationship between predicted and measured draught force, **Swan Hill** site

1. **Sweep tine**

Table A5.28: Summary of analysis for sweep tine, Swan Hill

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	25.03	25.03	1093.76	<**0.001**	**0.90**	**0.15**
Residual	118	2.70	0.02				
Total	119	27.73	0.23				

Table A5.29: Estimates of parameters for sweep tine, Swan Hill

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.44	0.06	-7.24	<**0.001**
Measured	1.66	0.05	33.07	<**0.001**

2. **Chisel tine**

Table A5.30: Summary of analysis for chisel tine, Swan Hill

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	6.27	6.27	927.39	<**0.001**	**0.89**	**0.08**
Residual	118	0.80	0.007				
Total	119	7.07	0.059				

Table A5.31: Estimates of parameters for chisel tine, Swan Hill

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.13	0.027	-4.98	<**0.001**
Measured	1.08	0.035	30.45	<**0.001**

3. **Opener tine**

Table A5.32: Summary of analysis for opener tine, Swan Hill

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	8.35	8.35	673.53	<**0.001**	**0.85**	**0.11**
Residual	118	1.46	0.012				
Total	119	9.81	0.082				

Table A5.33: Estimates of parameters for opener tine, Swan Hill

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.11	0.030	3.66	<**0.001**
Measured	0.69	0.026	25.95	<**0.001**

A5.2.7: Relationship between predicted and measured draught force, **Loxton** site

1. **Sweep tine**

Table A5.34: Summary of analysis for sweep tine, Loxton

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	6.67	6.67	223.95	<**0.001**	**0.65**	**0.17**
Residual	118	3.52	0.03				
Total	119	10.19	0.09				

Table A5.35: Estimates of parameters for sweep tine, Loxton

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.07	0.096	-0.68	**0.50**
Measured	1.10	0.074	14.97	<**0.001**

2. **Chisel tine**

Table A5.36: Summary of analysis for chisel tine, Loxton

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	3.65	3.65	287.28	<**0.001**	**0.71**	**0.11**
Residual	118	1.50	0.013				
Total	119	5.15	0.043				

Table A5.37: Estimates of parameters for chisel tine, Loxton

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.68	0.07	-9.23	<**0.001**
Measured	2.08	0.12	16.95	<**0.001**

3. **Opener tine**

Table A5.38: Summary of analysis for opener tine, Loxton

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	9.56	9.56	620.84	<**0.001**	**0.84**	**0.12**
Residual	118	1.82	0.015				
Total	119	11.38	0.096				

Table A5.39: Estimates of parameters for opener tine, Loxton

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.64	0.061	-10.53	<**0.001**
Measured	1.54	0.062	24.92	<**0.001**

A5.2.8: Relationship between predicted and measured draught force, **Waikerie** site

1. **Sweep tine**

Table A5.40: Summary of analysis for sweep tine, Waikerie

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	11.84	11.84	463.75	<**0.001**	**0.80**	**0.16**
Residual	118	3.01	0.026				
Total	119	14.85	0.125				

Table A5.41: Estimates of parameters for sweep tine, Waikerie

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.084	0.054	1.55	**0.125**
Measured	0.97	0.045	21.54	**<0.001**

2. **Chisel tine**

Table A5.42: Summary of analysis for chisel tine, Waikerie

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	1.93	1.93	132.20	<**0.001**	**0.52**	**0.12**
Residual	118	1.72	0.015				
Total	119	3.65	0.031				

Table A5.43: Estimates of parameters for chisel tine, Waikerie

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.06	0.048	-1.20	**0.233**
Measured	0.009	0.097	11.50	**<0.001**

3. **Opener tine**

Table A5.44: Summary of analysis for opener tine, Waikerie

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	3.95	3.95	137.73	<**0.001**	**0.54**	**0.170**
Residual	118	3.38	0.03				
Total	119	7.33	0.062				

Table A5.45: Estimates of parameters for opener tine, Waikerie

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-0.07	0.062	-1.14	**0.258**
Measured	0.88	0.075	11.74	**<0.001**

A5.3: Relationship between measured and predicted draught force based on the Godwin and O’Dogherty model for all tines for the rest of Northern region and Southern region sites

A5.3.1: Felton (QLD) site.

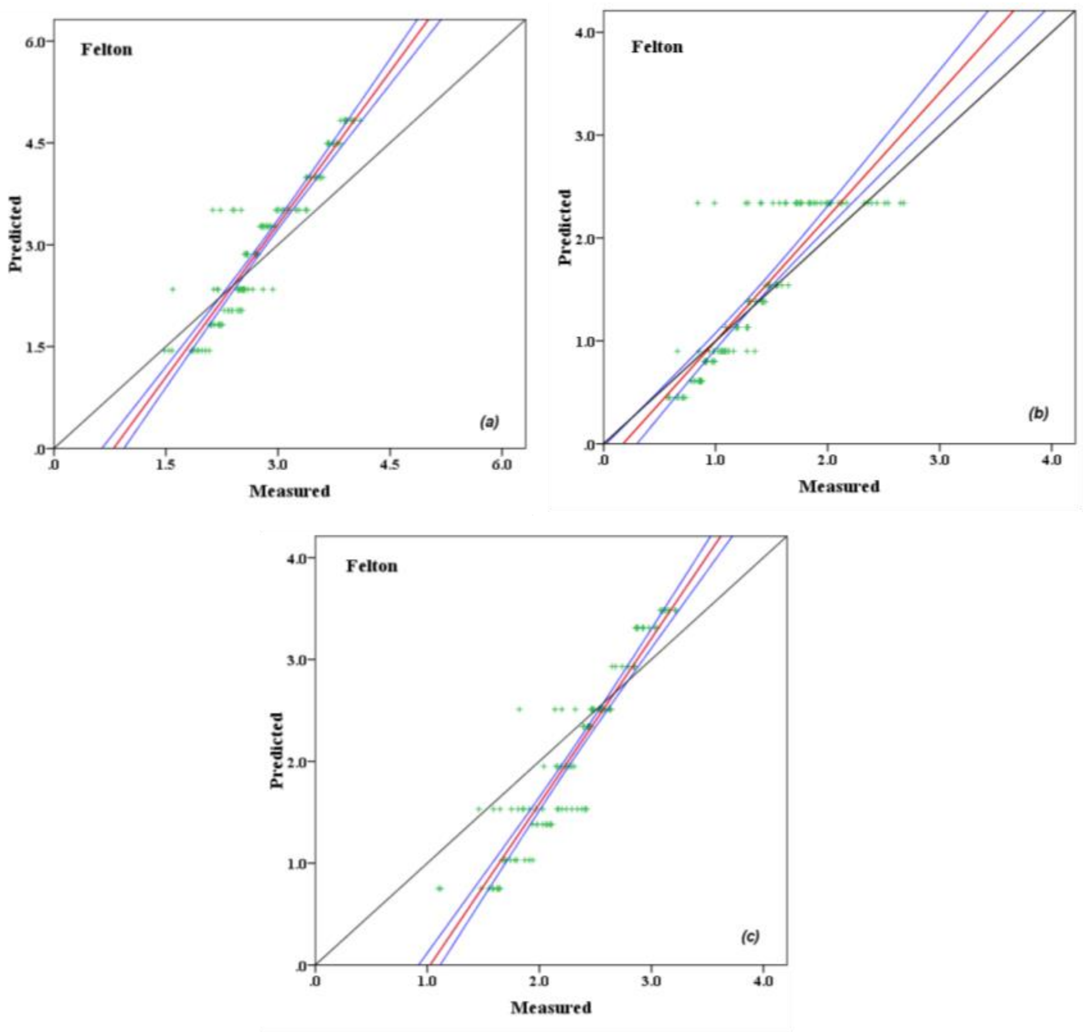


Figure 0-4: Relationship between measured and predicted draught force based on the Godwin and O’Dogherty (2007) tillage force prediction model for Felton (QLD) site. The red line is the relationship between measured and predicted values of draught force. Blue lines show the 95% confidence interval for the linear model fitted to the data, and the black line shows the 1:1 relationship between measured and predicted data. Figures show: (a) Sweep (b) Chisel and (c) Opener, respectively (n=120)

A5.3.2: Gatton (**QLD**) site.

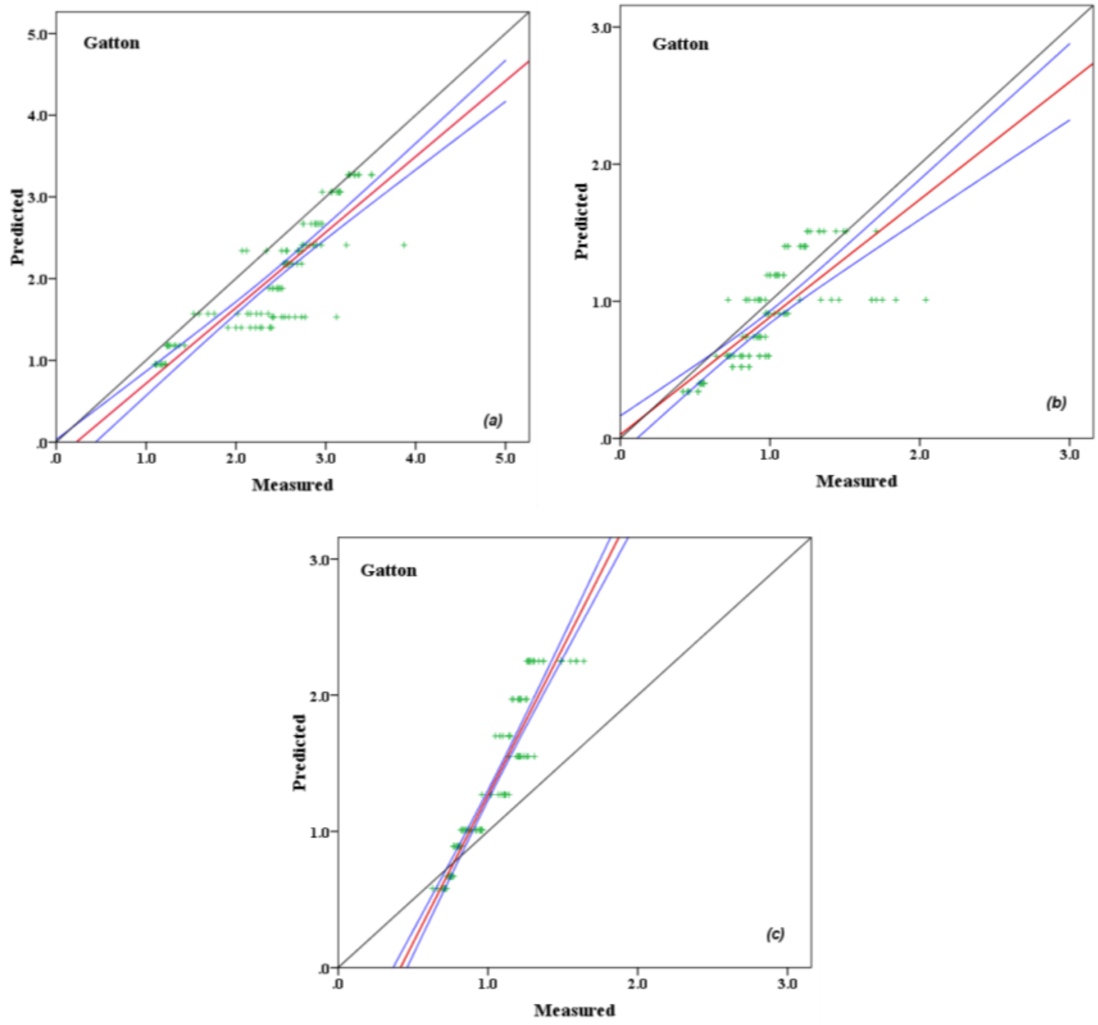


Figure 5-6: Relationship between measured and predicted draught force based on the Godwin and O'Dogherty (2007) tillage force prediction model for Gatton (QLD) site. The red line is the relationship between measured and predicted values of draught force. Blue lines show the 95% confidence interval for the linear model fitted to the data, and the black line shows the 1:1 relationship between measured and predicted data. Figures show: (a) Sweep (b) Chisel and (c) Opener, respectively (n=120)

A5.3.3: Kingaroy (**QLD**) site.

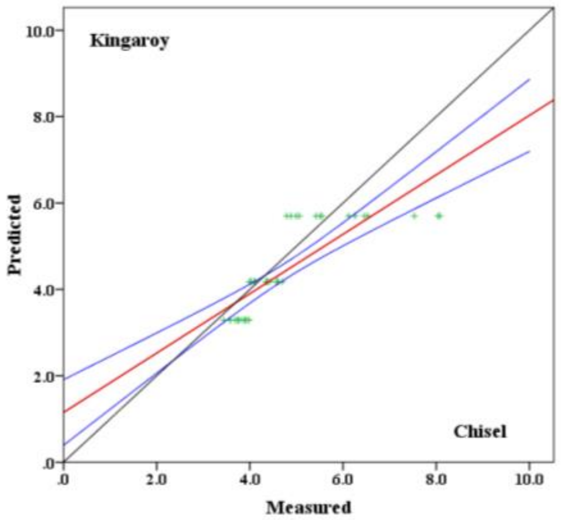


Figure 5.7: Relationship between measured and predicted draught force based on the Godwin and O'Dogherty (2007) tillage force prediction model for Kingaroy (QLD) site. The red line is the relationship between measured and predicted values of draught force. Blue lines show the 95% confidence interval for the linear model fitted to the data, and the black line shows the 1:1 relationship between measured and predicted data (n=40)

A5.3.4: Hopetoun (VIC) site.

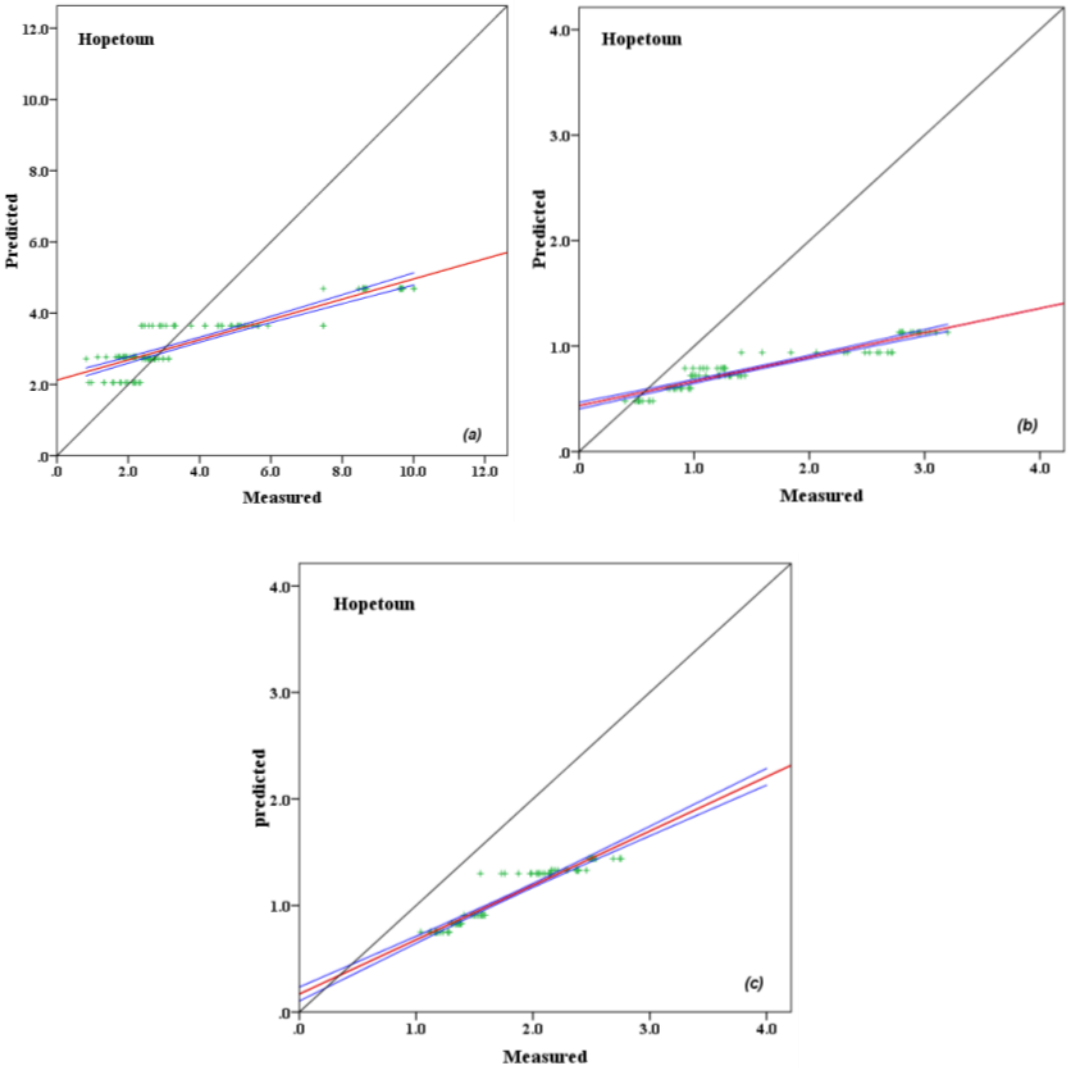


Figure 0.1.8: Relationship between measured and predicted draught force based on the Godwin and O'Dogherty (2007) tillage force prediction model for Hopetoun (VIC) site. The red line is the relationship between measured and predicted values of draught force. Blue lines show the 95% confidence interval for the linear model fitted to the data, and the black line shows the 1:1 relationship between measured and predicted data. Figures show: (a) Sweep (b) Chisel and (c) Opener (n=120, 80 and 80), respectively

A5.3.5: Loxton (**SA**) site.

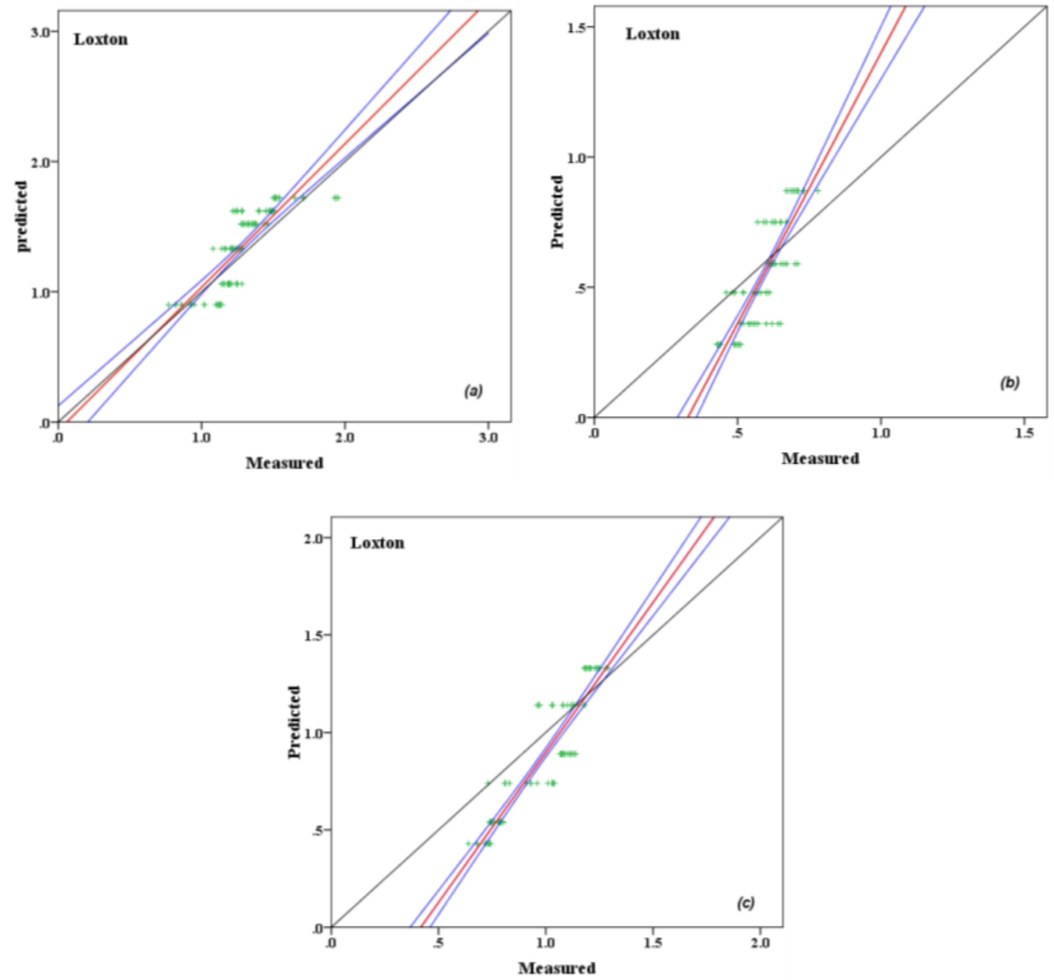


Figure 5.10: Relationship between measured and predicted draught force based on the Godwin and O'Dogherty (2007) tillage force prediction model for Loxton (SA) site. The red line is the relationship between measured and predicted values of draught force. Blue lines show the 95% confidence interval for the linear model fitted to the data, and the black line shows the 1:1 relationship between measured and predicted data. Figures show: (a) Sweep (b) Chisel and (c) Opener, respectively (n=120)

APPENDIX TO CHAPTER 6

APPENDIX TO CHAPTER 6

Appendix A6.1: Statistical analyses corresponding to soil physical properties in Chapter 6

A6.1.1: Statistical analysis – penetration resistance measurements of soil in **Felton** site

Factors structure:

Traffic system: PCB, PTL

Depth: 0-500 mm, depth interval was 25 mm

Table A6.1: Analysis of variance – penetration resistance measurements of soil in Felton site

Variate: **Penetration resistance (MPa)**

Source of variation	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2
Traffic	1	145.769	145.769	1637.026	**<0.001**	**0.86**
Depth	19	217.701	11.458	128.676	**<0.001**	
Traffic . Depth	19	45.418	2.39	26.845	**<0.001**	
Residual	760	67.674	0.089			
Total	799	476.564	0.60			

A6.1.2: Statistical analysis – moisture content measurements of soil in **Felton** site

Factors structure:

Traffic system: PCB, PTL

Depth: 0-500 mm, depth interval was 100 mm

Table A6.2: Analysis of variance – moisture content measurements of soil in Felton site

Variate: **Moisture content (%)**

Source of variation	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2
Traffic	1	181.010	181.010	161.439	**<0.001**	**0.87**
Depth	4	182.228	45.557	40.631	**<0.001**	
Traffic . Depth	4	287.392	71.848	64.080	**<0.001**	
Residual	90	100.911	1.121			
Total	99	751.541	7.591			

A6.1.3: Statistical analysis – penetration resistance measurements of soil in **Pittsworth** site

Factors structure:

Traffic system: PCB, PTL

Depth: 0-500 mm, depth interval was 25 mm

Table A6.3: Analysis of variance – penetration resistance measurements of soil in Pittsworth site

Variate: **Penetration resistance (MPa)**

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	120.668	120.668	640.073	**<0.001**	**0.56**
Depth	19	26.464	1.393	7.388	**<0.001**	
Traffic . Depth	19	36.798	1.937	10.273	**<0.001**	
Residual	760	143.277	0.189			
Total	799	327.207	0.410			

A6.1.4: Statistical analysis – moisture content measurements of soil in **Pittsworth** site

Factors structure:

Traffic system: PCB, PTL

Depth: 0-500 mm, depth interval was 100 mm

Table A6.4: Analysis of variance – moisture content measurements of soil in Pittsworth site

Variate: **Moisture content (%)**

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	8.381	8.381	5.420	**<0.022**	**0.92**
Depth	4	1505.566	376.392	243.430	**<0.001**	
Traffic . Depth	4	25.393	6.348	4.106	**0.004**	
Residual	90	139.158	1.546			
Total	99	1678.498	16.955			

A6.1.5: Statistical analysis – penetration resistance measurements of soil in **Gatton** site

Factors structure:

Traffic system: Non-wheeled soil, wheeled soil

Depth: 0-500 mm, depth interval was 25 mm

Table A6.5: Analysis of variance – penetration resistance measurements of soil in Gatton site

Variate: **Penetration resistance (MPa)**

Source of variation	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2
Traffic	1	218.311	218.311	1032.756	**<0.001**	**0.88**
Depth	19	798.962	42.051	198.927	**<0.001**	
Traffic . Depth	19	146.785	7.726	36.547	**<0.001**	
Residual	760	160.654	0.211			
Total	799	1324.711	1.658			

A6.1.6: Statistical analysis – moisture content measurements of soil in **Gatton** site

Factors structure:

Depth: 0-500 mm, depth interval was 100 mm

Table A6.6: Analysis of variance – moisture content measurements of soil in Gatton site

Variate: **Moisture content (%)**

Source of variation	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2
Depth	4	756.769	189.192	434.014	**<0.001**	**0.98**
Residual	45	19.616	0.436			
Total	49	776.385	15.845			

A6.1.7: Statistical analysis – penetration resistance measurements of soil in **Kingaroy** site

Factors structure:

Table A6.7: Analysis of variance – penetration resistance measurements of soil in Kingaroy site

Variate: **Penetration resistance (MPa)**

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Depth	19	405.455	21.340	39.918	**<0.001**	**0.67**
Residual	380	203.143	0.535			
Total	399	608.598	1.525			

A6.1.8: Statistical analysis – moisture content measurements of soil in **Kingaroy** site

Factors structure:

Depth: 0-500 mm, depth interval was 100 mm

Table A6.8: Analysis of variance – moisture content measurements of soil in Kingaroy site

Variate: **Moisture content (%)**

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Depth	4	966.108	241.527	322.700	**<0.001**	**0.97**
Residual	45	33.681	0.748			
Total	49	999.789	20.404			

A6.1.9: Statistical analysis – penetration resistance measurements of soil in **Hopetoun** site

Factors structure:

Traffic system: PCB, PTL

Depth: 0-500 mm, depth interval was 25 mm

Table A6.9: Analysis of variance – penetration resistance measurements of soil in Hopetoun site

Variate: **Penetration resistance (MPa)**

Source of variation	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2
Traffic	1	302.494	302.494	856.699	**<0.001**	**0.84**
Depth	19	1063.033	55.949	158.455	**<0.001**	
Traffic . Depth	19	38.808	2.043	5.785	**<0.001**	
Residual	760	268.350	0.353			
Total	799	1672.685	2.0935			

A6.1.10: Statistical analysis – moisture content measurements of soil in **Hopetoun** site

Factors structure:

Traffic system: PCB, PTL

Depth: 0-500 mm, depth interval was 100 mm

Table A6.10: Analysis of variance – moisture content measurements of soil in Hopetoun site

Variate: **Moisture content (%)**

Source of variation	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2
Traffic	1	37.283	37.283	45.340	**<0.001**	**0.96**
Depth	4	1590.592	397.648	483.578	**<0.001**	
Traffic . Depth	4	64.503	16.126	19.610	**<0.001**	
Residual	90	74.007	0.822			
Total	99	1766.386	17.842			

A6.1.11: Statistical analysis – penetration resistance measurements of soil in **Sawn Hill** site

Factors structure:

Traffic system: PCB, PTL

Depth: 0-500 mm, depth interval was 25 mm

Table A6.11: Analysis of variance – penetration resistance measurements of soil in Sawn Hill site

Variate: **Penetration resistance (MPa)**

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	31.134	31.134	54.079	**<0.001**	**0.59**
Depth	19	456.880	24.046	41.768	**<0.001**	
Traffic . Depth	19	131.549	6.924	12.026	**<0.001**	
Residual	760	437.539	0.576			
Total	799	1057.102	1.323			

A6.1.12: Statistical analysis – moisture content measurements of soil in **Sawn Hill** site

Factors structure:

Traffic system: PCB, PTL

Depth: 0-500 mm, depth interval was 100 mm

Table A6.12: Analysis of variance – moisture content measurements of soil in Sawn Hill site

Variate: **Moisture content (%)**

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	14.183	14.183	21.519	**<0.001**	**0.87**
Depth	4	311.994	77.999	118.344	**<0.001**	
Traffic . Depth	4	82.024	20.506	31.113	**<0.001**	
Residual	90	59.317	0.659			
Total	99	467.518	4.722			

A6.1.13: Statistical analysis – penetration resistance measurements of soil in **Loxton** site

Factors structure:

Traffic system: PCB, PTL

Depth: 0-500 mm, depth interval was 25 mm

Table A6.13: Analysis of variance – penetration resistance measurements of soil in Loxton site

Variate: **Penetration resistance (MPa)**

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	139.036	139.036	501.052	**<0.001**	**0.86**
Depth	19	1139.116	59.953	216.058	**<0.001**	
Traffic . Depth	19	55.130	2.902	10.457	**<0.001**	
Residual	760	210.891	0.277			
Total	799	1544.173	1.933			

A6.1.14: Statistical analysis – moisture content measurements of soil in **Loxton** site

Factors structure:

Traffic system: PCB, PTL

Depth: 0-500 mm, depth interval was 100 mm

Table A6.14: Analysis of variance – moisture content measurements of soil in Loxton site

Variate: **Moisture content (%)**

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	15.070	15.070	83.781	**<0.001**	**0.68**
Depth	4	10.213	2.553	14.195	**<0.001**	
Traffic . Depth	4	8.620	2.155	11.981	**<0.001**	
Residual	90	16.189	0.180			
Total	99	50.092	0.506			

A6.1.15: Statistical analysis – penetration resistance measurements of soil in **Waikerie** site

Factors structure:

Traffic system: Non-wheeled soil, wheeled soil

Depth: 0-500 mm, depth interval was 25 mm

Table A6.15: Analysis of variance – penetration resistance measurements of soil in Waikerie site

Variate: **Penetration resistance (MPa)**

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	46.904	46.904	242.760	**<0.001**	**0.88**
Depth	19	955.564	50.293	260.297	**<0.001**	
Traffic . Depth	19	73.068	3.846	19.904	**<0.001**	
Residual	760	146.842	0.193			
Total	799	1222.379	1.530			

A6.1.16: Statistical analysis – moisture content measurements of soil in **Waikerie** site

Factors structure:

Traffic system: Non-wheeled soil, wheeled soil

Depth: 0-500 mm, depth interval was 100 mm

Table A6.16: Analysis of variance – moisture content measurements of soil in Waikerie site

Variate: **Moisture content (%)**

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Traffic	1	7.935	7.935	78.990	**<0.001**	**0.75**
Depth	4	10.456	2.614	26.019	**<0.001**	
Traffic . Depth	4	9.096	2.274	22.635	**<0.001**	
Residual	90	9.042	0.100			
Total	99	36.528	0.369			

Appendix A6.2: PR and MC results for the rest of Northern and Southern region sites in Chapter 6

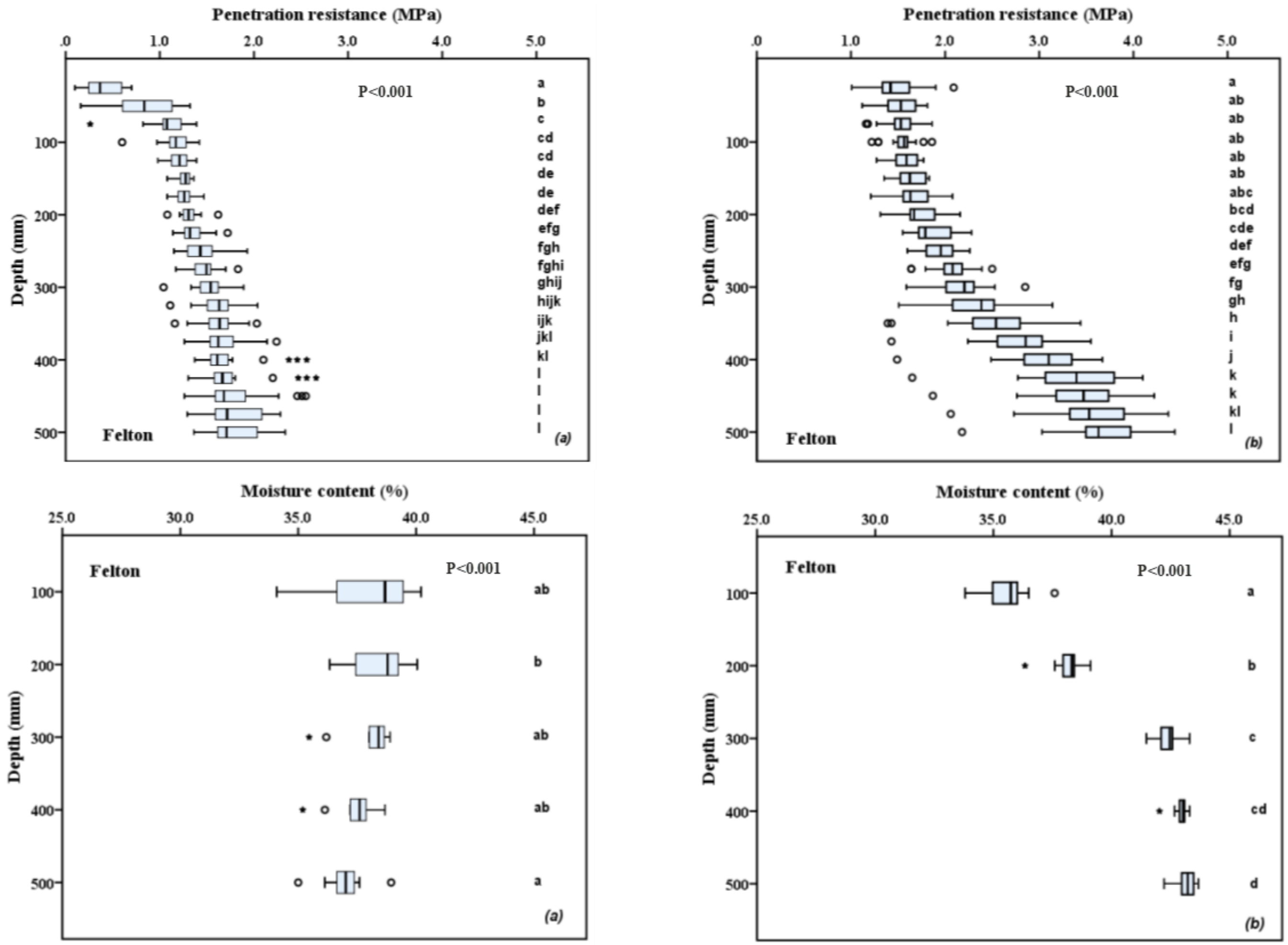


Figure A6.2.1: Penetration resistance and moisture content of soil as a function of depth (n=20), (n=10), respectively. Box plots show: Min, Q1, Med, Q3 and Max. P < 0.001. The symbols (○) and (*) denote mild and extreme outliers, respectively. Different letters indicate that mean values are significantly different at a 95% confidence interval. Figures show: (a) Crop Beds and (b) Permanent traffic lanes; PR (top) and MC (bottom) for Felton (QLD) site

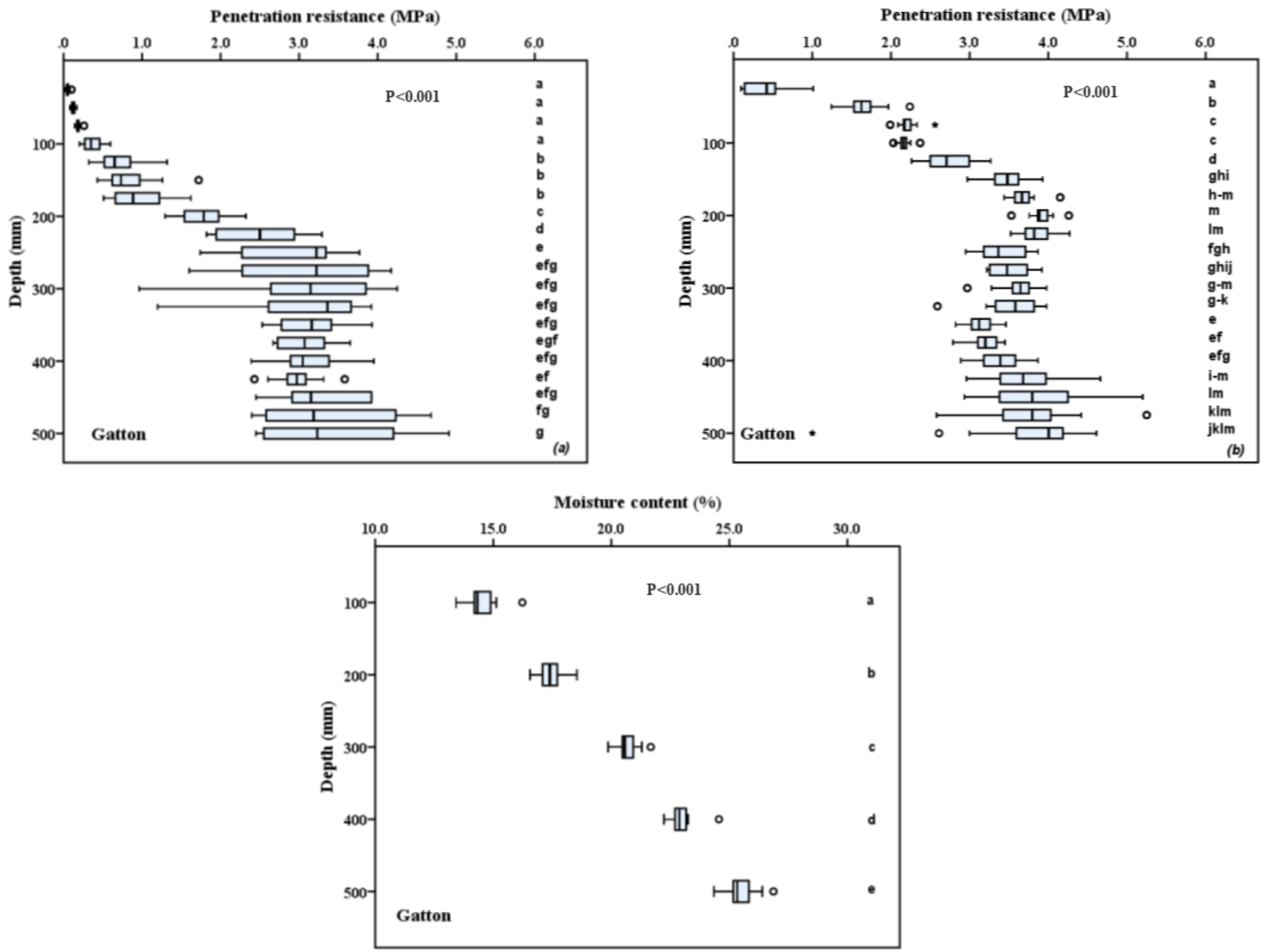
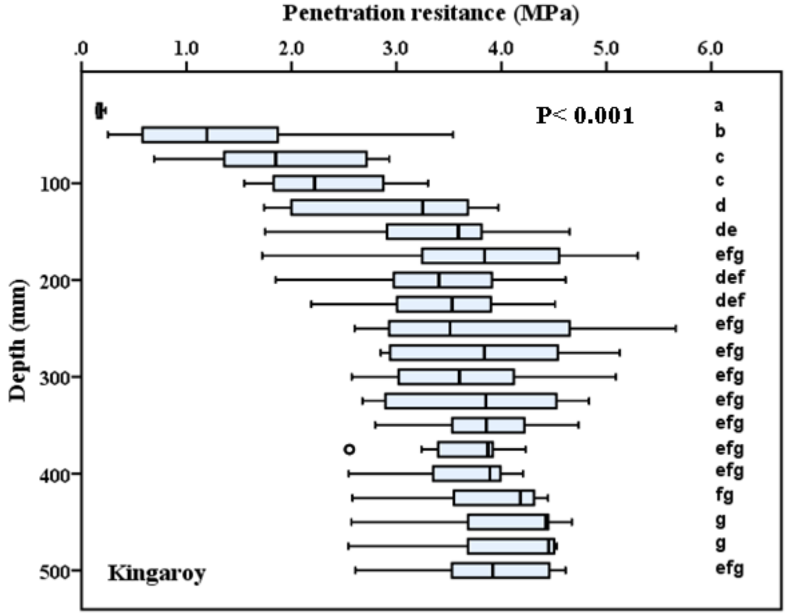


Figure A6.2.2: Penetration resistance and moisture content of soil as a function of depth (n=20), (n=10), respectively. Box plots show: Min, Q1, Med, Q3 and Max. P < 0.001. The symbols (○) and (*) denote mild and extreme outliers, respectively. Different letters indicate that mean values are significantly different at a 95% confidence interval. Figures show: (a) non-wheeled soil (b) wheeled soil; PR (top) and MC (bottom) for Gatton (QLD) site



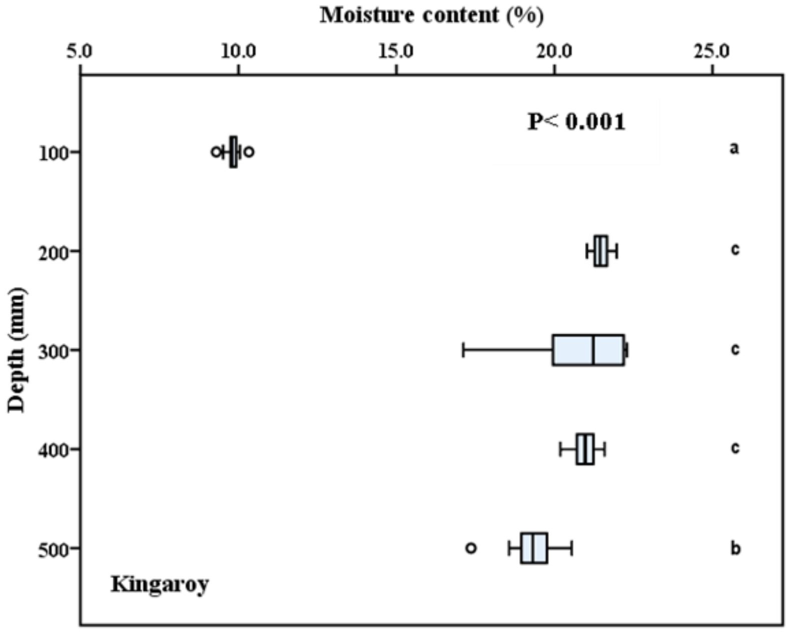


Figure A6.2.3: Penetration resistance and moisture content of soil as a function of depth (n=20), (n=10), respectively. Box plots show: Min, Q1, Med, Q3 and Max. P < 0.001. The symbols (○) and (*) denote mild and extreme outliers, respectively. Different letters indicate that mean values are significantly different at a 95% confidence interval. Figures show: PR (top) and MC (bottom) for Kingaroy (QLD) site

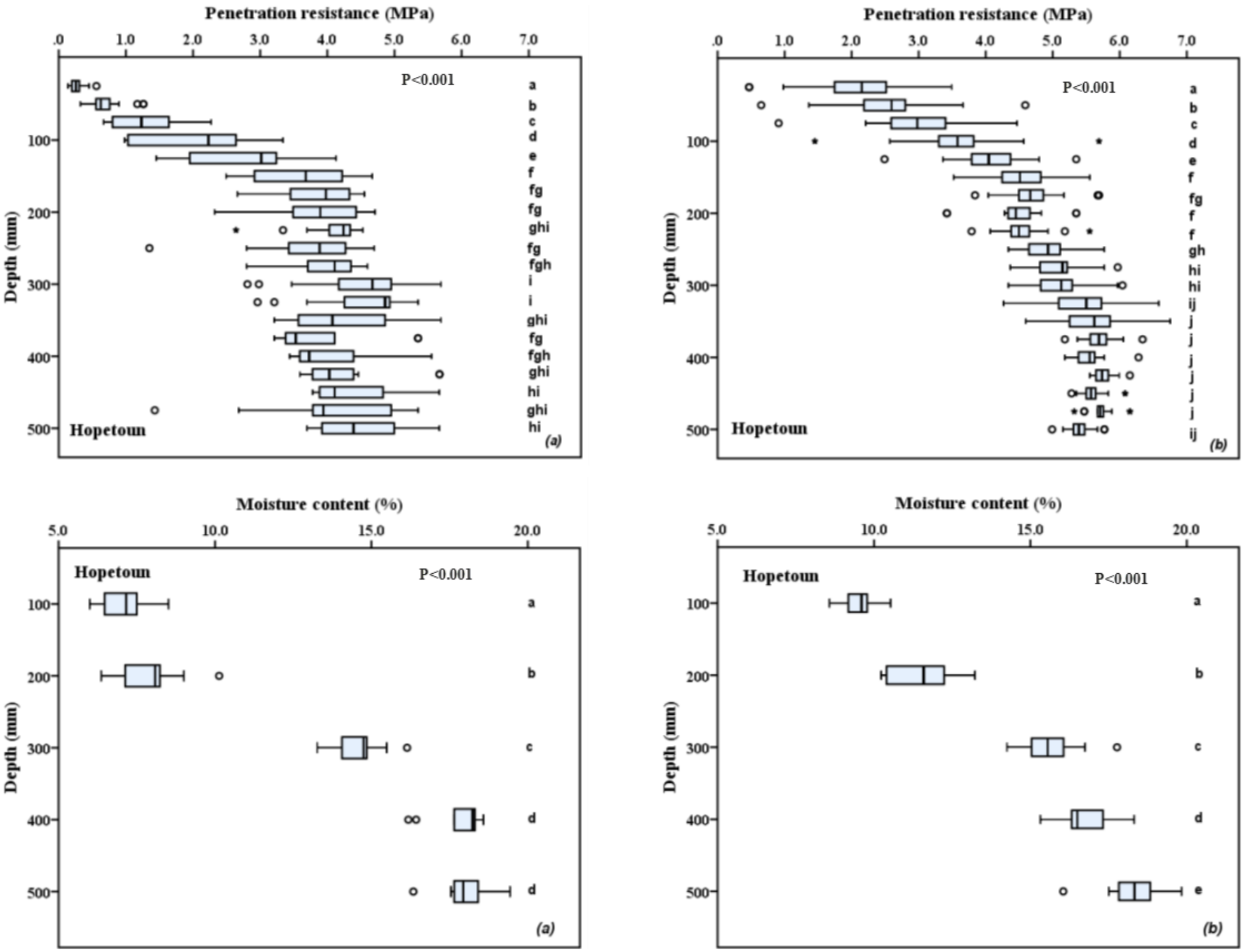


Figure A6.2.4: Penetration resistance and moisture content of soil as a function of depth (n=20), (n=10), respectively. Box plots show: Min, Q1, Med, Q3 and Max. P < 0.001. The symbols (○) and (*) denote mild and extreme outliers, respectively. Different letters indicate that mean values are significantly different at a 95% confidence interval. Figures show: (a) PCB (b) PTL; PR (top) and MC (bottom) for Hopetoun (VIC) site

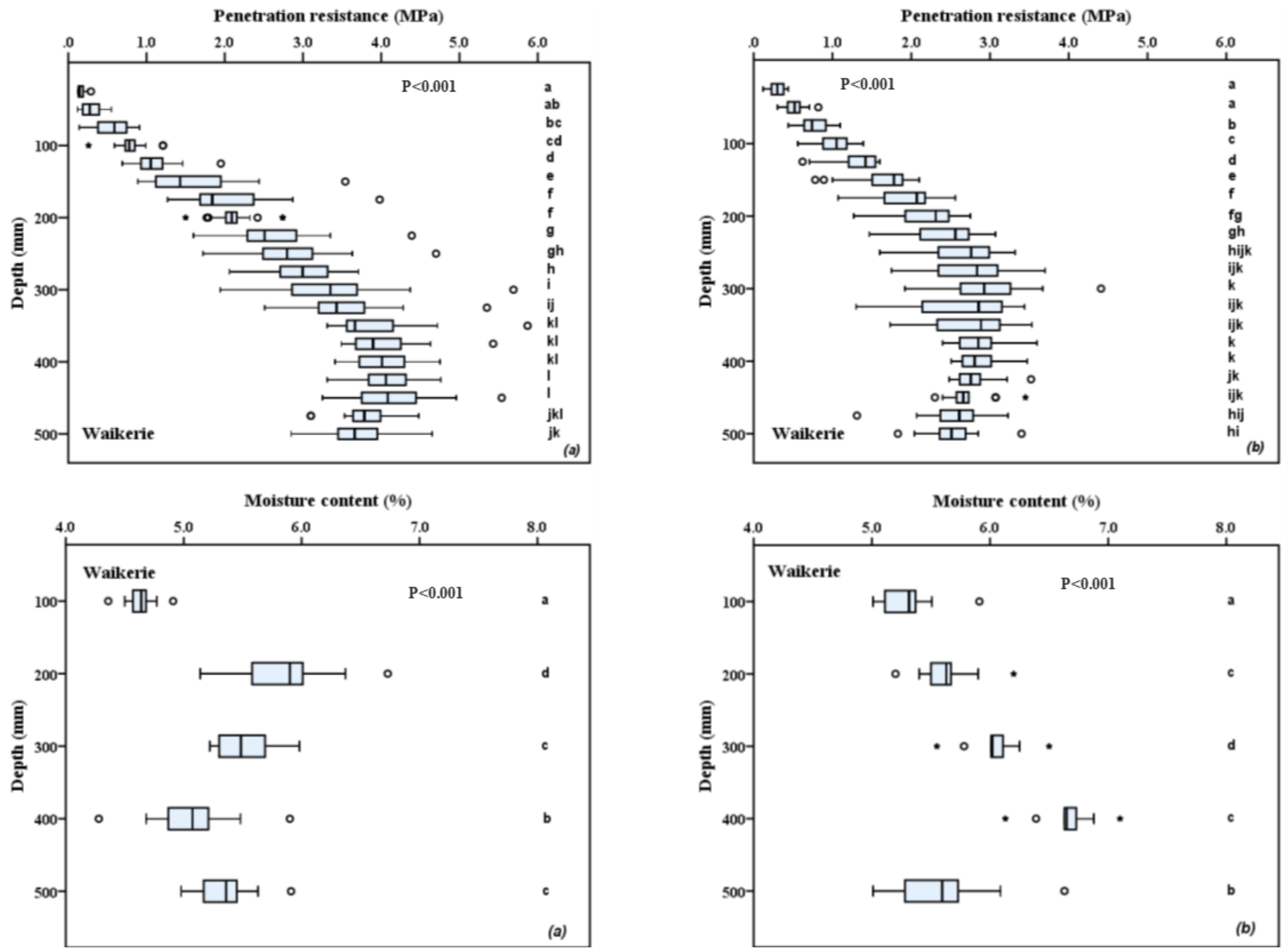


Figure A6.2.5: Penetration resistance and moisture content of soil as a function of depth (n=20), (n=10), respectively. Box plots show: Min, Q1, Med, Q3 and Max. P < 0.001. The symbols (○) and (*) denote mild and extreme outliers, respectively. Different letters indicate that mean values are significantly different at a 95% confidence interval. Figures show: (a) non-wheeled soil (b) wheeled soil; PR (top) and MC (bottom) for Waikerie (SA) site

Appendix A6.3: Statistical analyses corresponding to motion resistance in Chapter 6

A6.3.1: Statistical analysis – motion resistance measurements of tractor in **Felton** site

Factors structure:

Condition: Road, PTL, PCB

Ground speed: 2.2, 3.3, 4.4 m s^{-1}

Table A6.17: Analysis of variance – motion resistance measurements of tractor in Felton site

Variate: **Motion resistance (kN)**

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Condition	2	1688.001	844.000	206.845	**<0.001**	**0.63**
Speed	2	106.345	53.173	13.031	**<0.001**	
Condition . Speed	4	5.421	1.355	0.332	**0.856**	
Residual	261	1064.974	4.080			
Total	269	2864.741	10.650			

A6.3.2: Statistical analysis – motion resistance measurements of tractor in **Pittsworth** site

Factors structure:

Condition: Road, PTL, PCB

Ground speed: 2.2, 3.3, 4.4 m s^{-1}

Table A6.18: Analysis of variance – motion resistance measurements of tractor in Pittsworth site

Variate: **Motion resistance (kN)**

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Condition	2	1207.871	603.935	983.399	**<0.001**	**0.89**
Depth	2	27.449	13.724	22.348	**<0.001**	
Condition . Depth	4	1.982	0.495	0.807	**0.522**	
Residual	261	160.288	0.614			
Total	269	1397.589	5.195			

A6.3.3: Statistical analysis – motion resistance measurements of tractor in **Gatton** site

Factors structure:

Condition: Road, wheeled soil, non-wheeled soil

Ground speed: 0.55, 0.97 m s^{-1}

Table A6.19: Analysis of variance – motion resistance measurements of tractor in Gatton site

Variate: **Motion resistance (kN)**

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Condition	2	205.730	102.865	592.990	**<0.001**	**0.88**
Speed	1	9.158	9.158	52.793	**<0.001**	
Condition . Speed	2	0.763	0.381	2.198	**0.114**	
Residual	174	30.184	0.173	592.990		
Total	179	245.835	1.373			

A6.3.4: Statistical analysis – motion resistance measurements of tractor in **Hopetoun** site

Factors structure:

Condition: Road, PTL, PCB

Ground speed: 2.2, 3.3, 4.4 m s^{-1}

Table A6.20: Analysis of variance – motion resistance measurements of tractor in Hopetoun site

Variate: **Motion resistance (kN)**

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Condition	2	638.278	319.139	717.965	**<0.001**	**0.86**
Speed	2	62.153	31.076	69.913	**<0.001**	
Condition . Speed	4	9.283	2.321	5.221	**<0.001**	
Residual	261	116.016	0.445			
Total	269	825.729	3.069			

A6.3.5: Statistical analysis – motion resistance measurements of tractor in **Swan Hill** site

Factors structure:

Condition: Road, PTL, PCB

Ground speed: 2.2, 3.3, 4.4 m s^{-1}

Table A6.21: Analysis of variance – motion resistance measurements of tractor in Swan Hill site

Variate: **Motion resistance (kN)**

Source of variation	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2
Condition	2	513.821	256.910	322.566	**<0.001**	**0.74**
Speed	2	76.426	38.213	47.978	**<0.001**	
Condition . Speed	4	12.035	3.009	3.778	**0.005**	
Residual	261	207.876	0.796			
Total	269	810.157	3.012			

A6.3.6: Statistical analysis – motion resistance measurements of tractor in **Loxton** site

Factors structure:

Condition: Road, PTL, PCB

Ground speed: 2.2, 3.3, 4.4 m s^{-1}

Table A6.22: Analysis of variance – motion resistance measurements of tractor in Loxton site

Variate: **Motion resistance (kN)**

Source of variation	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2
Condition	2	1496.091	748.046	608.567	**<0.001**	**0.86**
Speed	2	343.983	171.992	139.922	**<0.001**	
Condition . Speed	4	52.509	13.127	10.679	**<0.001**	
Residual	261	320.819	1.229			
Total	269	2213.402	8.228			

A6.3.7: Statistical analysis – motion resistance measurements of tractor in **Waikerie** site

Factors structure:

Traffic system: Road, wheeled soil, non-wheeled soil

Ground speed: 2.2, 2.8, 3.3 m s^{-1}

Table A6.23: Analysis of variance – motion resistance measurements of tractor in Waikerie site

Variate: **Motion resistance (kN)**

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Condition	2	1099.688	549.844	1587.052	**<0.001**	**0.93**
Speed	2	66.575	33.288	96.080	**<0.001**	
Condition . Speed	4	2.016	0.504	1.455	**0.216**	
Residual	261	90.425	0.346			
Total	269	1258.704	4.679			

Appendix A6.4: Results of mean motion resistance for Northern region sites and Southern region sites in Chapter 6

Table A6.24: The mean motion resistance values in different condition at range of ground speed for Northern region sites

Site / Tractor mass	Motion resistance (kN)				
	Ground speed (m s^{-1})				
Felton (106 kN)	**Condition**	**2.2**	**3.3**	**4.4**	**Mean**
	Road	5.01	5.87	6.55	**5.81**
	SD	**± 0.57**	**± 0.91**	**± 0.45**	**± 0.92**
	Permanent traffic lanes	8.50	9.41	9.76	**9.22**
	SD	**± 3.06**	**± 2.54**	**± 2.33**	**± 2.68**
	Permanent crop beds	11.11	11.74	12.92	**11.92**
	SD	**± 2.63**	**± 2.42**	**± 1.18**	**± 2.28**
	n	30	30	30	**90**
	Ground speed (m s^{-1})				
Pittsworth (116 kN*)	**Condition**	**2.2**	**3.3**	**4.4**	**Mean**
	Road	4.82	5.10	5.50	**5.14**
	SD	**± 0.51**	**± 0.37**	**± 0.50**	**± 0.54**
	Permanent traffic lanes	8.21	8.66	8.86	**8.58**
	SD	**± 0.24**	**± 0.57**	**± 0.67**	**± 0.59**
	Permanent crop beds	9.76	10.12	10.77	**10.21**
	SD	**± 0.62**	**± 0.59**	**± 1.82**	**± 1.22**
	n	30	30	30	**90**
	Ground speed (m.s^{-1})				
Gatton (52 kN)	**Condition**	**0.55**	**0.97**	**-**	**Mean**
	Road	3.06	3.33	-	**3.20**
	SD	**± 0.52**	**± 0.33**	**-**	**± 0.45**
	Wheeled soil	4.69	5.24	-	**4.97**
	SD	**± 0.23**	**± 0.54**	**-**	**± 0.50**
	Non-wheeled soil	6.48	7.02	-	**6.75**
	SD	**± 0.54**	**± 0.15**	**-**	**± 0.48**
	n	30	30	-	**60**

* Tractor mass + Tillage unit mass

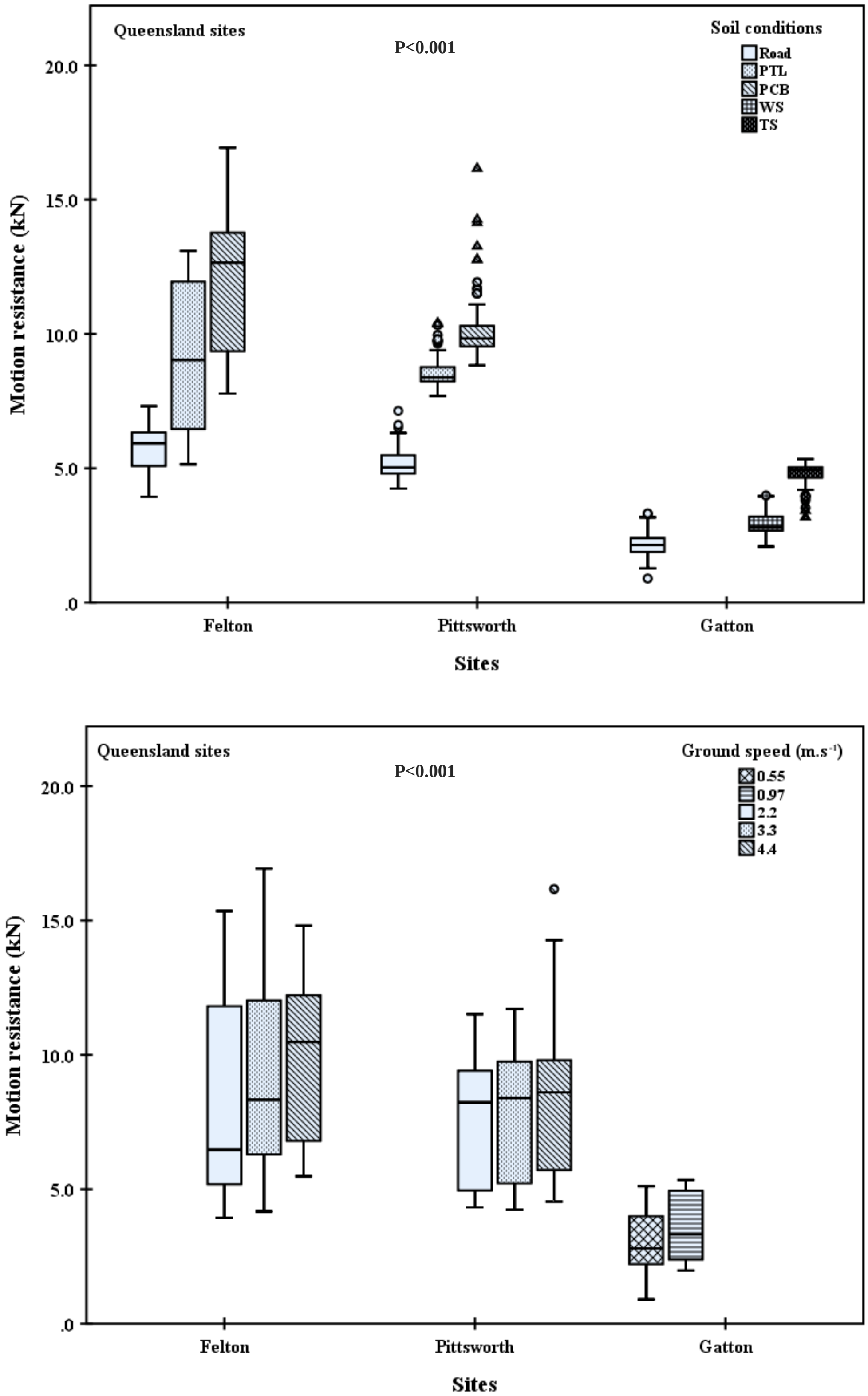
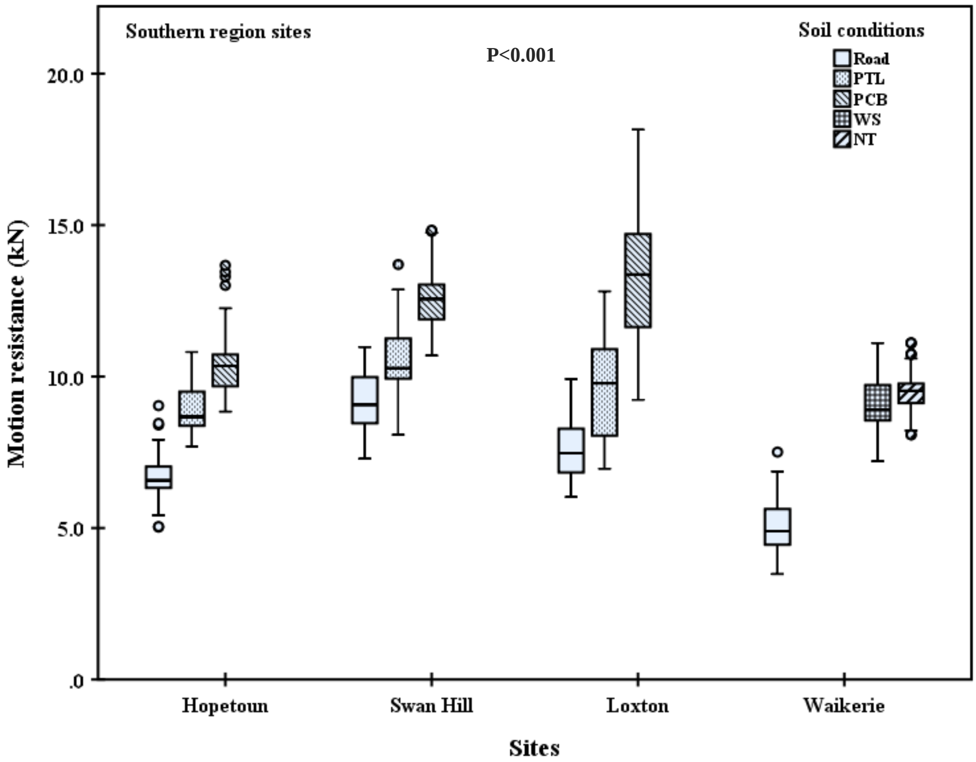


Figure A6.4.1: The effect of wheel traffic and ground speed on motion resistance of tractors for Queensland sites. Box plots show: Min, Q1, Med, Q3 and Max (n=30). P < 0.001. The symbols (○) and (▲) denote mild and extreme outliers, respectively. Figures show: soil conditions (top) and Ground speed (bottom), respectively

Table A6.25: The mean motion resistance values in different condition at range of ground speed for Southern region sites

Site / Tractor mass	Condition	2.2	3.3	4.4	Mean
	Motion resistance (kN)				
		Ground speed (m s^{-1})			
Hopetoun (85 kN)	**Road**	6.14	6.76	7.06	**6.66**
	SD	**± 0.65**	**± 0.30**	**± 0.71**	**± 0.69**
	Permanent traffic lanes	8.59	8.82	9.42	**8.95**
	SD	**± 0.54**	**± 0.68**	**± 0.92**	**± 0.80**
	Permanent crop beds	9.51	10.38	11.28	**10.39**
	SD	**± 0.46**	**± 0.45**	**± 0.98**	**± 0.99**
	n	30	30	30	**90**
		Ground speed (m s^{-1})			
	Condition	**2.2**	**3.3**	**4.4**	**Mean**
Swan Hill (152 kN)	**Road**	8.65	9.33	9.76	**9.24**
	SD	**± 1.01**	**± 0.94**	**± 0.80**	**± 1.02**
	Permanent traffic lanes	10.02	10.68	11.39	**10.60**
	SD	**± 0.64**	**± 0.87**	**± 0.97**	**± 1.16**
	Permanent crop beds	11.20	11.78	12.64	**11.87**
	SD	**± 0.74**	**± 0.97**	**± 1.02**	**± 0.97**
	n	30	30	30	**90**
		Ground speed (m s^{-1})			
	Condition	**2.2**	**3.3**	**4.4**	**Mean**
Loxton (174 kN)	**Road**	6.73	7.86	8.13	**7.57**
	SD	**± 0.55**	**± 0.53**	**± 1.10**	**± 0.99**
	Permanent traffic lanes	8.86	10.31	11.61	**10.26**
	SD	**± 0.93**	**± 1.41**	**± 0.81**	**± 1.58**
	Permanent crop beds	11.02	12.51	14.91	**12.81**
	SD	**± 1.28**	**± 1.04**	**± 1.74**	**± 2.14**
	n	30	30	30	**90**
		Ground speed (m s^{-1})			
	Condition	**2.2**	**2.8**	**3.3**	**Mean**
Waikerie (65 kN)	**Road**	4.55	4.74	5.76	**5.02**
	SD	**± 0.48**	**± 0.43**	**± 0.67**	**± 0.76**
	Wheeled soil	8.49	9.03	9.74	**9.09**
	SD	**± 0.56**	**± 0.70**	**± 0.82**	**± 0.86**
	Non-Wheeled soil	8.91	9.48	10.05	**9.48**
	SD	**± 0.52**	**± 0.47**	**± 0.52**	**± 0.68**
	n	30	30	30	**90**



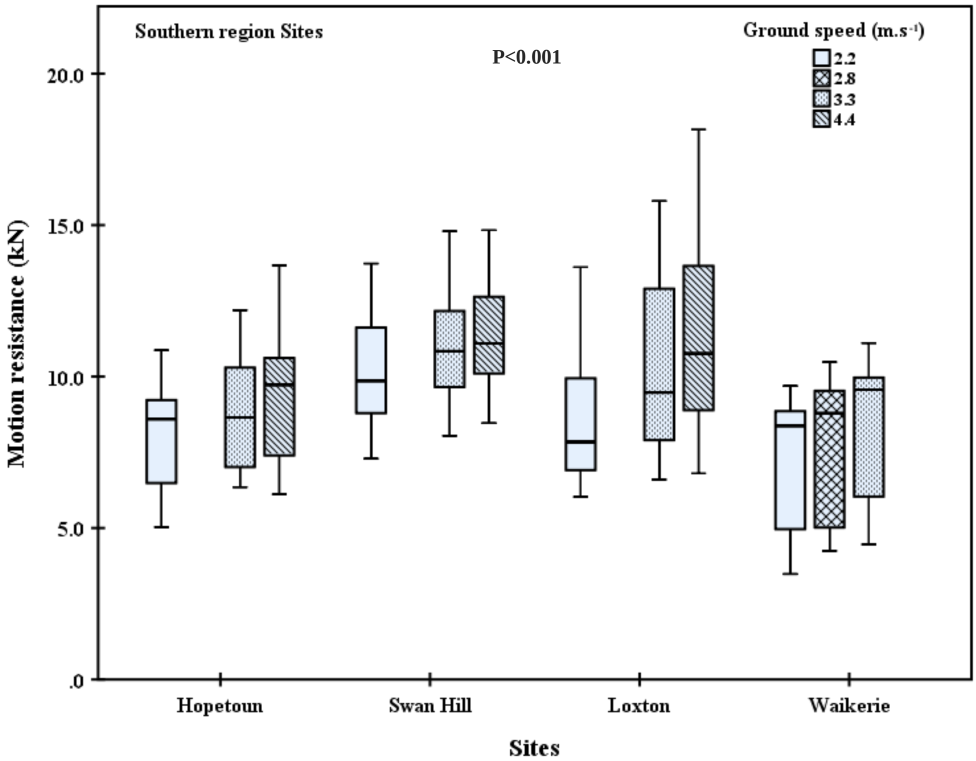


Figure A6.4.2: The effect of wheel traffic and ground speed on motion resistance of tractors for Southern region sites. Box plots show: Min, Q1, Med, Q3 and Max (n=30). P < 0.001. The symbols (○) denote mild outliers. Figures show: soil conditions (top) and Ground speed (bottom), respectively

Appendix A6.5: Regression analyses corresponding to relationship between motion resistance and cone index in Chapter 6

A6.5.1: Regression analysis – linear model, relationship between motion resistance and cone index, **Felton** site.

1. **PCB**

    Response variate: Motion resistance

    Fitted terms: Constant, cone index

Table A4.5: Summary of analysis for PCB, Felton

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	98.819	98.819	154.156	<**0.001**	**0.85**	**0.801**
Residual	28	17.949	0.641				
Total	29	116.768	4.026				

Table A6.27: Estimates of parameters for PCB, Felton

Parameter	estimate	s.e.	t(96)	t pr.
Constant	24.455	1.020	23.979	**<0.001**
Cone index	-12.047	0.970	-12.416	**<0.001**

2. **PTL**

    Response variate: Motion resistance

    Fitted terms: Constant, cone index

Table A6.28: Summary of analysis for PTL, Felton

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	169.084	169.084	166.232	<**0.001**	**0.86**	**1.009**
Residual	28	28.480	1.017				
Total	29	197.565	6.813				

Table A6.29: Estimates of parameters for PTL, Felton

Parameter	estimate	s.e.	t(96)	t pr.
Constant	37.073	2.161	17.155	**<0.001**
Cone index	-17.515	1.358	-12.893	**<0.001**

A6.5.2 Regression analysis – linear model, relationship between motion resistance and cone index, **Pittsworth** site.

1. PCB

Response variate: Motion resistance

Fitted terms: Constant, cone index

Table A6.30: Summary of analysis for PCB, Pittsworth

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	19.756	19.756	59.440	<**0.001**	**0.68**	**0.577**
Residual	28	9.306	0.332				
Total	29	29.063	1.002				

Table A6.31: Estimates of parameters for PCB, Pittsworth

Parameter	estimate	s.e.	t(96)	t pr.
Constant	14.127	0.518	27.259	**<0.001**
Cone index	-4.228	0.548	-7.710	**<0.001**

2. PTL

Response variate: Motion resistance

Fitted terms: Constant, cone index

Table A6.32: Summary of analysis for PTL, Pittsworth

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	6.579	6.579	719.954	<**0.001**	**0.96**	**0.096**
Residual	28	0.256	0.009				
Total	29	6.835	0.236				

Table A6.33: Estimates of parameters for PTL, Pittsworth

Parameter	estimate	s.e.	t(96)	t pr.
Constant	10.890	0.088	123.811	**<0.001**
Cone index	-1.061	0.040	-26.832	**<0.001**

A6.3.3 Regression analysis – linear model, relationship between motion resistance and cone index, **Gatton** site.

1. Non-wheeled soil

Response variate: Motion resistance

Fitted terms: Constant, cone index

Table A6.34: Summary of analysis for non-wheeled soil, Gatton

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	3.174	3.174	694.221	**<0.001**	**0.96**	**0.068**
Residual	28	0.128	0.005				
Total	29	3.302	0.114				

Table A6.35: Estimates of parameters for non-wheeled soil, Gatton

Parameter	estimate	s.e.	t(96)	t pr.
Constant	5.727	0.039	146.718	**<0.001**
Cone index	-2.345	0.089	-26.348	**<0.001**

2. Wheeled soil

Response variate: Motion resistance

Fitted terms: Constant, cone index

Table A6.36: Summary of analysis for wheeled soil, Gatton

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	3.591	3.591	157.886	**<0.001**	**0.85**	**0.151**
Residual	28	0.637	0.023				
Total	29	4.228	0.146				

Table A6.37: Estimates of parameters for wheeled soil, Gatton

Parameter	estimate	s.e.	t(96)	t pr.
Constant	9.399	0.513	18.339	**<0.001**
Cone index	-3.008	0.239	-12.565	**<0.001**

A6.5.4 Regression analysis – linear model, relationship between motion resistance and cone index, **Hopetoun** site.

1. PCB

Response variate: Motion resistance

Fitted terms: Constant, cone index

Table A6.38: Summary of analysis for PCB, Hopetoun

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	9.449	9.449	204.946	**<0.001**	**0.88**	**0.215**
Residual	28	1.291	0.046				
Total	29	10.740	0.370				

Table A6.39: Estimates of parameters for PCB, Hopetoun

Parameter	estimate	s.e.	t(96)	t pr.
Constant	12.804	0.173	73.941	**<0.001**
Cone index	-1.267	0.089	-14.316	**<0.001**

2. PTL

Response variate: Motion resistance

Fitted terms: Constant, cone index

Table A6.40: Summary of analysis for PTL, Hopetoun

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	11.581	11.581	174.894	**<0.001**	**0.86**	**0.257**
Residual	28	1.854	0.066				
Total	29	13.435	0.463				

Table A6.41: Estimates of parameters for PTL, Hopetoun

Parameter	estimate	s.e.	t(96)	t pr.
Constant	13.065	0.315	41.480	**<0.001**
Cone index	-1.211	0.092	-13.225	**<0.001**

A6.3.5 Regression analysis – linear model, relationship between motion resistance and cone index, **Swan Hill** site.

1. **PCB**

Response variate: Motion resistance

Fitted terms: Constant, cone index

Table A6.42: Summary of analysis for PCB, Swan Hill

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	21.645	21.645	383.507	**<0.001**	**0.93**	**0.238**
Residual	28	1.580	0.056				
Total	29	23.226	0.801				

Table A6.43: Estimates of parameters for PCB, Swan Hill

Parameter	estimate	s.e.	t(96)	t pr.
Constant	18.233	0.291	62.717	**<0.001**
Cone index	-2.444	0.125	-19.583	**<0.001**

2. **PTL**

Response variate: Motion resistance

Fitted terms: Constant, cone index

Table A6.44: Summary of analysis for PTL, Swan Hill

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	12.225	12.225	54.029	**<0.001**	**0.66**	**0.476**
Residual	28	6.336	0.226				
Total	29	18.561	0.640				

Table A6.45: Estimates of parameters for PTL, Swan Hill

Parameter	estimate	s.e.	t(96)	t pr.
Constant	15.222	0.634	23.995	**<0.001**
Cone index	-1.255	0.171	-7.350	**<0.001**

A6.5.6 Regression analysis – **linear model**, relationship between motion resistance and cone index, **Loxton** site.

1. PCB

Response variate: Motion resistance

Fitted terms: Constant, cone index

Table A6.46: Summary of analysis for PCB, Loxton

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	48.992	48.992	389.082	<**0.001**	**0.93**	**0.355**
Residual	28	3.526	0.126				
Total	29	52.518	1.811				

Table A6.47: Estimates of parameters for PCB, Loxton

Parameter	estimate	s.e.	t(96)	t pr.
Constant	19.923	0.345	57.797	**<0.001**
Cone index	-5.552	0.281	-19.725	**<0.001**

2. PTL

Response variate: Motion resistance

Fitted terms: Constant, cone index

Table A6.48: Summary of analysis for PTL, Loxton

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	27.999	27.999	365.682	<**0.001**	**0.93**	**0.277**
Residual	28	2.144	0.077				
Total	29	30.143	1.039				

Table A6.49: Estimates of parameters for PTL, Loxton

Parameter	estimate	s.e.	t(96)	t pr.
Constant	14.272	0.254	56.287	**<0.001**
Cone index	-1.948	0.102	-19.123	**<0.001**

A6.5.7 Regression analysis – linear model, relationship between motion resistance and cone index, **Waikerie** site.

1. Non-wheeled soil

Response variate: Motion resistance

Fitted terms: Constant, cone index

Table A6.50: Summary of analysis for non-wheeled soil, Waikerie

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	6.171	6.171	210.578	**<0.001**	**0.88**	**0.171**
Residual	28	0.821	0.029				
Total	29	6.992	0.241				

Table A6.51: Estimates of parameters for non-wheeled soil, Pittsworth

Parameter	estimate	s.e.	t(96)	t pr.
Constant	11.128	0.118	94.563	**<0.001**
Cone index	-2.039	0.141	-14.511	**<0.001**

2. Wheeled soil

Response variate: Motion resistance

Fitted terms: Constant, cone index

Table A6.52: Summary of analysis for wheeled soil, Waikerie

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	10.730	10.730	117.775	**<0.001**	**0.81**	**0.302**
Residual	28	2.551	0.091				
Total	29	13.281	0.458				

Table A6.53: Estimates of parameters for wheeled soil, Waikerie

Parameter	estimate	s.e.	t(96)	t pr.
Constant	12.244	0.296	41.346	**<0.001**
Cone index	-3.230	0.298	-10.852	**<0.001**

Appendix A6.6: Results of relationship between motion resistance and cone index for the rest of Northern and Southern region sites in Chapter 6

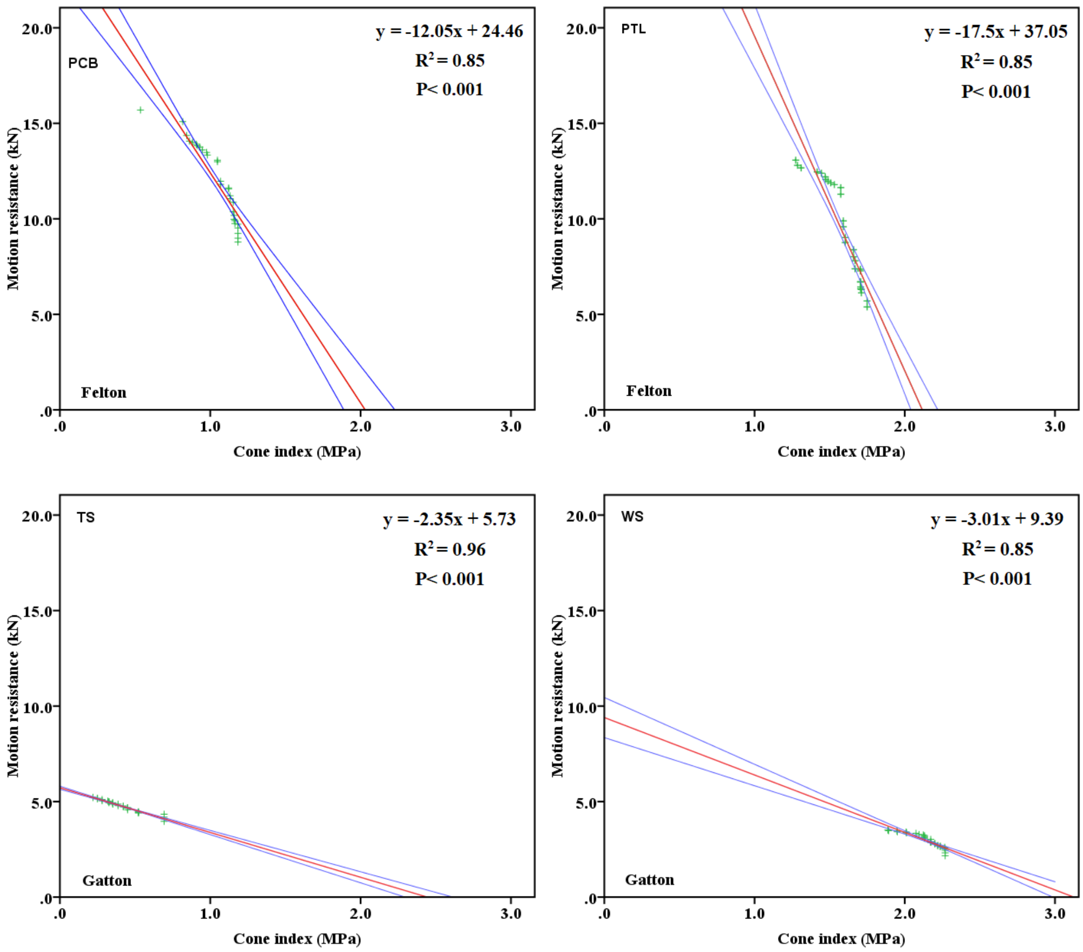


Figure A6.6.1: Linear regression analyses – relationships between motion resistance and cone index for depth (0-150 mm) for Northern region sites. The red line is the relationship between motion resistance and cone index. Blue lines show the 95% confidence interval for the linear model fitted to the data. Figures show: PCB soil and TS (left) and PTL soil and WS (right) for Felton (QLD) (top) and Gatton (QLD) (bottom), respectively (n=30)

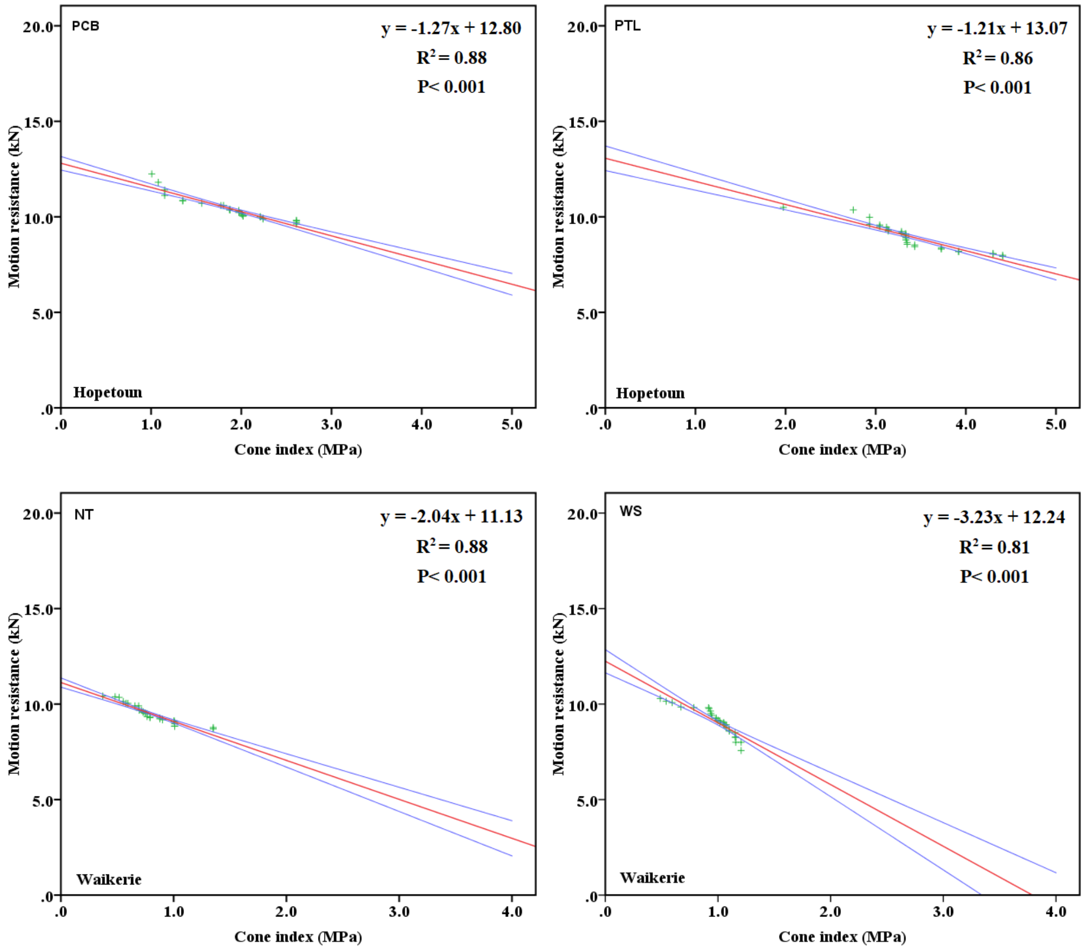
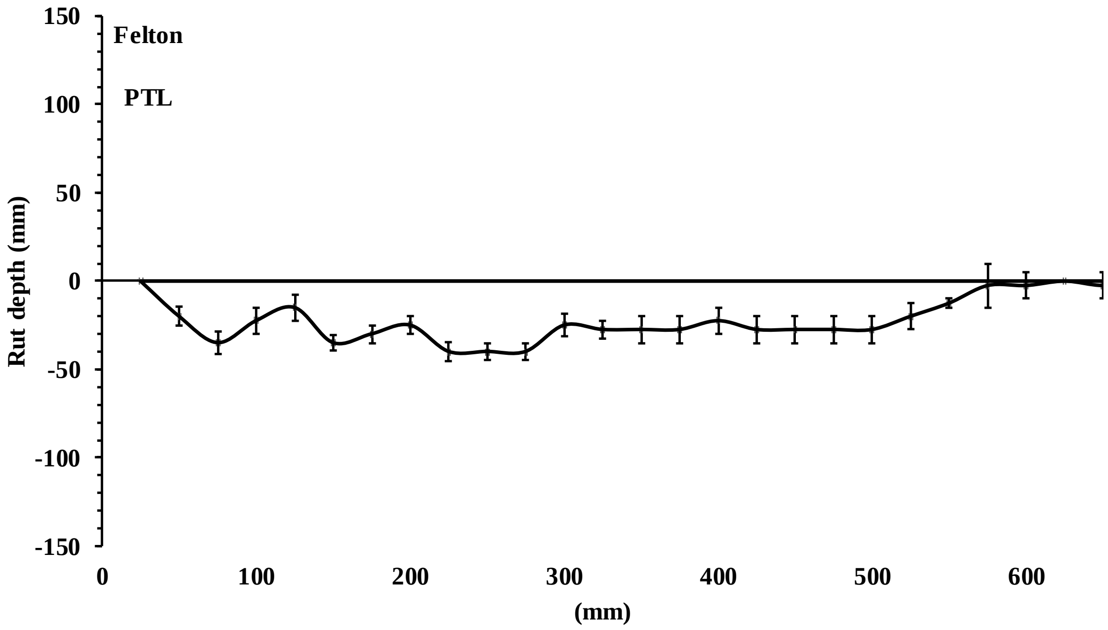


Figure A6.6.2: Linear regression analyses – relationships between motion resistance and cone index for depth (0-150 mm) for Southern region sites. The red line is the relationship between motion resistance and cone index. Blue lines show the 95% confidence interval for the linear model fitted to the data. Figures show: PCB soil and NT soil (left) and PTL soil and WS (right) for Hopetoun (VIC) (top) and Waikerie (SA) (bottom), respectively (n=30)

Appendix A6.7: Results of rut depth for Northern and Southern region sites



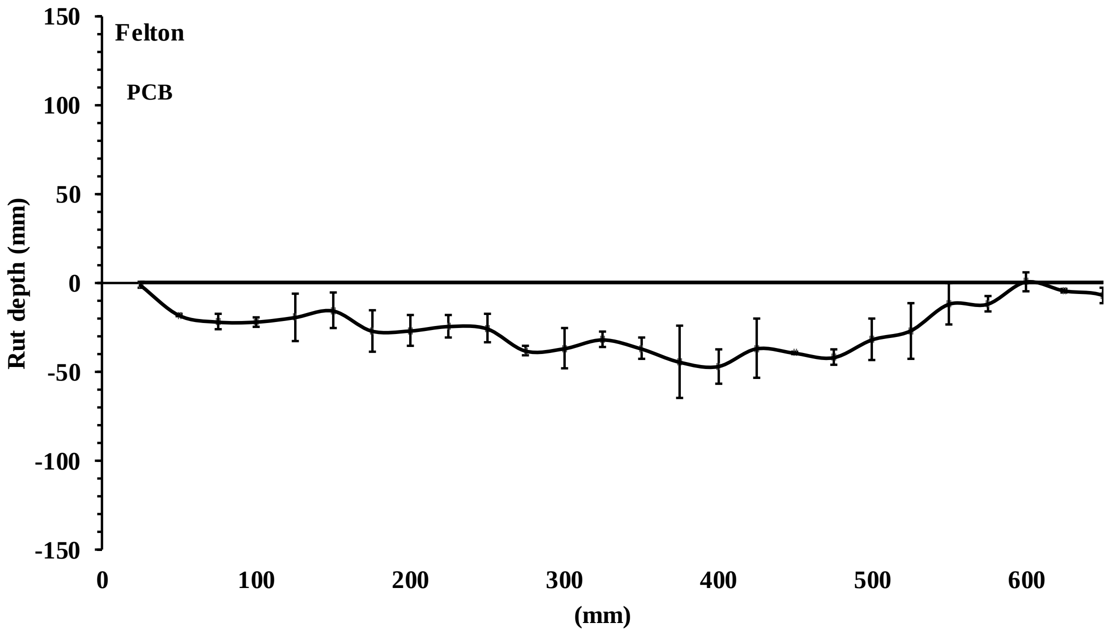
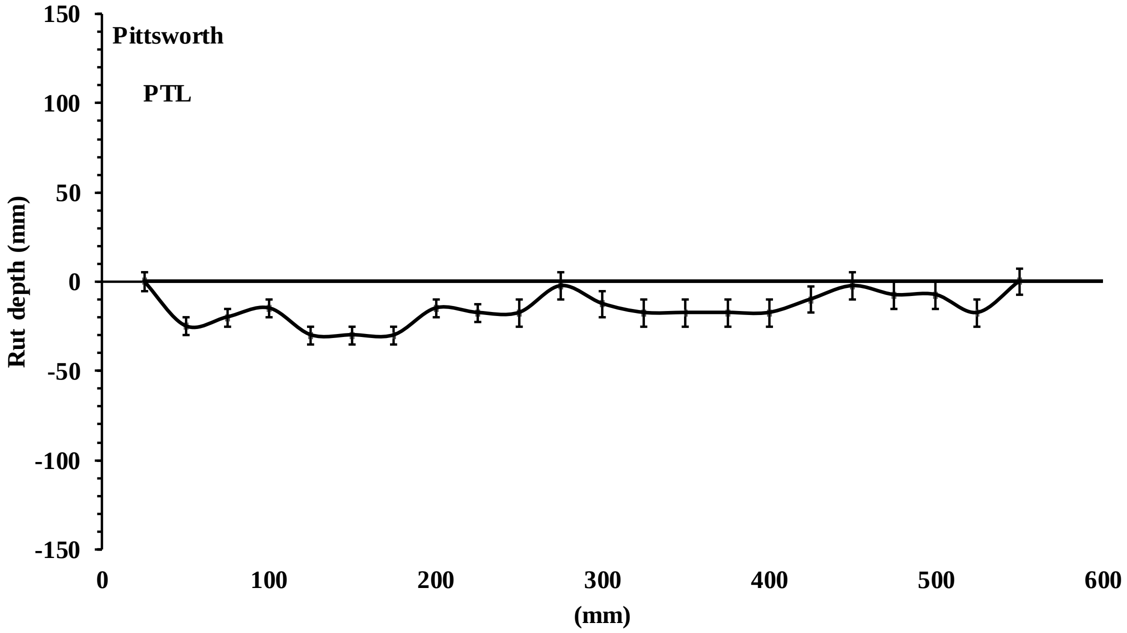


Figure A6.7.1: Rut depth in a different soil condtion at Felton site; permanent traffic lane top, permanent crop bed bottom. Error bars denote standard deviation (SD) of mean (n = 4)



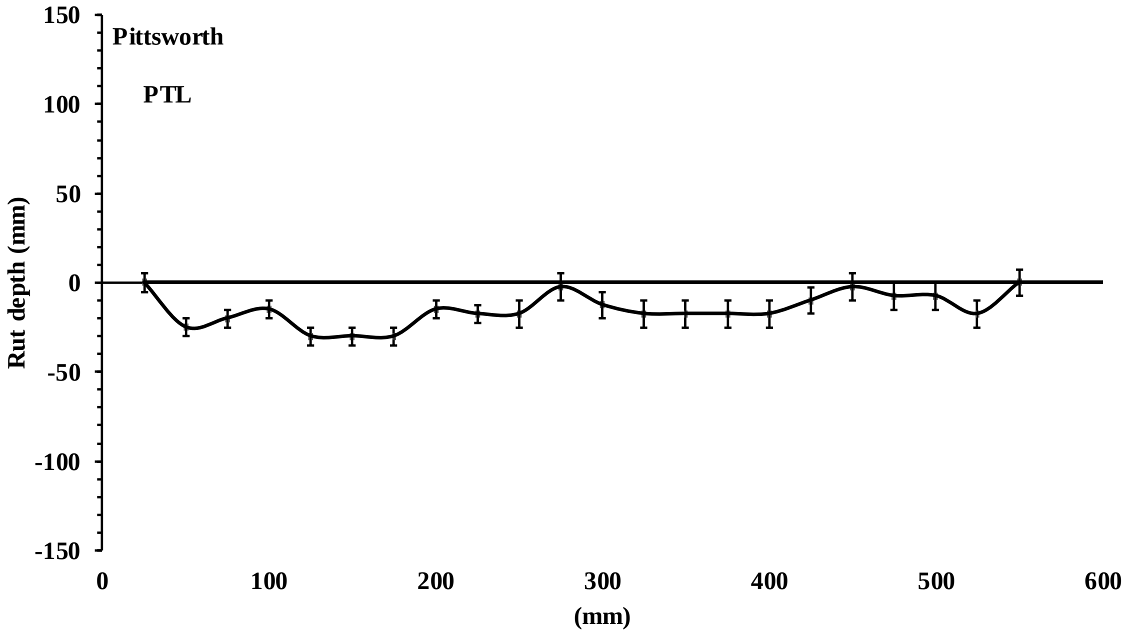


Figure A6.7.2: Rut depth in a different soil condtion at Pittsworth site; permanent traffic lane top, permanent crop bed bottom. Error bars denote standard deviation (SD) of mean (n = 4)

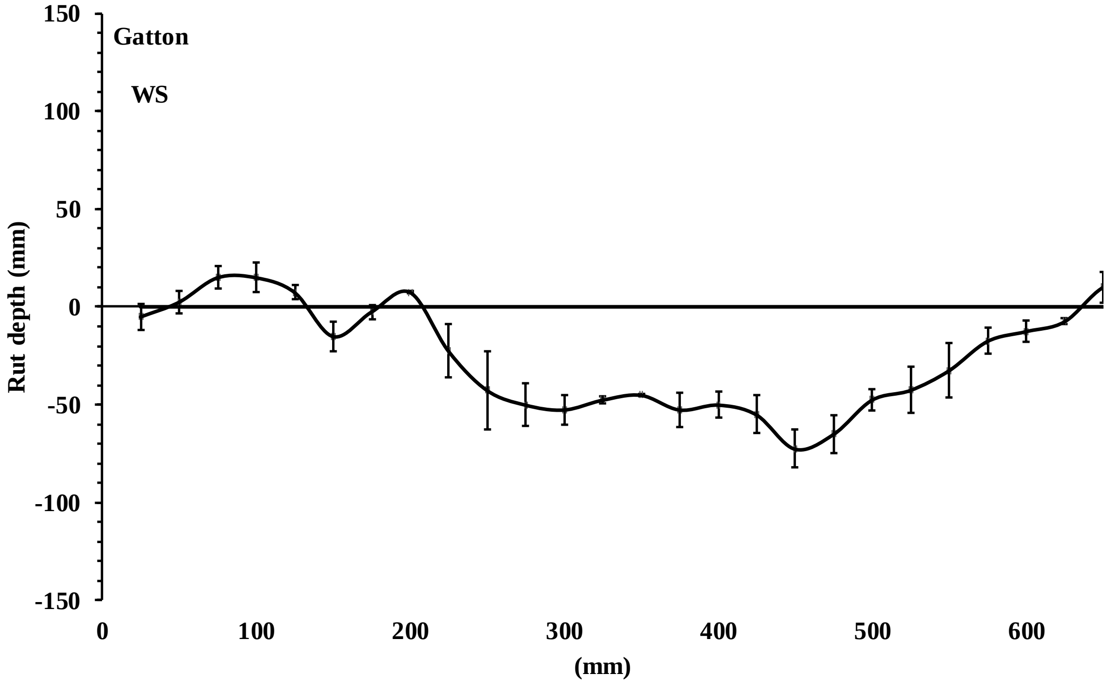
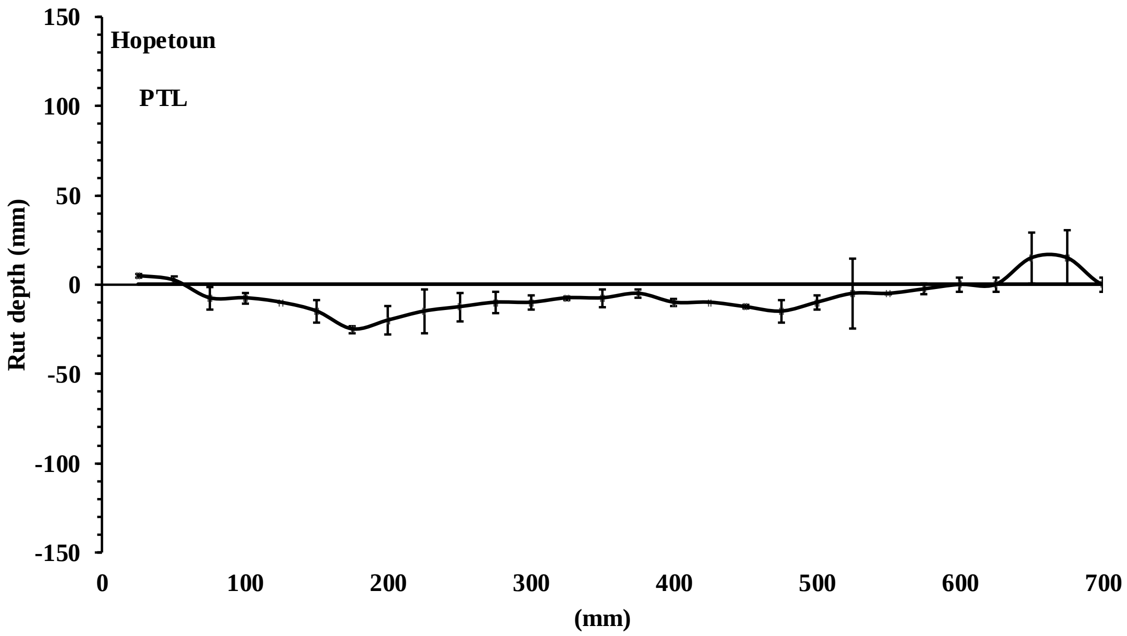


Figure A6.7.3: Rut depth in wheeled soil at Gatton site. Error bars denote standard deviation (SD) of mean (n = 4)



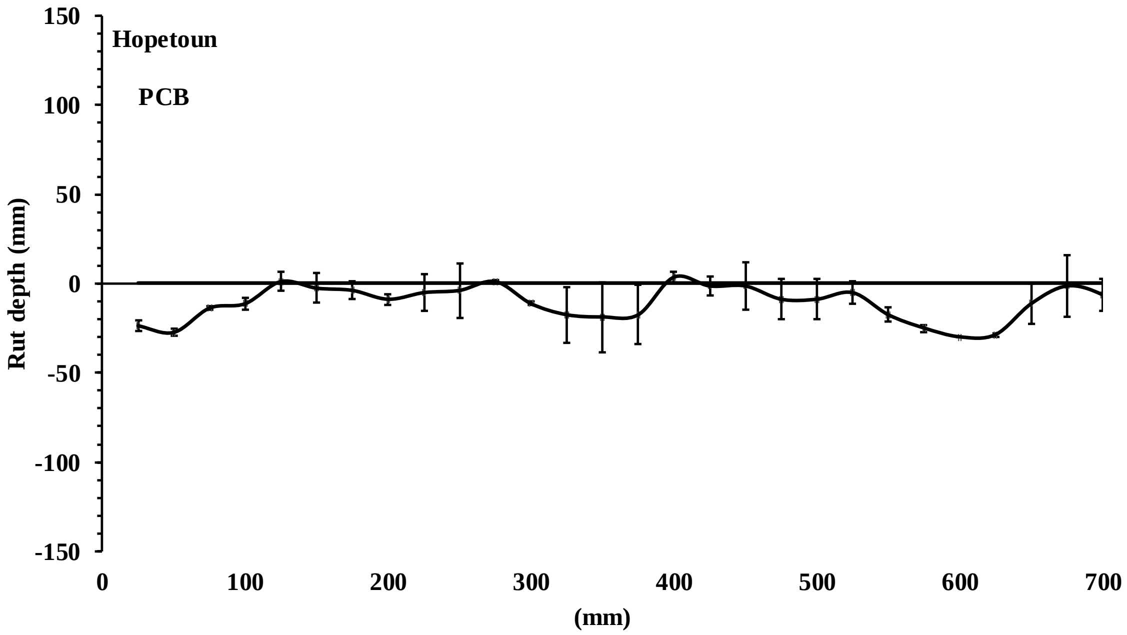
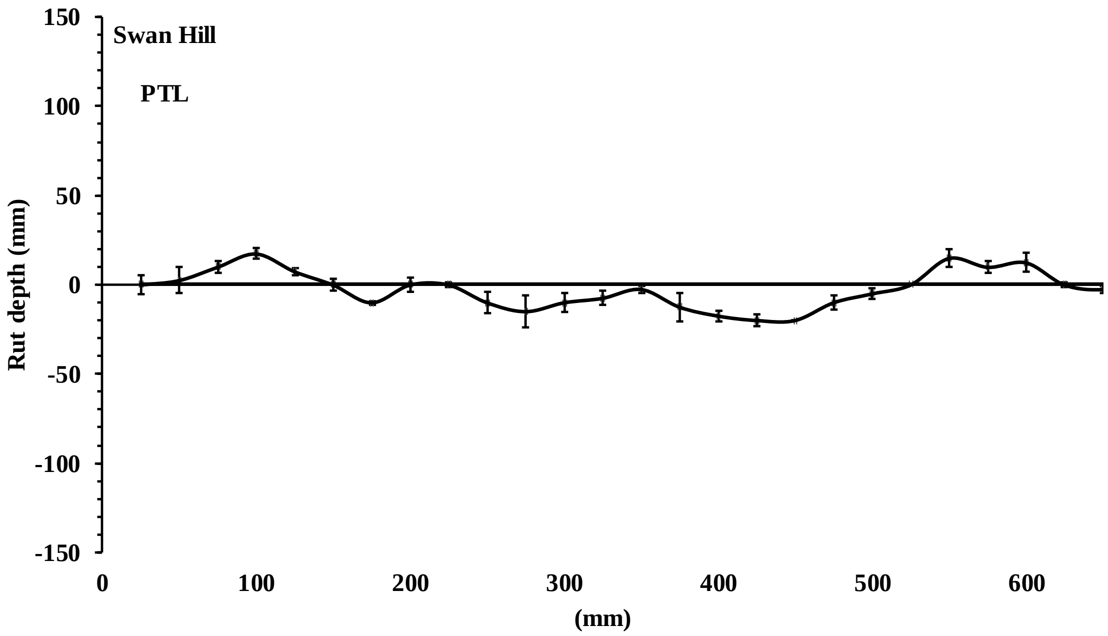


Figure A6.7.4: Rut depth in a different soil condtion at Hopetoun site; permanent traffic lane top, permanent crop bed bottom. Error bars denote standard deviation (SD) of mean (n = 4)



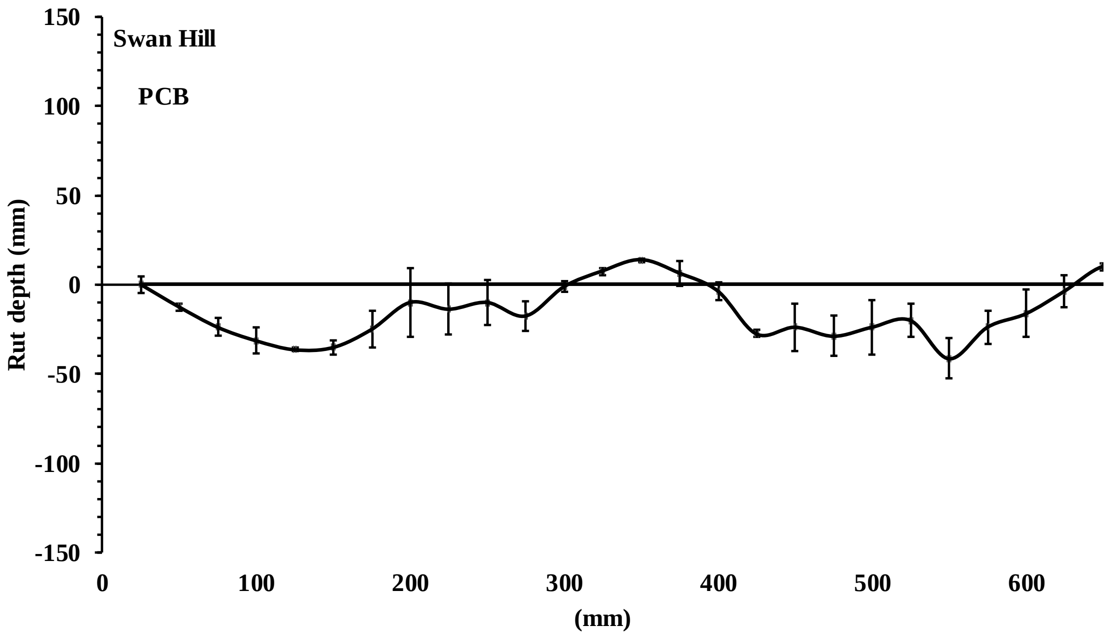
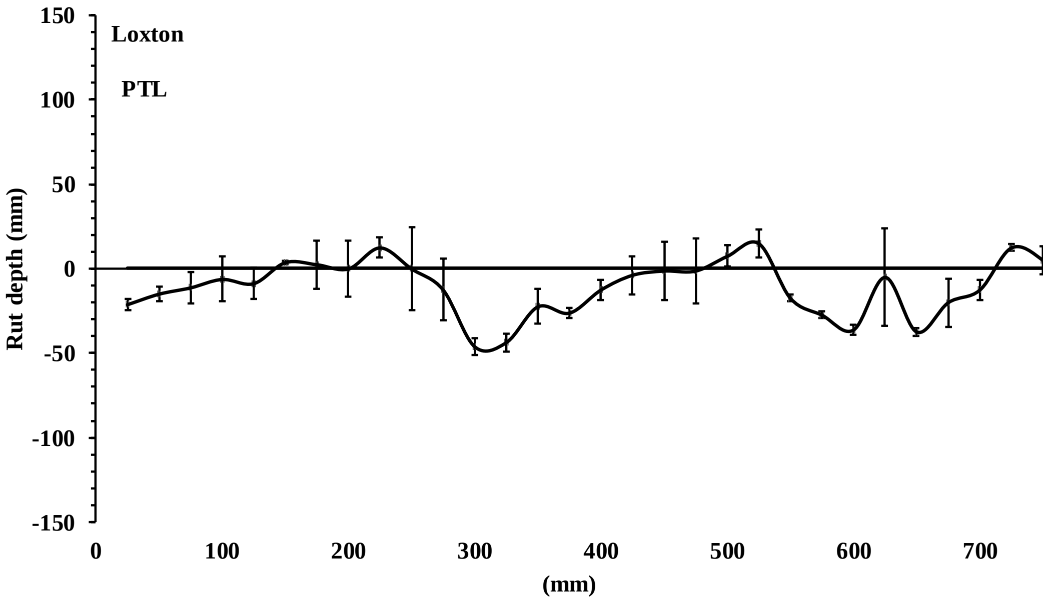


Figure A6.7.5: Rut depth in a different soil condtion at Swan Hill site; permanent traffic lane top, permanent crop bed bottom. Error bars denote standard deviation (SD) of mean (n = 4)



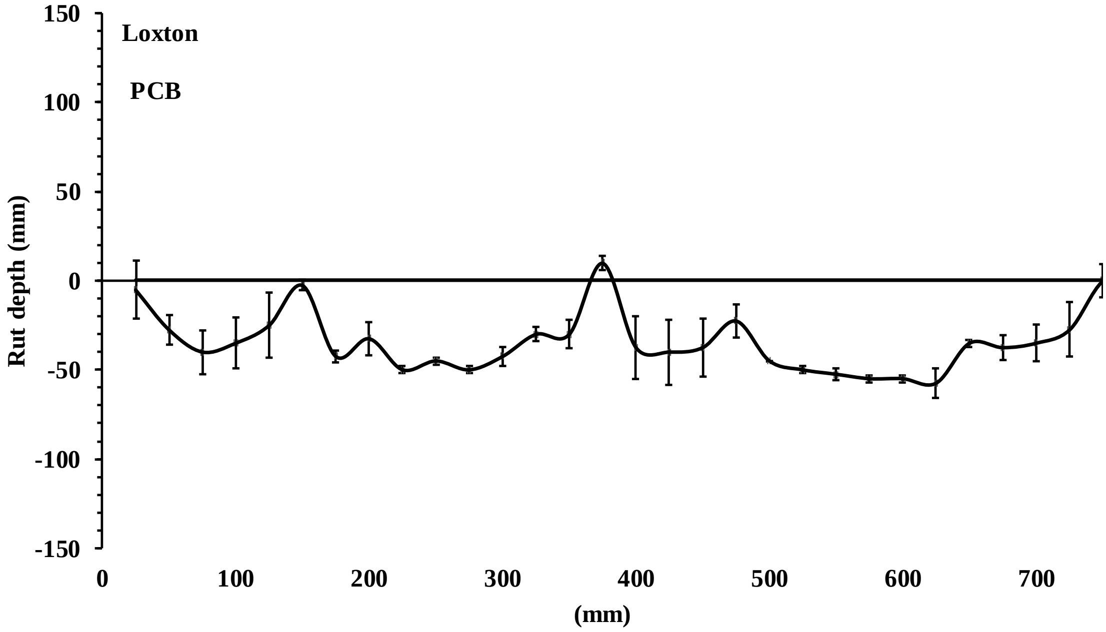


Figure A6.7.6: Rut depth in a different soil condtion at Loxton site; permanent traffic lane top, permanent crop bed bottom. Error bars denote standard deviation (SD) of mean (n = 4)

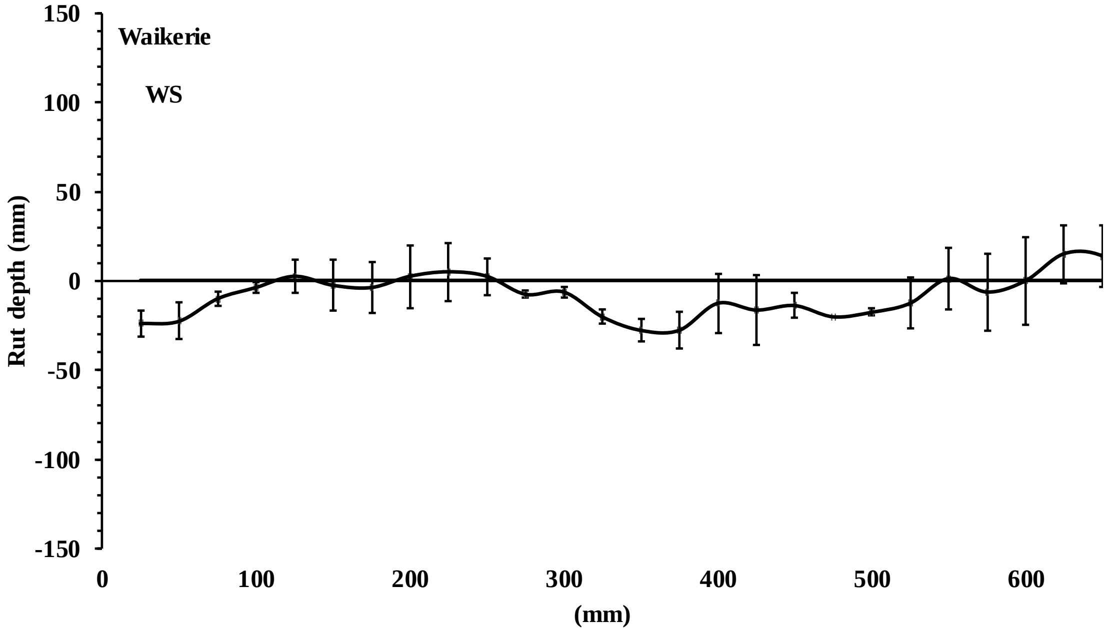


Figure A6.7.7: Rut depth in wheeled soil at Waikerie site. Error bars denote standard deviation (SD) of mean (n = 4)

Appendix A6.8: Regression analyses corresponding to relationship between measured and predicted motion resistance in Chapter 6: Regression analysis – linear model;

A6.8.1: Relationship between predicted and measured motion resistance, **Felton** site.

1. Gee-Clough model

1.1 NT

Table A6.54: Summary of analysis for NT, Felton

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	1.2	1.2	48.243	**<0.001**	**0.63**	**0.158**
Residual	28	0.696	0.025				
Total	29	1.896	0.065				

Table A6.55: Estimates of parameters for NT, Felton

Parameter	estimate	s.e.	t(96)	t pr.
Constant	5.230	0.176	29.653	**<0.001**
Measured	0.101	0.015	6.946	**<0.001**

1.2 PTL

Table A6.56: Summary of analysis for PTL, Felton

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	0.168	0.168	106.302	**<0.001**	**0.79**	**0.04**
Residual	28	0.044	0.002				
Total	29	0.213	0.007				

Table A6.57: Estimates of parameters for PTL, Felton

Parameter	estimate	s.e.	t(96)	t pr.
Constant	5.821	0.027	212.848	**<0.001**
Measured	0.029	0.003	10.310	**<0.001**

2. Brixius model

2.1 NT

Table A6.58: Summary of analysis for NT, Felton

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	18.944	18.944	48.520	**<0.001**	**0.63**	**0.625**
Residual	28	10.932	0.390				
Total	29	29.876	1.03				

Table A6.59: Estimates of parameters for NT, Felton

Parameter	estimate	s.e.	t(96)	t pr.
Constant	4.530	0.699	6.483	**<0.001**
Measured	0.403	0.058	6.966	**<0.001**

2.2 PTL

Table A6.60: Summary of analysis for PTL, Felton

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	2.138	2.138	106.391	**<0.001**	**0.79**	**0.142**
Residual	28	0.563	0.020				
Total	29	2.701	0.093				

Table A6.61: Estimates of parameters for PTL, Felton

Parameter	estimate	s.e.	t(96)	t pr.
Constant	6.591	0.097	67.661	**<0.001**
Measured	0.104	0.010	10.315	**<0.001**

A6.8.2: Relationship between predicted and measured motion resistance, **Pittsworth** site.

1. Gee-Clough model

1.1 NT

Table A6.62: Summary of analysis for NT, Pittsworth

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	1.153	1.153	212.117	<**0.001**	**0.88**	**0.074**
Residual	28	0.152	0.005				
Total	29	1.306	0.045				

Table A6.63: Estimates of parameters for NT, Pittsworth

Parameter	estimate	s.e.	t(96)	t pr.
Constant	4.252	0.140	30.294	**<0.001**
Measured	0.199	0.014	14.564	**<0.001**

1.2 PTL

Table A6.64: Summary of analysis for PTL, Pittsworth

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	0.768	0.768	463.129	<**0.001**	**0.79**	**0.04**
Residual	28	0.046	0.002				
Total	29	0.815	0.028				

Table A6.65: Estimates of parameters for PTL, Pittsworth

Parameter	estimate	s.e.	t(96)	t pr.
Constant	3.009	0.134	22.486	**<0.001**
Measured	0.335	0.016	21.520	**<0.001**

2. Brixius model

2.1 NT

Table A6.66: Summary of analysis for NT, Pittsworth

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	17.731	17.731	209.354	**<0.001**	**0.88**	**0.291**
Residual	28	2.371	0.085				
Total	29	20.102	0.693				

Table A6.67: Estimates of parameters for NT, Pittsworth

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.526	0.554	0.950	**0.35**
Measured	0.781	0.054	14.469	**<0.001**

2.2 PTL

Table A6.68: Summary of analysis for PTL, Pittsworth

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	8.091	8.091	470.864	**<0.001**	**0.94**	**0.131**
Residual	28	0.481	0.017				
Total	29	8.573	0.296				

Table A6.69: Estimates of parameters for PTL, Pittsworth

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-2.874	0.431	-6.674	**<0.001**
Measured	1.088	0.050	21.699	**<0.001**

A6.8.3: Relationship between predicted and measured motion resistance, **Gatton** site.

1. Gee-Clough model

1.1 TS

Table A6.70: Summary of analysis for TS, Gatton

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	12.939	12.939	187.821	<**0.001**	**0.87**	**0.262**
Residual	28	1.929	0.069				
Total	29	14.867	0.513				

Table A6.71: Estimates of parameters for TS, Gatton

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-4.292	0.688	-6.239	**<0.001**
Measured	1.980	0.144	13.705	**<0.001**

1.2 WS

Table A6.72: Summary of analysis for WS, Gatton

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	0.011	0.011	127.006	<**0.001**	**0.81**	**0.01**
Residual	28	0.003	0.000				
Total	29	0.014	0.000				

Table A6.73: Estimates of parameters for WS, Gatton

Parameter	estimate	s.e.	t(96)	t pr.
Constant	3.159	0.014	228.312	**<0.001**
Measured	0.052	0.005	11.270	**<0.001**

2. Brixius model

2.1 TS

Table A6.74: Summary of analysis for TS, Gatton

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	96.434	96.434	189.738	**<0.001**	**0.87**	**0.713**
Residual	28	14.231	0.508				
Total	29	110.665	3.816				

Table A6.75: Estimates of parameters for TS, Gatton

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-17.213	1.869	-9.211	**<0.001**
Measured	5.405	0.392	13.775	**<0.001**

2.2 WS

Table A6.76: Summary of analysis for WS, Gatton

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	0.089	0.089	123.006	**<0.001**	**0.81**	**0.027**
Residual	28	0.020	0.001				
Total	29	0.109	0.004				

Table A6.77: Estimates of parameters for WS, Gatton

Parameter	estimate	s.e.	t(96)	t pr.
Constant	3.085	0.039	78.735	**<0.001**
Measured	0.145	0.013	11.091	**<0.001**

A6.8.4: Relationship between predicted and measured motion resistance, **Hopetoun** site.

1. Gee-Clough model

1.2 NT

Table A6.78: Summary of analysis for NT, Hopetoun

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	0.587	0.587	523.992	<**0.001**	**0.95**	**0.033**
Residual	28	0.031	0.001				
Total	29	0.618	0.021				

Table A6.79: Estimates of parameters for NT, Hopetoun

Parameter	estimate	s.e.	t(96)	t pr.
Constant	2.231	0.106	20.994	<**0.001**
Measured	0.234	0.010	22.891	<**0.001**

1.2 PTL

Table A6.80: Summary of analysis for PTL, Hopetoun

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	0.049	0.049	111.096	<**0.001**	**0.79**	**0.021**
Residual	28	0.012	0.000				
Total	29	0.062	0.002				

Table A6.81: Estimates of parameters for PTL, Hopetoun

Parameter	estimate	s.e.	t(96)	t pr.
Constant	3.889	0.052	75.480	<**0.001**
Measured	0.061	0.006	10.540	<**0.001**

2. Brixius model

2.1 NT

Table A6.82: Summary of analysis for NT, Hopetoun

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	8.338	8.338	580.531	**<0.001**	**0.95**	**0.120**
Residual	28	0.402	0.014				
Total	29	8.741	0.301				

Table A6.83: Estimates of parameters for NT, Hopetoun

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-3.276	0.381	-8.607	**<0.001**
Measured	0.881	0.037	24.094	**<0.001**

2.2 PTL

Table A6.84: Summary of analysis for PTL, Hopetoun

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	0.524	0.524	113.379	**<0.001**	**0.80**	**0.068**
Residual	28	0.129	0.005				
Total	29	0.654	0.022				

Table A6.85: Estimates of parameters for PTL, Hopetoun

Parameter	estimate	s.e.	t(96)	t pr.
Constant	2.554	0.166	15.343	**<0.001**
Measured	0.198	0.019	10.648	**<0.001**

A6.8.5: Relationship between predicted and measured motion resistance, **Swan Hill** site.

1. Gee-Clough model

1.1 NT

Table A6.86: Summary of analysis for NT, Swan Hill

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	0.486	0.486	424.259	**<0.001**	**0.94**	**0.034**
Residual	28	0.032	0.001				
Total	29	0.518	0.018				

Table A6.87: Estimates of parameters for NT, Swan Hill

Parameter	estimate	s.e.	t(96)	t pr.
Constant	5.779	0.089	65.127	**<0.001**
Measured	0.145	0.007	20.598	**<0.001**

1.2 PTL

Table A6.88: Summary of analysis for PTL, Swan Hill

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	0.172	0.172	31.324	**<0.001**	**0.53**	**0.074**
Residual	28	0.154	0.005				
Total	29	0.326	0.011				

Table A6.89: Estimates of parameters for PTL, Swan Hill

Parameter	estimate	s.e.	t(96)	t pr.
Constant	6.268	0.183	34.251	**<0.001**
Measured	0.096	0.017	5.597	**<0.001**

2. Brixius model

2.1 NT

Table A6.90: Summary of analysis for NT, Swan Hill

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	5.472	5.472	425.512	**<0.001**	**0.94**	**0.113**
Residual	28	0.360	0.013				
Total	29	5.832	0.201				

Table A6.91: Estimates of parameters for NT, Swan Hill

Parameter	estimate	s.e.	t(96)	t pr.
Constant	2.340	0.297	7.871	**<0.001**
Measured	0.485	0.024	20.628	**<0.001**

2.2 PTL

Table A6.92: Summary of analysis for PTL, Swan Hill

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	1.973	1.973	31.640	**<0.001**	**0.53**	**0.250**
Residual	28	1.746	0.062				
Total	29	3.719	0.128				

Table A6.93: Estimates of parameters for PTL, Swan Hill

Parameter	estimate	s.e.	t(96)	t pr.
Constant	3.948	0.616	6.407	**<0.001**
Measured	0.326	0.058	5.625	**<0.001**

A6.8.6: Relationship between predicted and measured motion resistance, **Waikerie** site.

1. Gee-Clough model

1.1 NT

Table A6.94: Summary of analysis for NT, Waikerie

Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**	**SE**
Regression	1	11.122	11.122	215.511	**<0.001**	**0.88**	**0.227**
Residual	28	1.445	0.052				
Total	29	12.567	0.433				

Table A6.95: Estimates of parameters for NT, Waikerie

Parameter	**estimate**	**s.e.**	**t(96)**	**t pr.**
Constant	-6.573	.816	-8.058	**<0.001**
Measured	1.261	.086	14.680	**<0.001**

1.2 WS

Table A6.96: Summary of analysis for WS, Waikerie

Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**	**SE**
Regression	1	4.194	4.194	46.338	**<0.001**	**0.62**	**0.301**
Residual	28	2.534	0.091				
Total	29	6.729	0.232				

Table A6.97: Estimates of parameters for WS, Waikerie

Parameter	**estimate**	**s.e.**	**t(96)**	**t pr.**
Constant	-0.141	0.752	-0.188	**0.852**
Measured	0.562	0.083	6.807	**<0.001**

2. Brixius model

2.1 NT

Table A6.98: Summary of analysis for NT, Waikerie

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	62.530	62.530	217.379	**<0.001**	**0.89**	**0.536**
Residual	28	8.054	0.288				
Total	29	70.585	2.434				

Table A6.99: Estimates of parameters for NT, Waikerie

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-20.516	1.926	-10.653	**<0.001**
Measured	2.991	.203	14.744	**<0.001**

2.2 WS

Table A6.100: Summary of analysis for WS, Waikerie

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	R^2	SE
Regression	1	24.165	24.165	48.428	**<0.001**	**0.63**	**0.706**
Residual	28	13.972	0.499				
Total	29	38.137	1.315				

Table A6.101: Estimates of parameters for WS, Waikerie

Parameter	estimate	s.e.	t(96)	t pr.
Constant	-5.420	1.766	-3.069	**0.005**
Measured	1.349	0.194	6.959	**<0.001**

Appendix A6.9: Relationship between measured and predicted motion resistance for all tines for the rest of Northern region and Southern region sites

A6.9.1: Felton (QLD) site

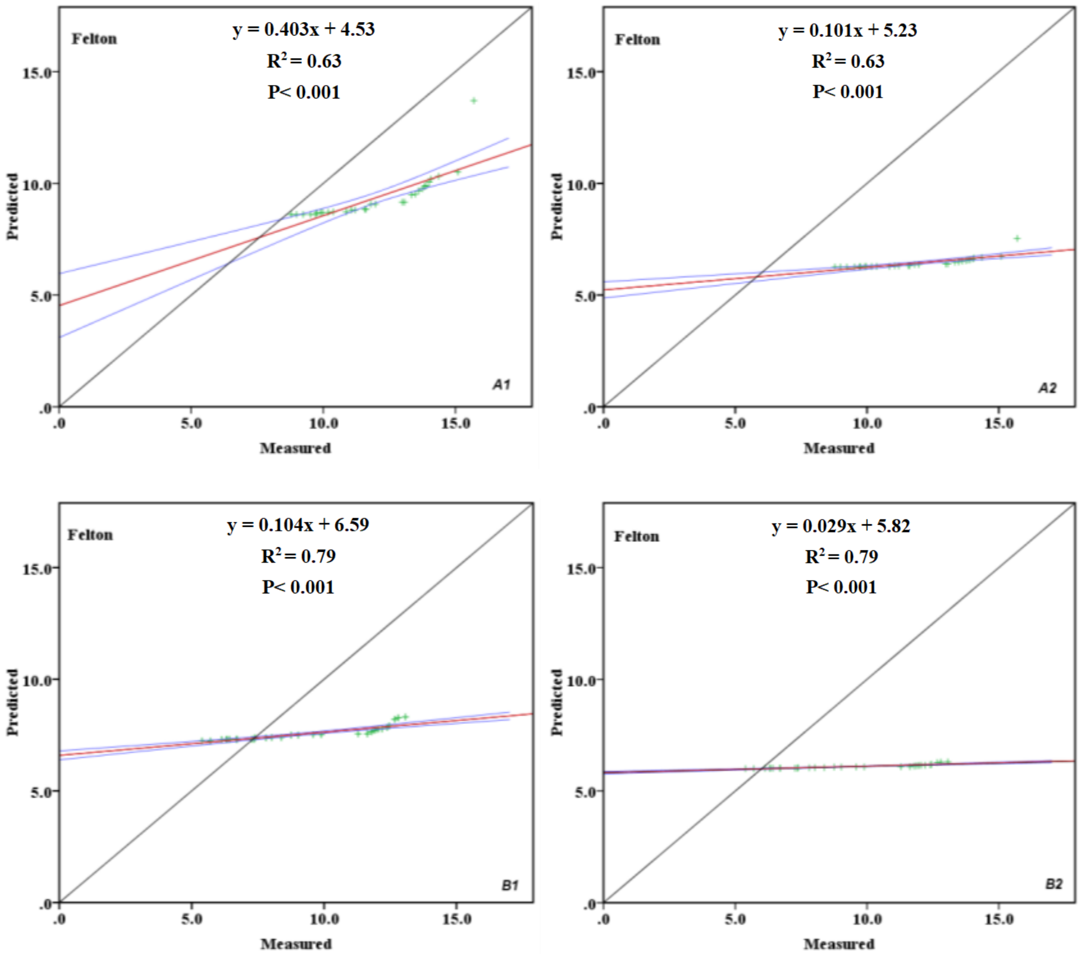


Figure A6.9.1: Relationship between measured and predicted motion resistance based on Brixius and Gee-Clough models for Felton (QLD) site. The red line is the relationship between measured and predicted values of draught force. Blue lines show the 95% confidence interval for the linear model fitted to the data, and the black line shows the 1:1 relationship between measured and predicted data. Figures show: (top) NT, (bottom) PTL; (left) Brixius model (right) Gee-Clough model, respectively (n=30)

A6.9.2: Gatton (QLD) site

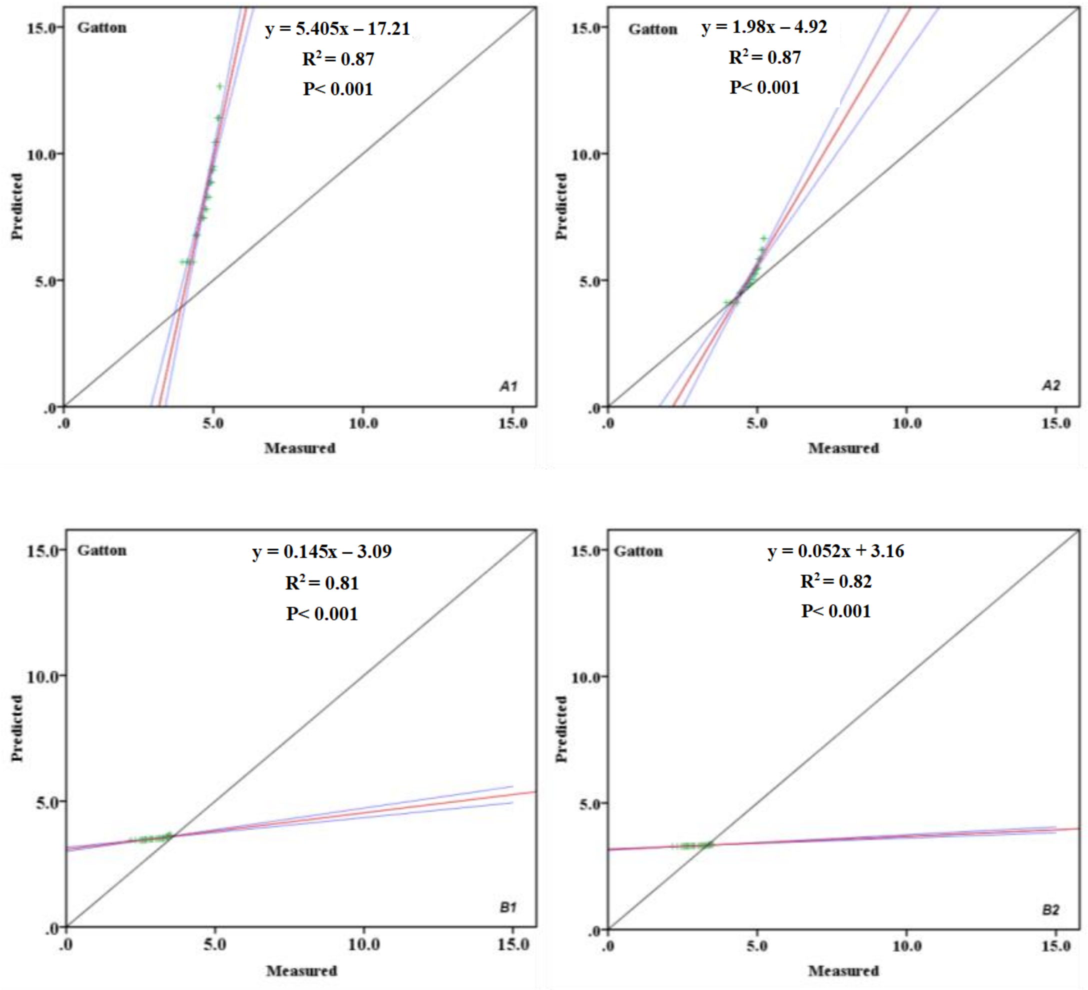


Figure A6.9.2: Relationship between measured and predicted motion resistance based on Brixius and Gee-Clough models for Gatton (QLD) site. The red line is the relationship between measured and predicted values of draught force. Blue lines show the 95% confidence interval for the linear model fitted to the data, and the black line shows the 1:1 relationship between measured and predicted data. Figures show: (top) TS, (bottom) WS; (left) Brixius model (right) Gee-Clough model, respectively (n=30)

A6.9.3: Hopetoun (VIC) site

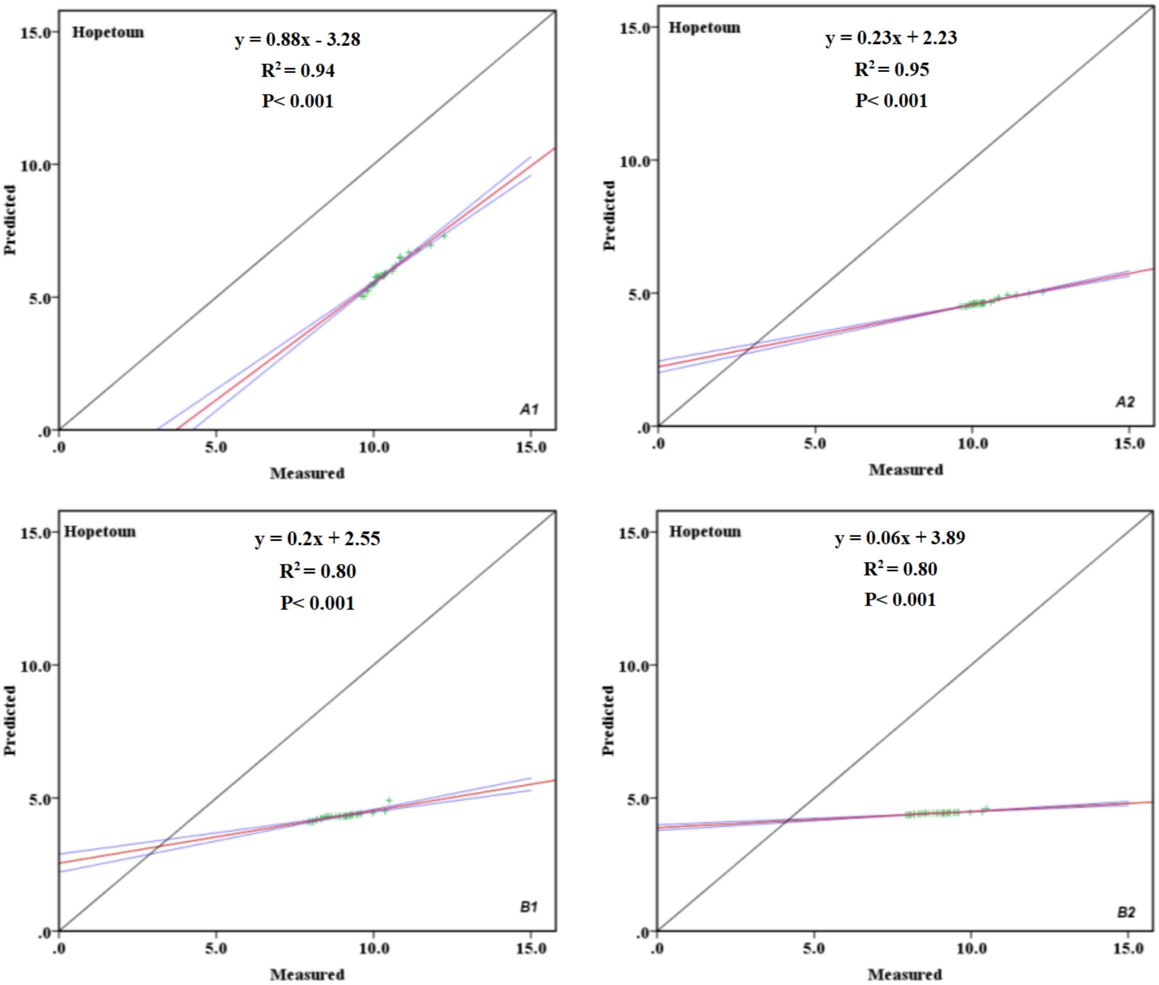


Figure A6.9.3: Relationship between measured and predicted motion resistance based on Brixius and Gee-Clough models for Hopetoun (VIC) site. The red line is the relationship between measured and predicted values of draught force. Blue lines show the 95% confidence interval for the linear model fitted to the data, and the black line shows the 1:1 relationship between measured and predicted data. Figures show: (top) NT, (bottom) PTL; (left) Brixius model (right) Gee-Clough model, respectively (n=30)

A6.9.4: Waikerie (SA) site

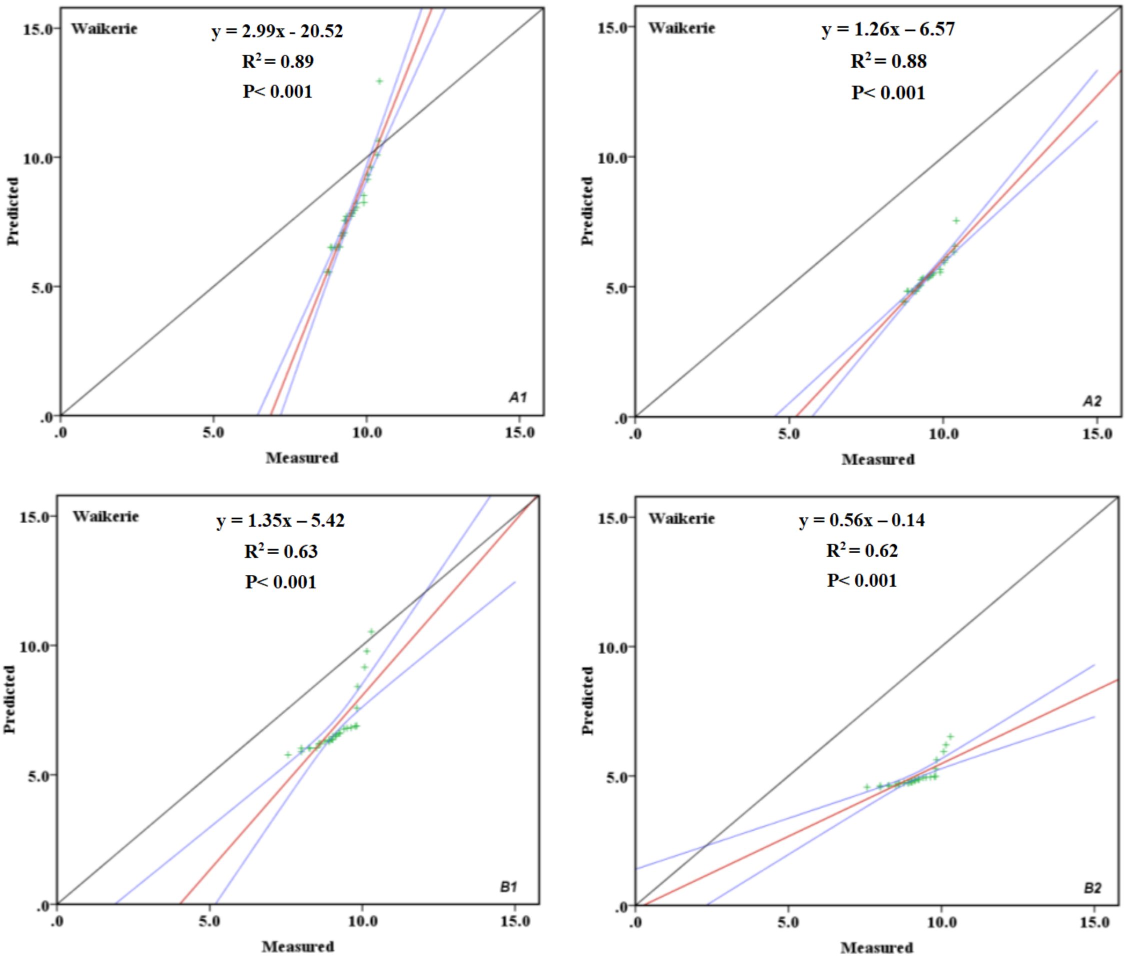


Figure A6.9.4: Relationship between measured and predicted motion resistance based on Brixius and Gee-Clough models for Waikerie (SA) site. The red line is the relationship between measured and predicted values of draught force. Blue lines show the 95% confidence interval for the linear model fitted to the data, and the black line shows the 1:1 relationship between measured and predicted data. Figures show: (top) NT, (bottom) WS; (left) Brixius model (right) Gee-Clough model, respectively (n=30)

APPENDIX TO CHAPTER 7

APPENDIX TO CHAPTER 7

Appendix A7.1: Statistical analyses corresponding to mobility number in Chapter 7

A7.1.1: Statistical analysis – mobility number calculations in **Felton** site

Factors structure:

Soil condition: PTL, NT

Table A7.1: Analysis of variance – mobility number calculations **(Felton site)**

Variate: **Mobility number**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	R^2
Soil condition	1	2437.218	2437.218	209.427	**<0.001**	**0.78**
Residual	58	674.977	11.638			
Total	59	3112.195	52.749			

A7.1.2: Statistical analysis – mobility number calculations in **Pittsworth** site

Factors structure:

Soil condition: PTL, NT

Table A7.2: Analysis of variance – mobility number calculations **(Pittsworth site)**

Variate: **Mobility number**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	R^2
Soil condition	1	12768.572	12768.572	148.378	**<0.001**	**0.72**
Residual	58	4991.140	86.054			
Total	59	17759.711	301.012			

A7.1.3: Statistical analysis – mobility number calculations in **Gatton** site

Factors structure:

Soil condition: WS, TS

Table A7.3: Analysis of variance – mobility number calculations **(Gatton site)**

Variate: **Mobility number**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	R^2
Soil condition	1	29153.783	29153.783	2061.380	**<0.001**	**0.97**
Residual	58	820.285	14.143			
Total	59	29974.068	508.035			

A7.1.4: Statistical analysis – mobility number calculations in **Hopetoun** site

Factors structure:

Soil condition: PTL, NT

Table A7.4: Analysis of variance – mobility number calculations **(Hopetoun site)**

Variate: **Mobility number**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Soil condition	1	33231.844	33231.844	141.315	**<0.001**	**0.71**
Residual	58	13639.324	235.161			
Total	59	46871.168	794.426			

A7.1.5: Statistical analysis – mobility number calculations in **Swan Hill** site

Factors structure:

Soil condition: PTL, NT

Table A7.5: Analysis of variance – mobility number calculations **(Swan Hill site)**

Variate: **Mobility number**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Soil condition	1	15204.743	15204.743	144.860	**<0.001**	**0.71**
Residual	58	6087.779	104.962			
Total	59	21292.522	360.890			

A7.1.6: Statistical analysis – mobility number calculations in **Waikerie** site

Factors structure:

Soil condition: WS, TS

Table A7.6: Analysis of variance – mobility number calculations **(Waikerie site)**

Variate: **Mobility number**						
Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**Fpr.**	**R^2**
Soil condition	1	0.000	0.000	0.000	**1**	**0.00**
Residual	58	705.903	12.171			
Total	59	705.903	11.964			

A7.1.7: Statistical analysis of dataset- mobility number calculations in most sites

Factors structure:

Site: Felton, Pittsworth, Gatton, Hopetoun, Swan Hill, Waikerie

Soil condition: Wheeled soil, non-wheeled soil

Table A7.7: Analysis of variance – mobility number calculations **in most of sites**

Variate: **Mobility number**						
Source of varaiation	**d.f.**	**s.s**	**m. s.**	**v.r.**	**Fpr.**	**R^2**
Site	5	187919.474	37583.895	485.865	**<0.001**	**0.91**
Soil condition	1	67992.729	67992.729	878.974	**<0.001**	
Site.Soil condition	5	24803.430	4960.686	64.129	**<0.001**	
Residual	348	26919.408	77.355			
Total	359	307635.041	856.922			

Appendix A7.2: Regression analyses corresponding to relationship between mobility number and motion resistance coefficient in Chapter 7:

Table A7.8: Summary of regression analysis of relationships between motion resistance coefficient and mobility number for studied sites.

Site	Exponential model	P-value	R^2	SE
Felton	$Y = 0.241\ e^{-0.03}$	0.001	**0.63**	0.17
Pittsworth	$Y = 0.01\ e^{-0.005}$	0.001	**0.83**	0.05
Gatton	$Y = 0.15\ e^{-0.008}$	0.001	**0.91**	0.06
Hopetoun	$Y = 0.15\ e^{-0.003}$	0.001	**0.93**	0.03
Swan Hill	$Y = 0.11\ e^{-0.006}$	0.001	**0.89**	0.04
Waikerie	$Y = 0.19\ e^{-0.02}$	0.001	**71**	0.04

A7.2.1: Relationship between motion resistance coefficient and mobility number, **Felton** site

Table A7.9: Summary of analysis, Felton

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	2.755	2.755	96.672	**<0.001**	**0.62**	**0.17**
Residual	58	1.653	0.028				
Total	59	4.408	0.075				

Table A7.10: Estimates of parameters, Felton

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.241	0.023	10.472	**<0.001**
Mobility number	-0.03	0.003	-0.791	**<0.001**

A7.2.2: Relationship between motion resistance coefficient and mobility number, **Pittsworth** site

Table A7.11: Summary of analysis, Pittsworth

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	0.645	0.645	276.327	**<0.001**	**0.82**	**0.05**
Residual	58	0.135	0.002				
Total	59	0.78	0.013				

Table A7.12: Estimates of parameters, Pittsworth

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.01	0.002	52.602	**<0.001**
Mobility number	-0.005	0.0004	-11.91	**<0.001**

A7.2.3: Relationship between motion resistance coefficient and mobility number, **Gatton** site

Table A7.13: Summary of analysis, Gatton

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	2.096	2.096	610.956	**<0.001**	**0.91**	**0.06**
Residual	58	0.199	0.003				
Total	59	2.295	0.039				

Table A7.14: Estimates of parameters, Gatton

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.15	0.002	73.562	**<0.001**
Mobility number	-0.008	0.0003	-24.718	**<0.001**

A7.2.4: Relationship between motion resistance coefficient and mobility number, **Hopetoun** site

Table A7.15: Summary of analysis, Hopetoun

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	0.559	0.559	835.121	**<0.001**	**0.93**	**0.03**
Residual	58	0.039	0.001				
Total	59	0.598	0.01				

Table A7.16: Estimates of parameters, Hopetoun

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.151	0.002	95.028	**<0.001**
Mobility number	-0.003	0.0001	-28.898	**<0.001**

A7.2.5: Relationship between motion resistance coefficient and mobility number, **Swan Hill** site

Table A7.17: Summary of analysis, Swan Hill

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	0.675	0.675	451.381	**<0.001**	**0.88**	**0.04**
Residual	58	0.087	0.001				
Total	59	0.761	0.013				

Table A7.18: Estimates of parameters, Swan Hill

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.112	0.002	52.644	**<0.001**
Mobility number	-0.006	0.0003	-21.246	**<0.001**

A7.2.6: Relationship between motion resistance coefficient and mobility number, **Waikerie** site

Table A7.19: Summary of analysis, Waikerie

Source	d.f.	s.s.	m.s.	v.r.	Fpr.	Adjusted R^2	SE
Regression	1	0.194	0.194	145.68	**<0.001**	**0.71**	**0.04**
Residual	58	0.077	0.001				
Total	59	0.271	0.005				

Table A7.20: Estimates of parameters, Waikerie

Parameter	estimate	s.e.	t(96)	t pr.
Constant	0.192	0.005	39.77	**<0.001**
Mobility number	-0.017	0.001	-12.07	**<0.001**